αβγ

Ecole Joliot Curie

100 years of studying the nucleus

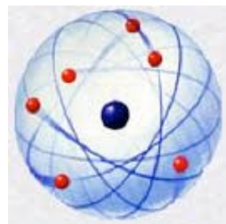
A. Lopez-Martens

CSNSM
CNRS IN2P3 Les deux infinis
UNIVERSITÉ PARIS-SUD 11

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



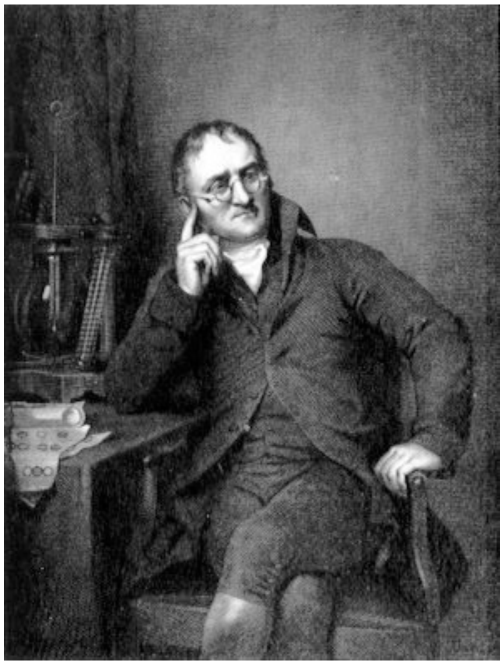
The Nobel Prize in Chemistry 1911 was awarded to Marie Curie *"in recognition of her services to the advancement of chemistry by the discovery of the elements radium and polonium, by the isolation of radium and the study of the nature and compounds of this remarkable element"*.

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."

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

Constituents of matter



John Dalton

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

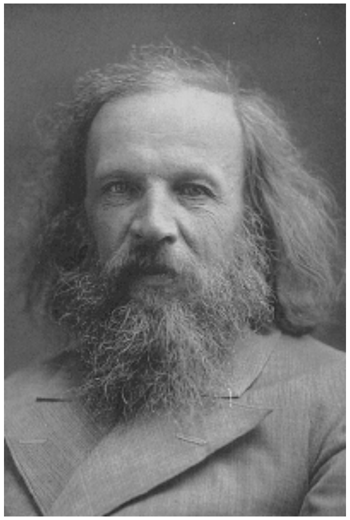
-atoms of the same element are identical

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?		

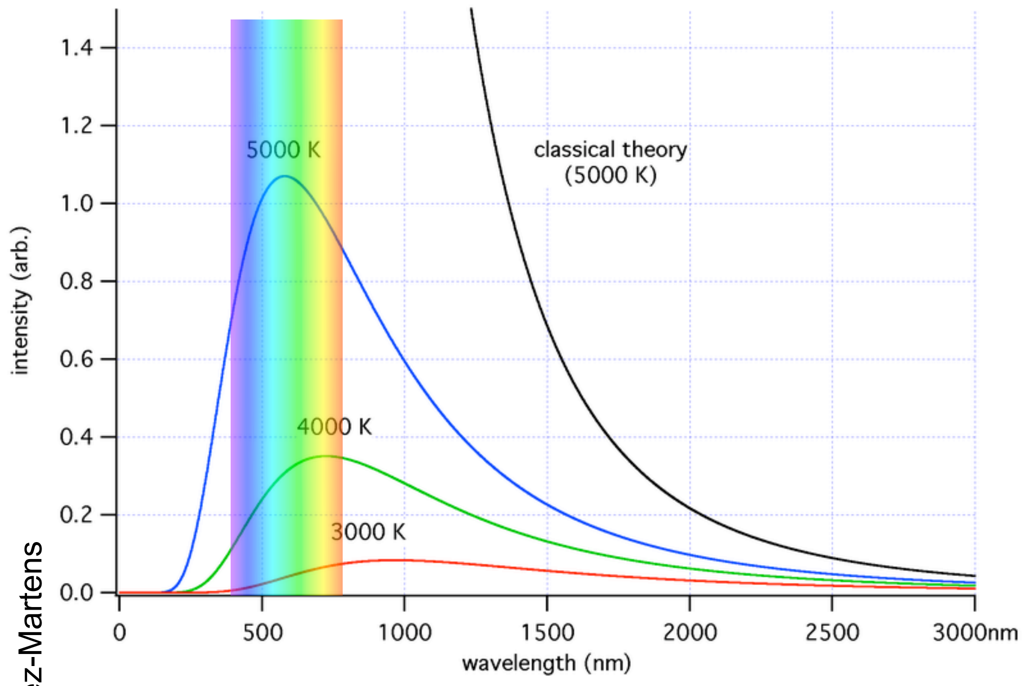
Д. Менделѣевъ (1869)

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.....

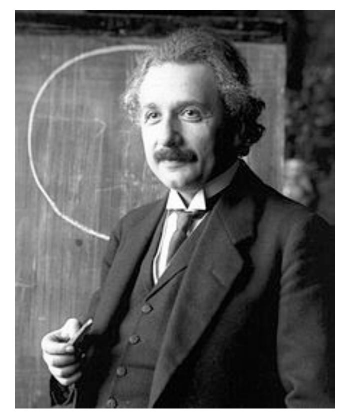
ultraviolet catastrophe: spectral distribution of

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**

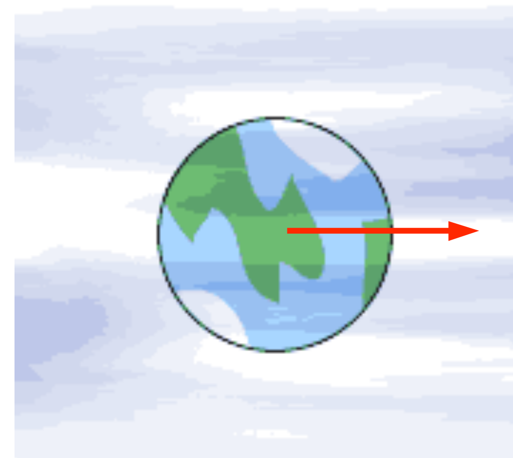


Albert Eisntein

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



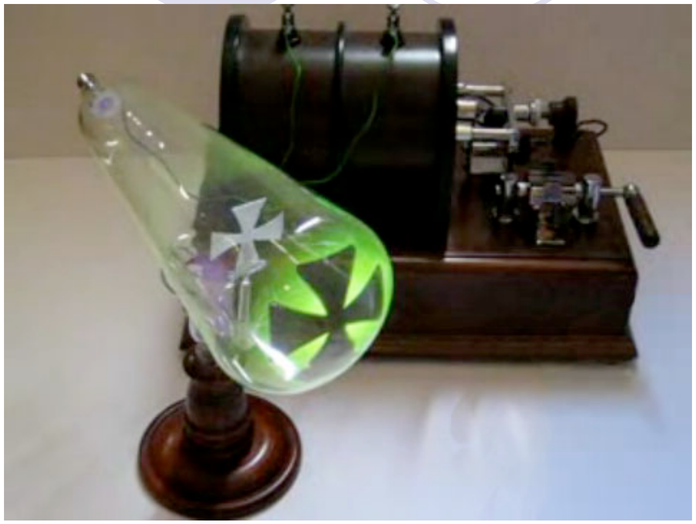
⇨ any object moving in the aether should measure a different speed of light

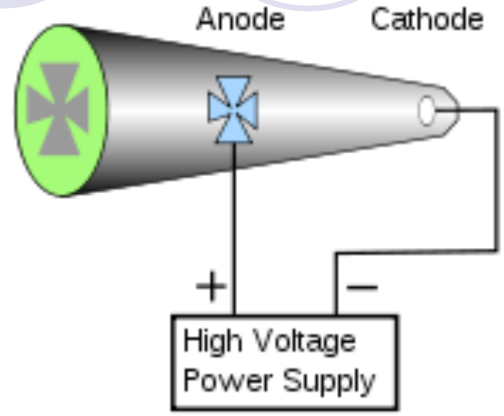
1887: failure of the Michelson-Morley interferometry experiment

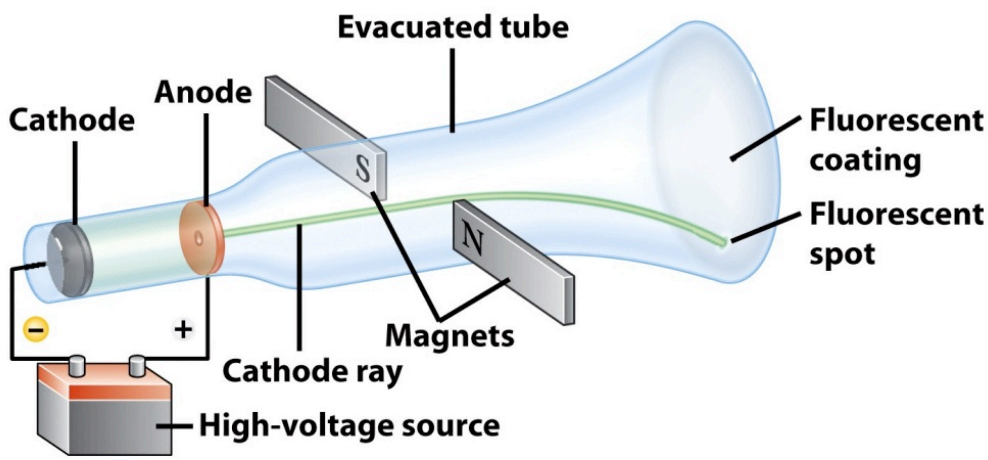
A. Einstein reconciles Newton's mechanics and Maxwell's electromagnetism with the theory of special relativity: "On the Electrodynamics of Moving Bodies"

$$E = mc^2$$

The cathode tube leads the revolution

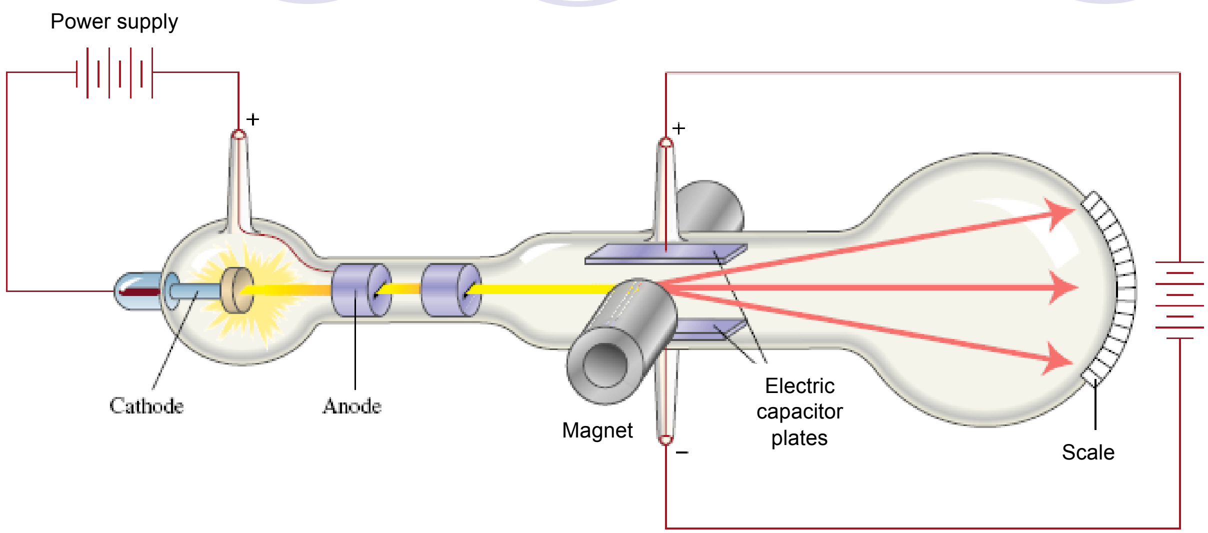


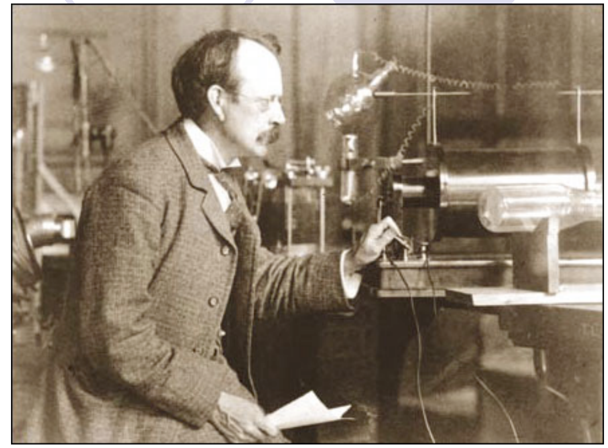




1895: Jean Perrin demonstrates that cathode rays are negatively charged particles

Atoms are no longer indivisible !



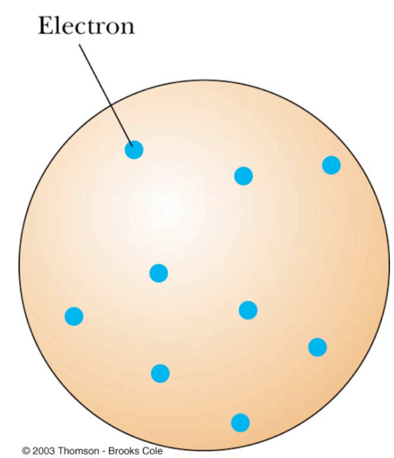


John Joseph Thomson

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

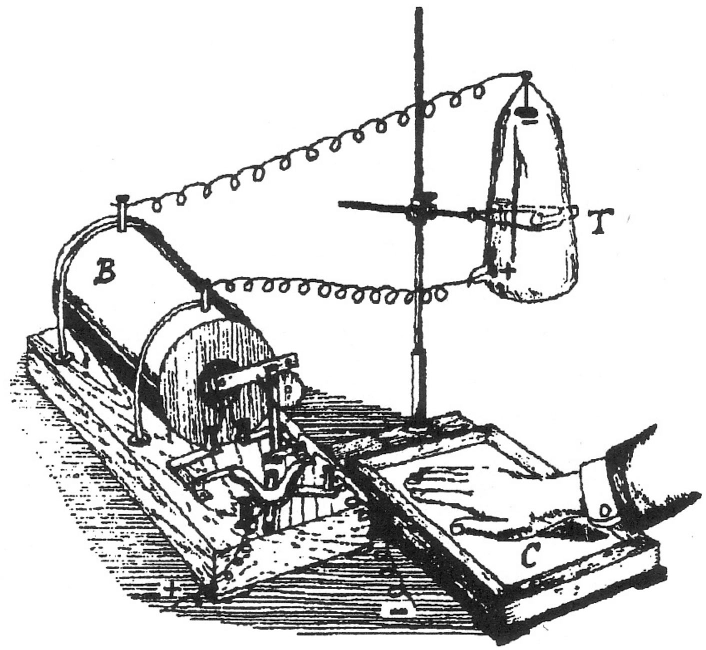
'plum pudding' model



From cathode rays to X rays

1895 W. Röntgen discovery of X rays

Wilhelm Röntgen

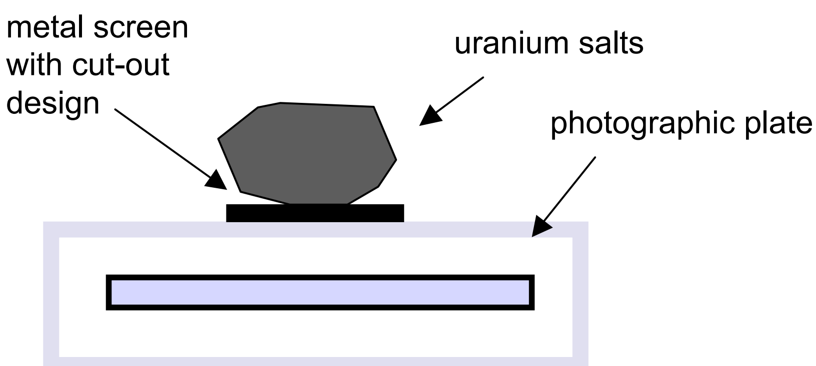


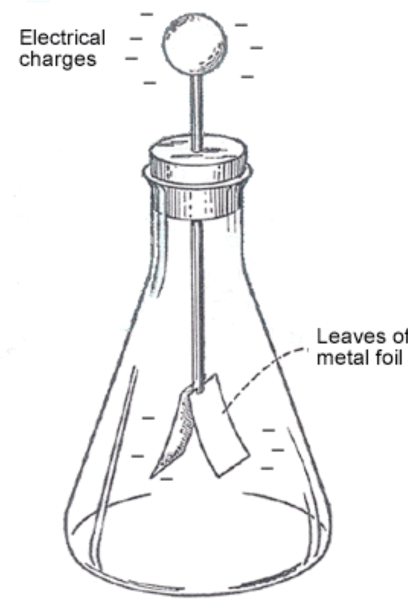
W. Röntgen receives the 1st Nobel Prize in Physics in 1901

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

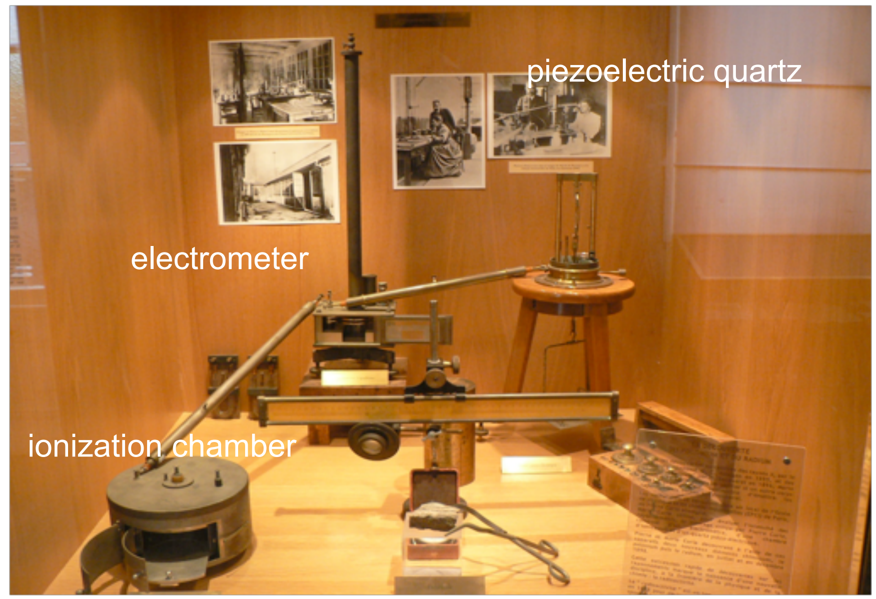
From Uranium rays to radioactivity

1898 Marie & Pierre Curie

extraction of polonium and radium


Marie Curie


Pierre Curie



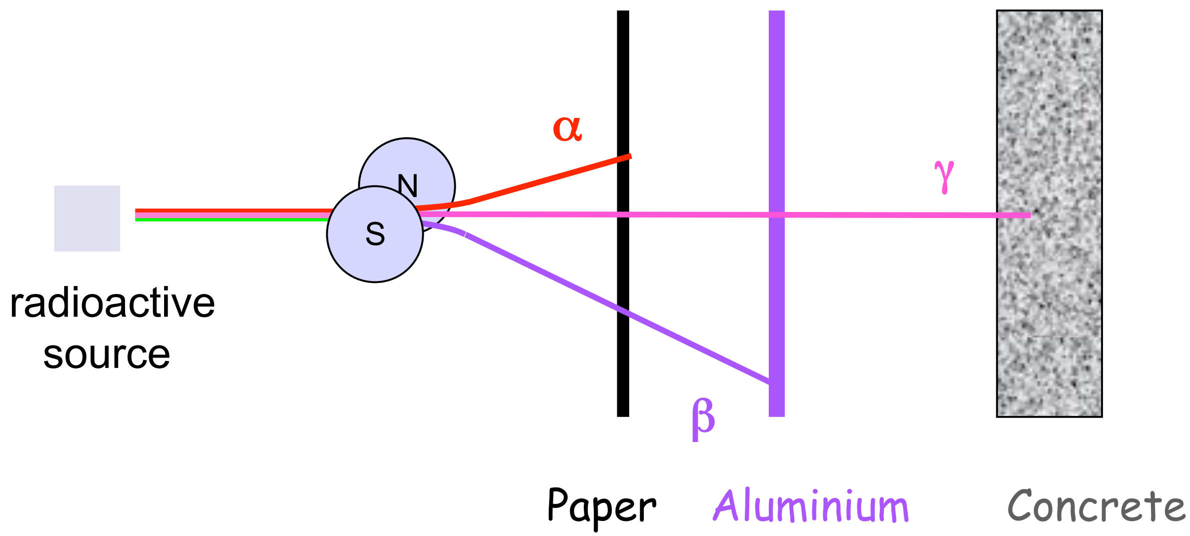

Laboratory at the Ecole de Physique et Chimie industrielle de Paris

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+}

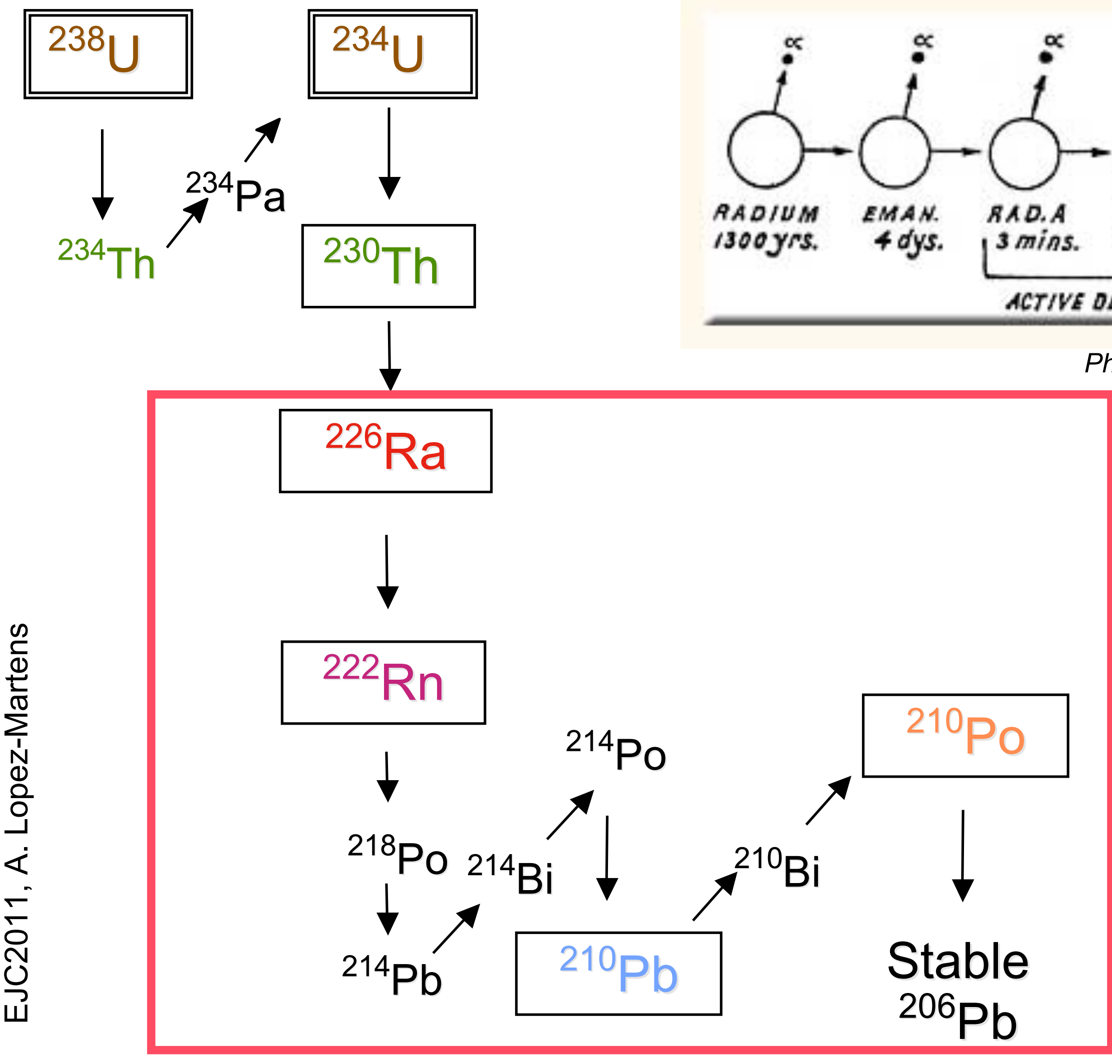
β= high energy e^-

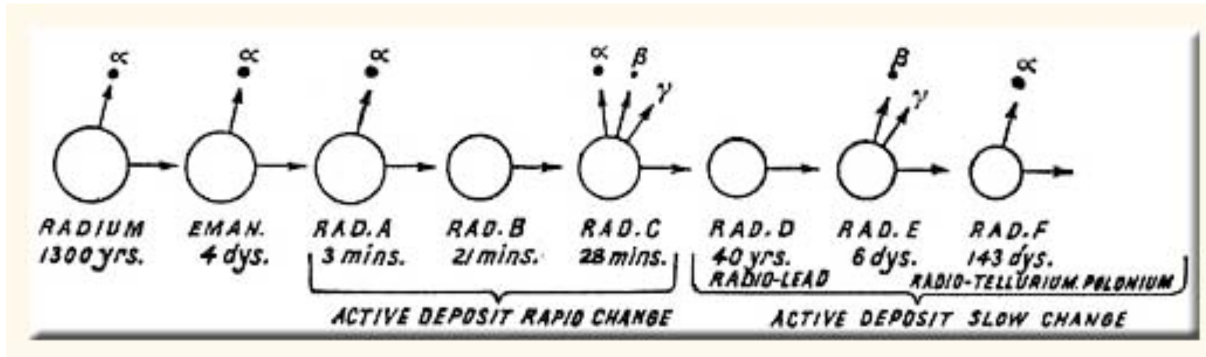
γ= photons - like X rays

Atoms transform !

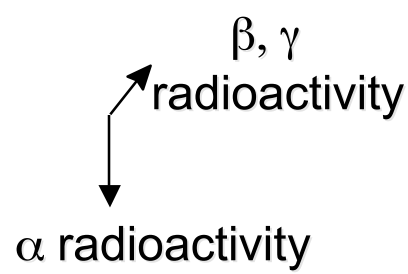
1902 E. Rutherford & F. Soddy

transmutation of atoms





Philosophical Transactions of the Royal Society of London, 1905



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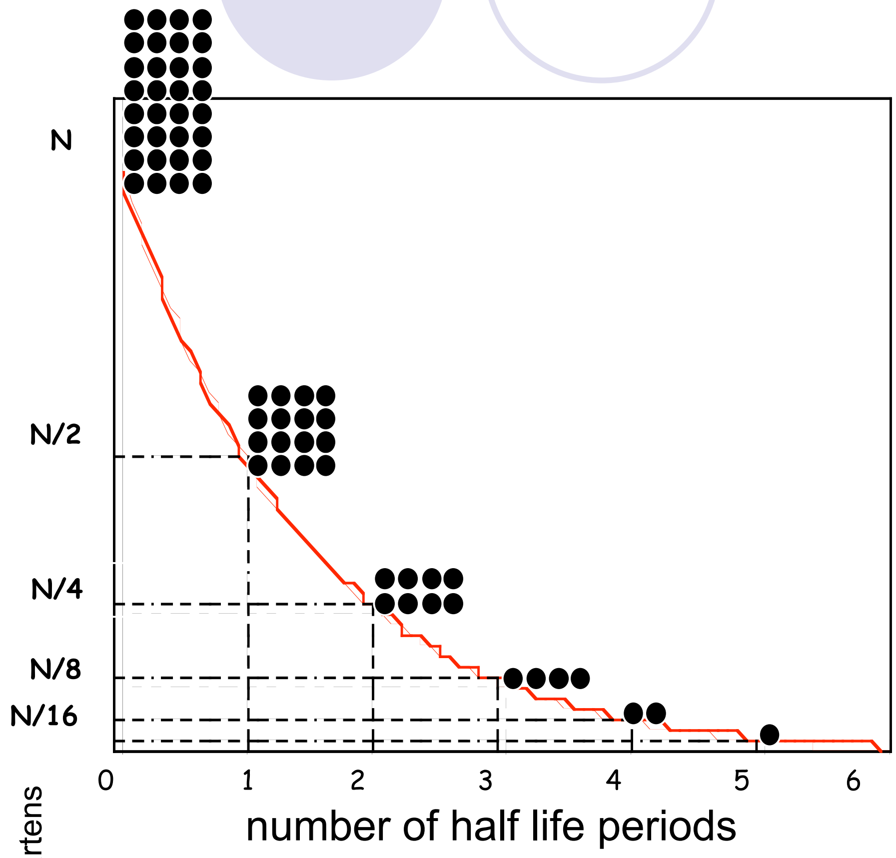
Radioactive decay



Number of nuclei at time t

Initial number of nuclei

Decay constant

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

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

Lifetime

Some examples of activity :

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

1910:

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

1 Ci = 37 billion decays/s

1 Bq = 1 decay/s

Radioactivity and Energy

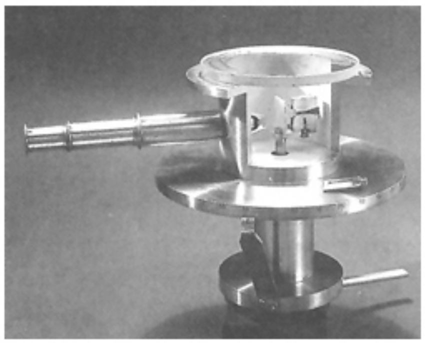
1903: Pierre Curie and his collaborator Albert Laborde find that radium gives off enough heat to melt more than its weight of ice in an hour

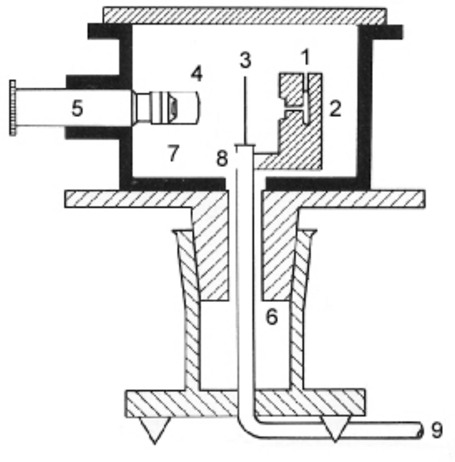
Where does this energy come from ?

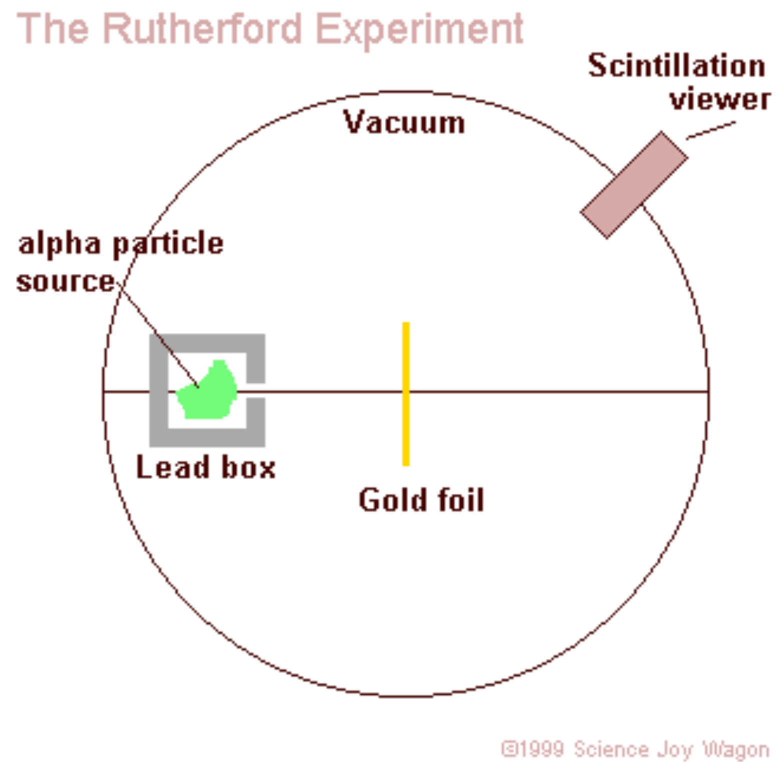
« There is reason to believe that an enormous store of latent energy is resident in the atoms of radioactive elements. If it were ever possible to control at will the rate of disintegration of the radio-elements, an enormous amount of energy could be obtained from a small amount of matter. »

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

Scattering of alpha particles





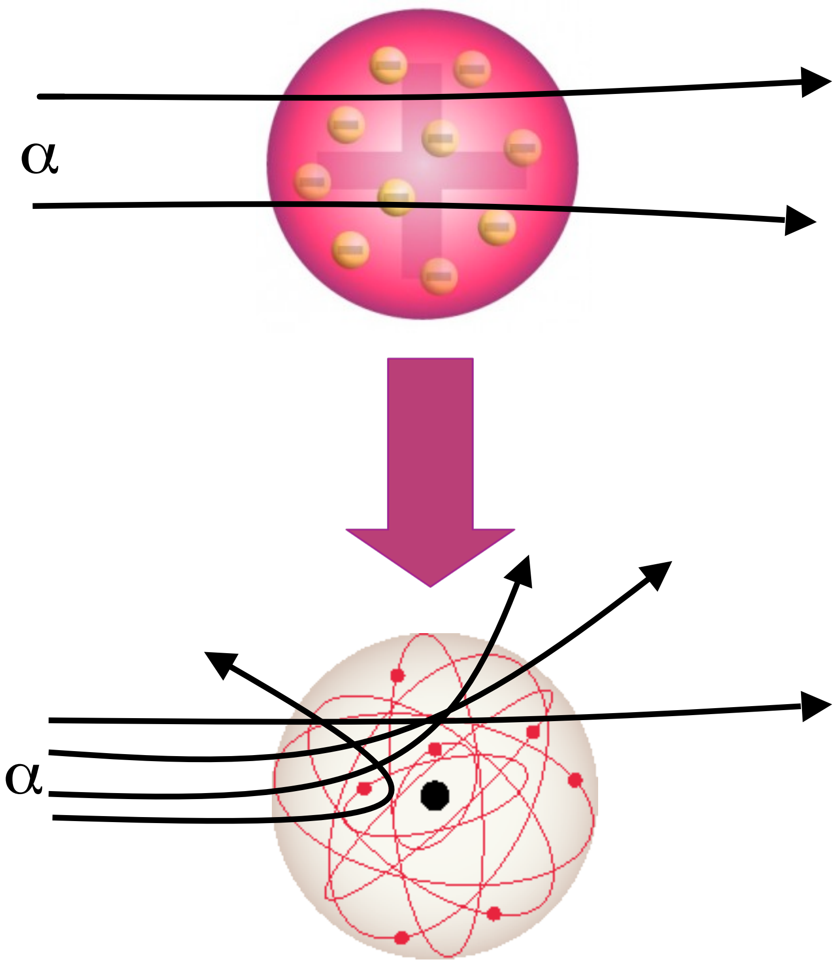


Experiment performed by H. Geiger and E. Marsden
(1909, University of Manchester)

"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! "

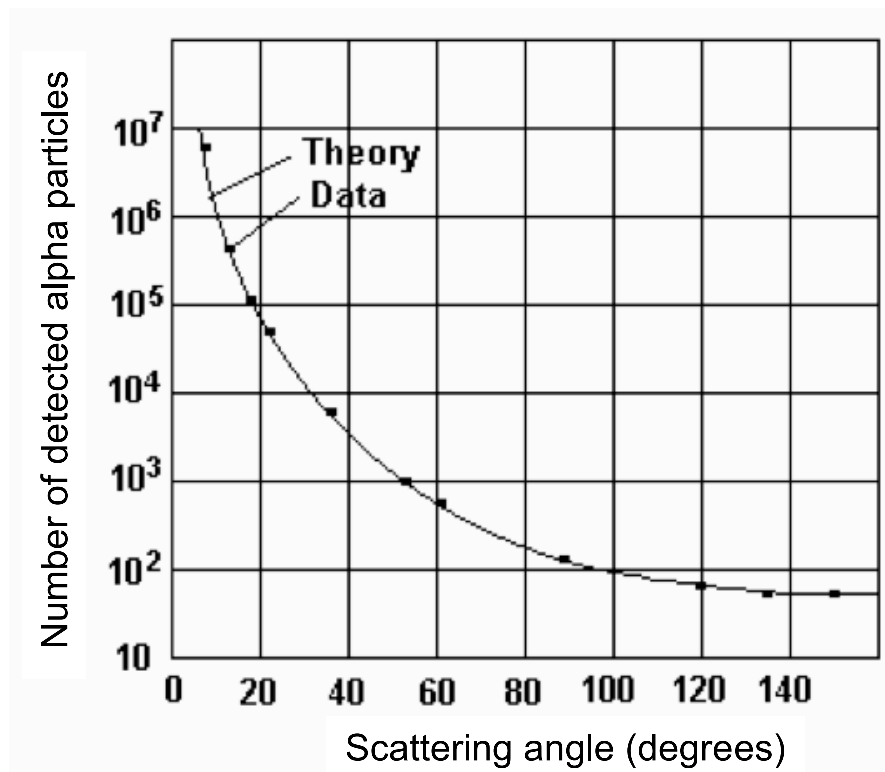
The nucleus is born !

'plum pudding' model

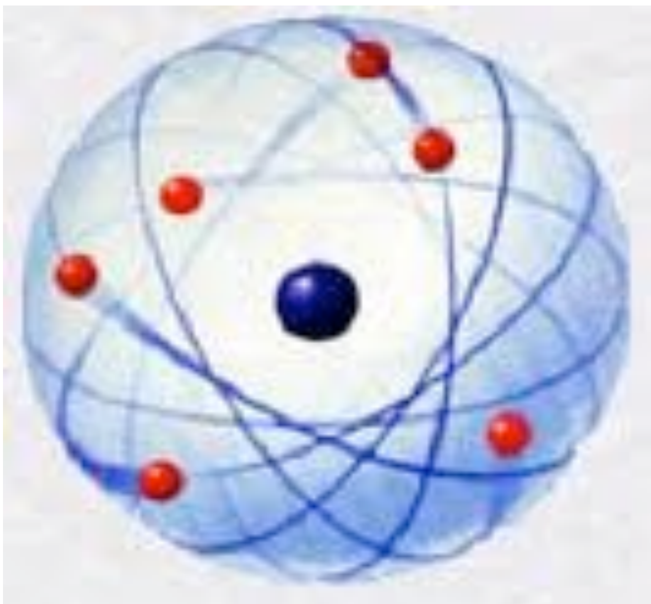


Nuclear model

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



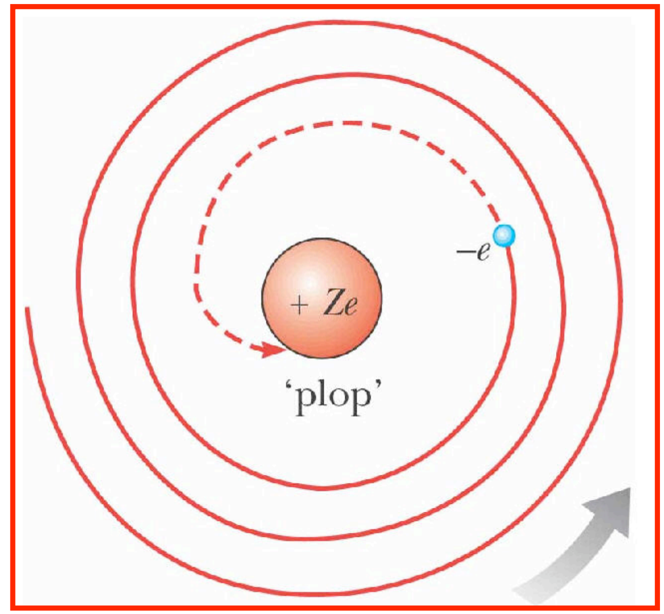
Consequences of Rutherford's model



10^{-14} m

10^{-10} m

Matter is empty !



The atom is unstable !

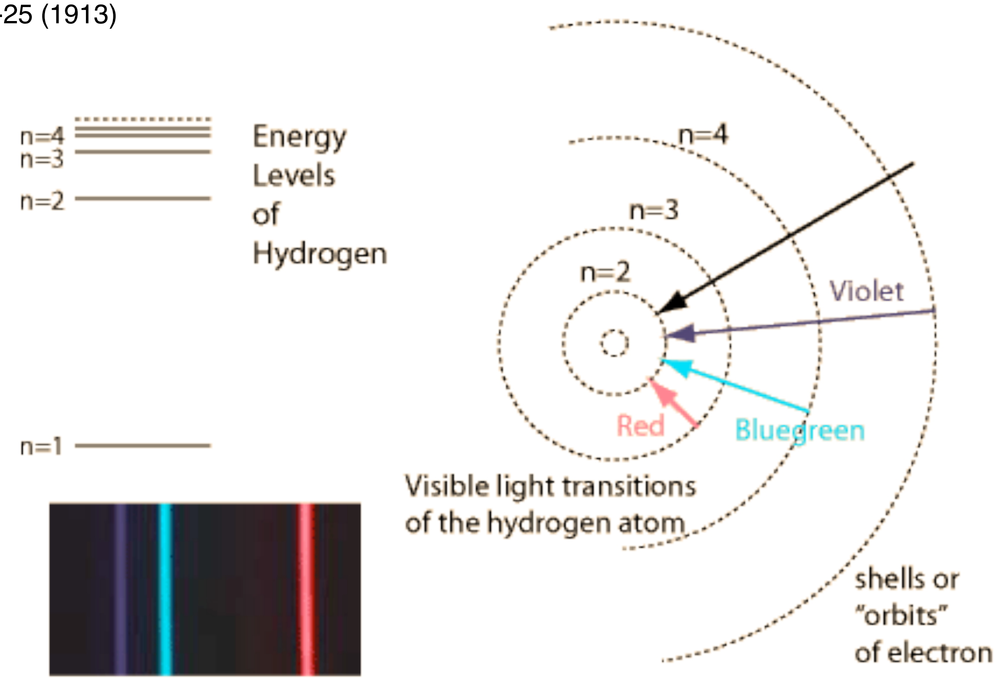
Bohr solves the problem with Planck's quanta

- 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)

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



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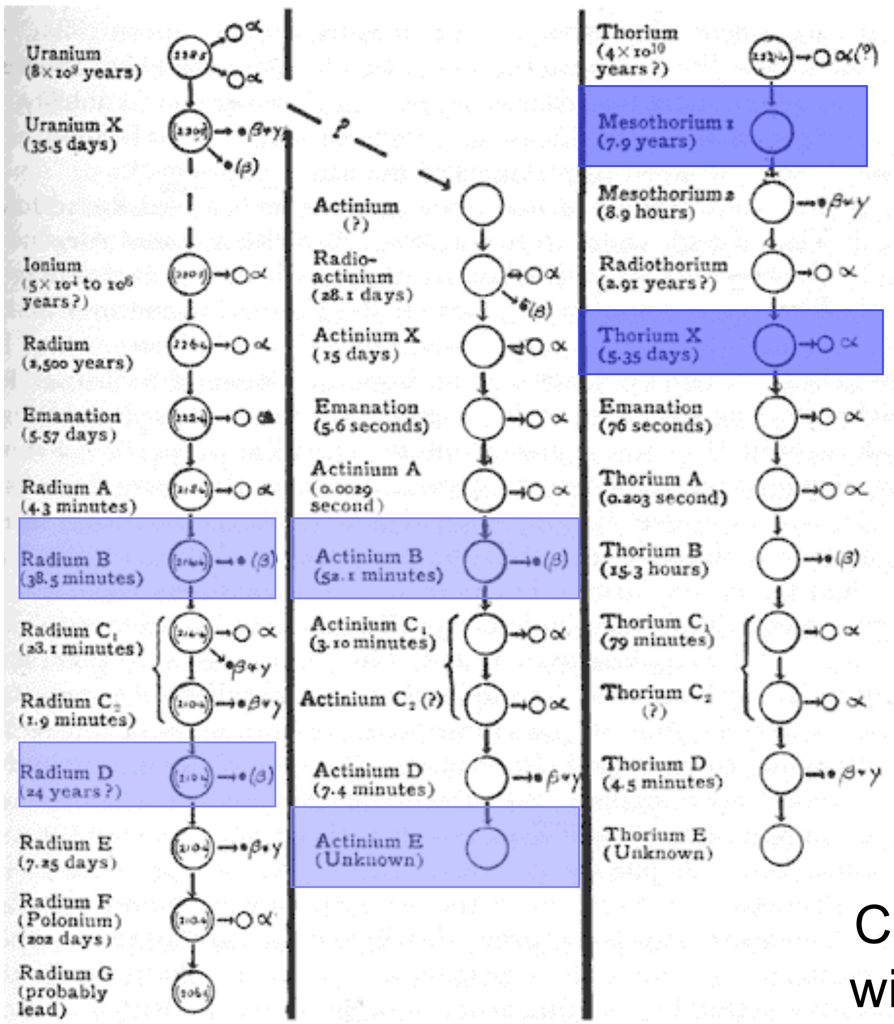
Dalton’s atom undermined



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

More than 40 radio-elements discovered in 15 years

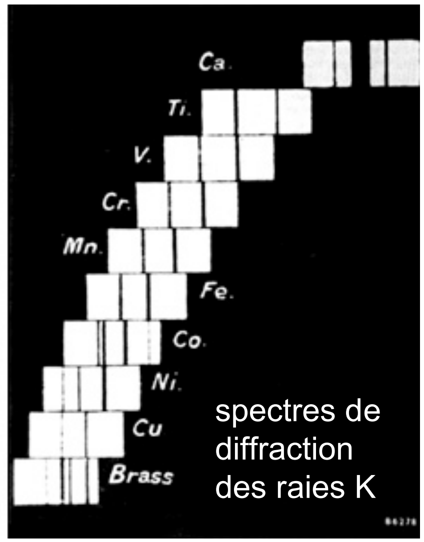
Problem: There are only 7 empty spaces in the periodic table between Bi and U!

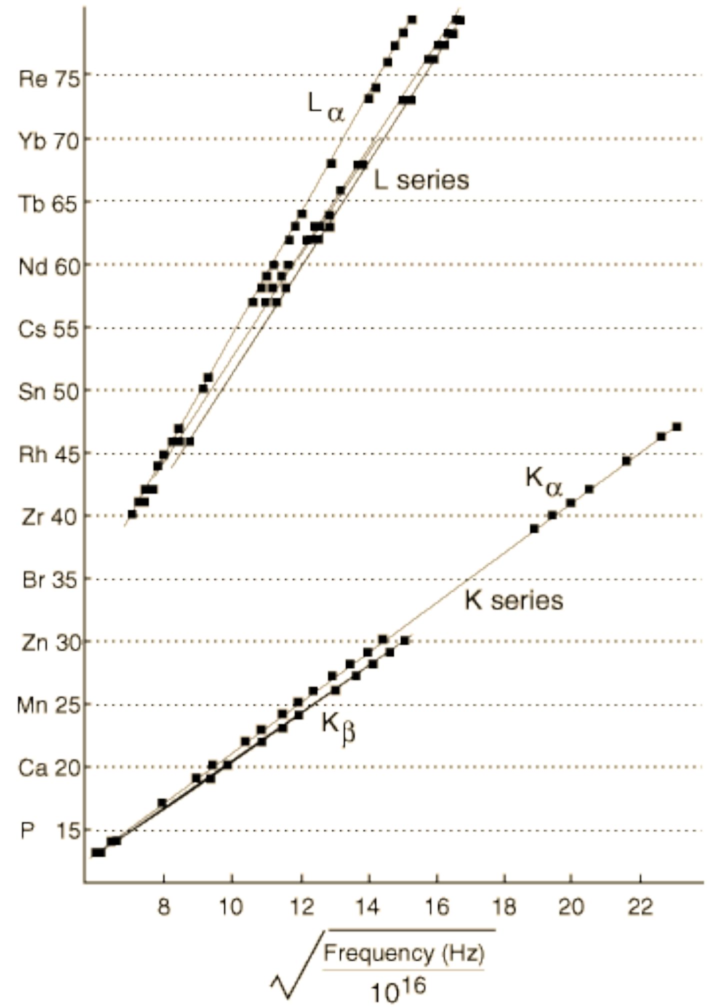
Inseparability of certain radio-elements

1913 Frederick Soddy

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

The periodic table finds its thread





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

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

The alchemists of the 20^{th} century

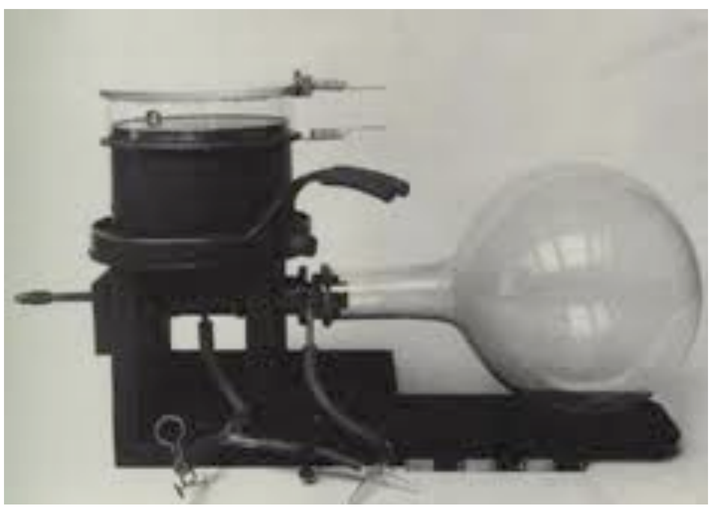
1919 E. Rutherford

1st artificial transmutation

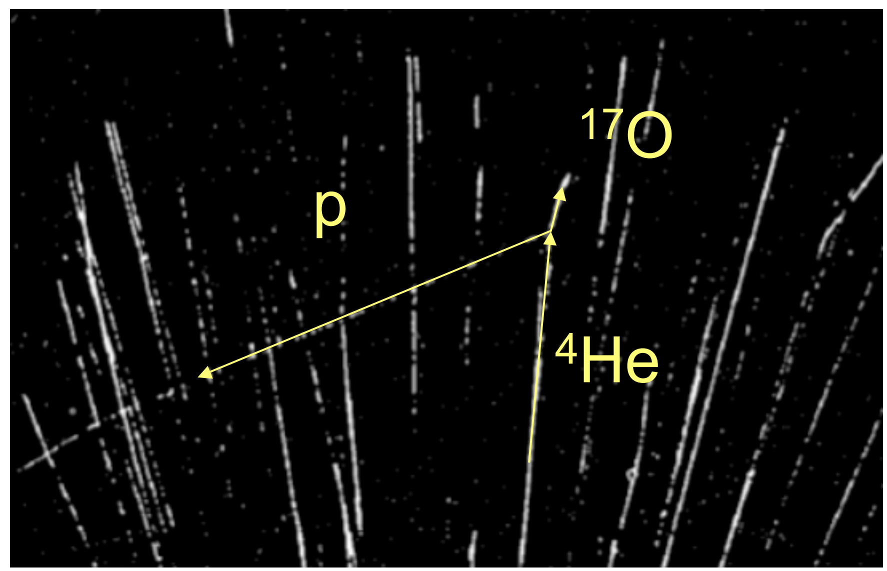
α + Nitrogen → Hydrogen

Rutherford calls H^+ proton

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

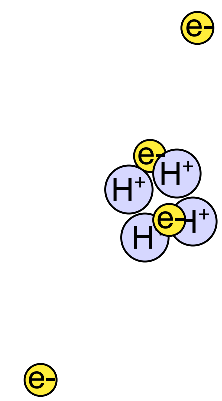


Cloud chamber (C.T.R. Wilson, 1912)



Structure of the nucleus

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

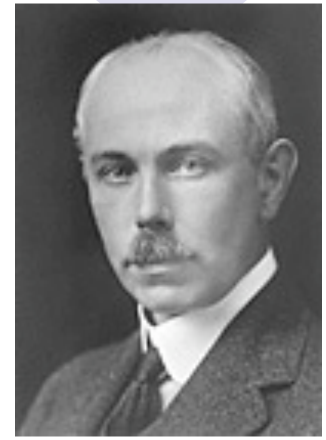


E. Rutherford suggests the existence of an e^--p pair, which would have all the characteristics of a neutral particle

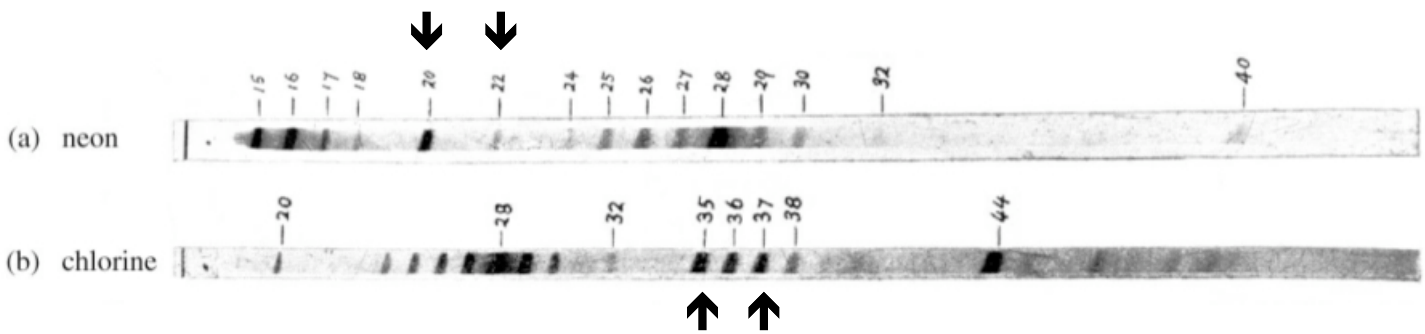
*Bakerian Lecture, Proc. Roy. Soc. A, **97**, 374 (1920)*

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

The beginnings of mass spectrometry



Francis Aston



1919: F. Aston verifies the concept of isotope and measures isotopic abundances

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

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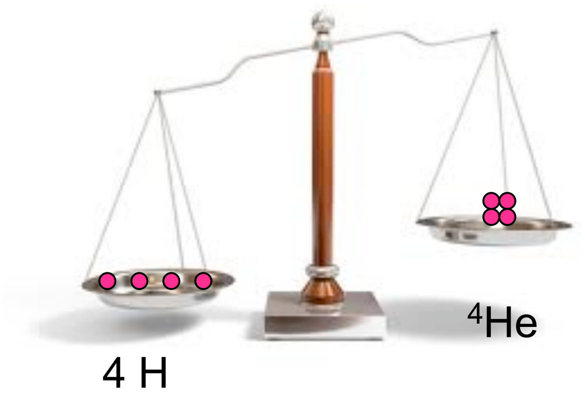
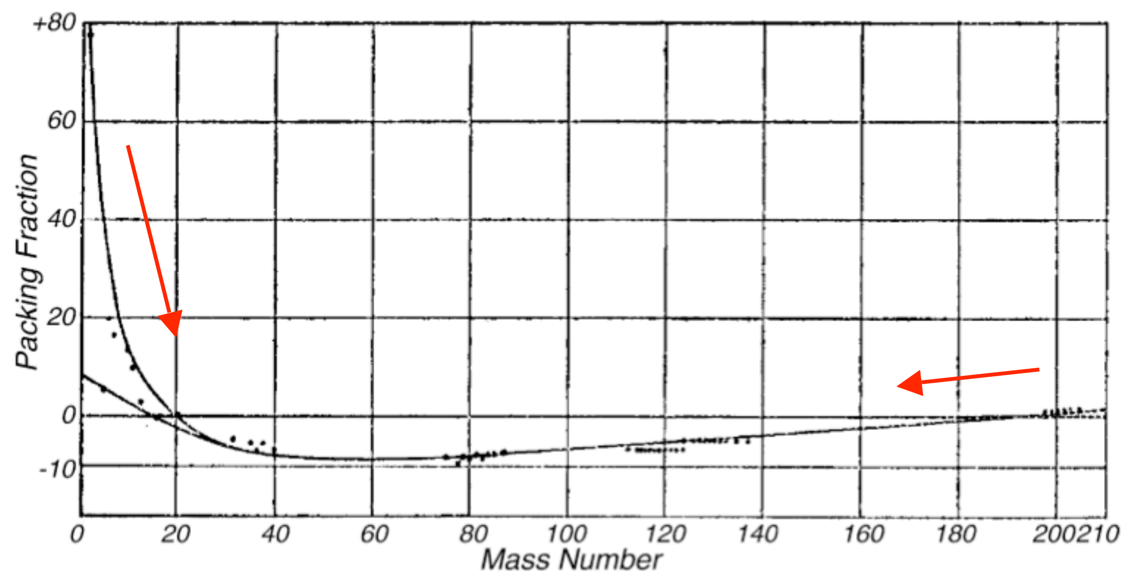
Mass excess



F. Aston proposes that mass is lost to form nuclei

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

'packing fraction'= 10 000 (M – A)/A



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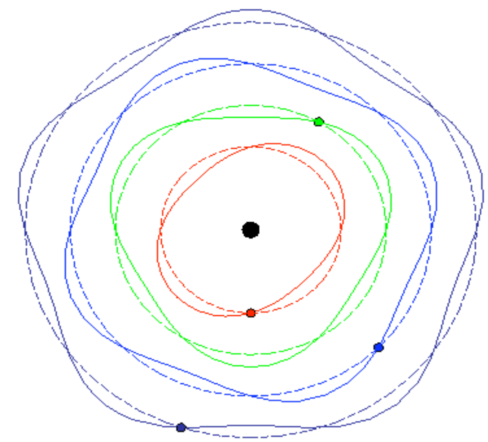
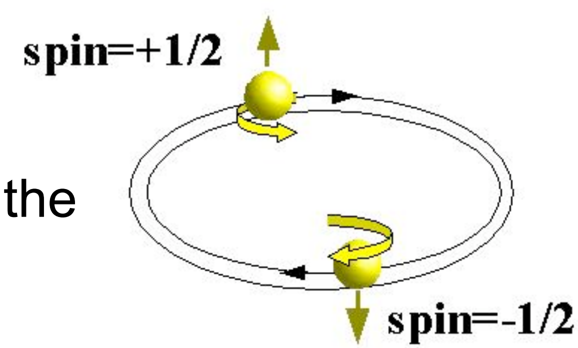
Development of Quantum Mechanics

1924: L. de Broglie formulates the hypothesis that all matter has a wave-like nature and reinterprets Bohr's condition as that of a stationary wave

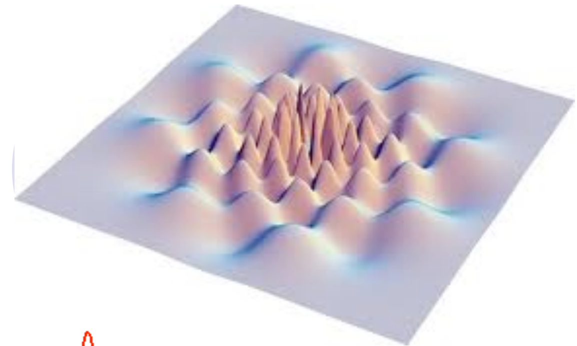


1924-1925: W. Pauli states the 'exclusion principle' according to which no more than one electron can occupy the same quantum state and postulates the existence of a new property of the electron, which may only take on 2 values

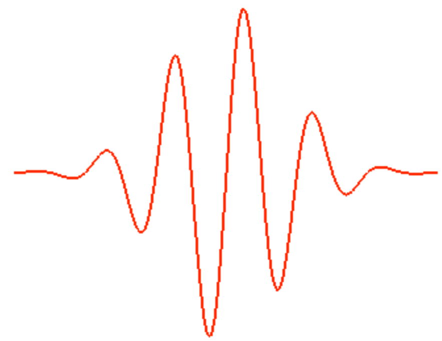
1925: G. Uhlenbeck and S. Goudsmit suggest that the new property is related to spin

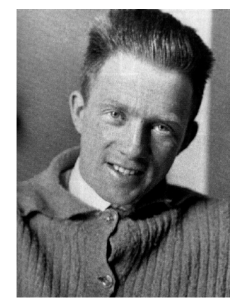


The Wave Function



1926 : E. Schrödinger describes the evolution of the particle wave function



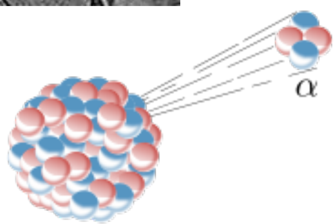


1926: W. Heisenberg states the Uncertainty Principle: “The more precisely the position is determined, the less precisely the momentum is known, and vice versa.”

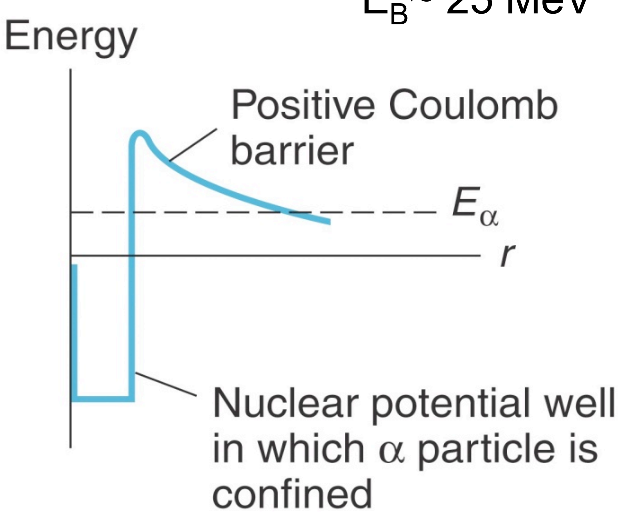
M. Born reconciles the particle and wave-like nature of matter : the wave function describes the probability of existence of a particle within a given region of space

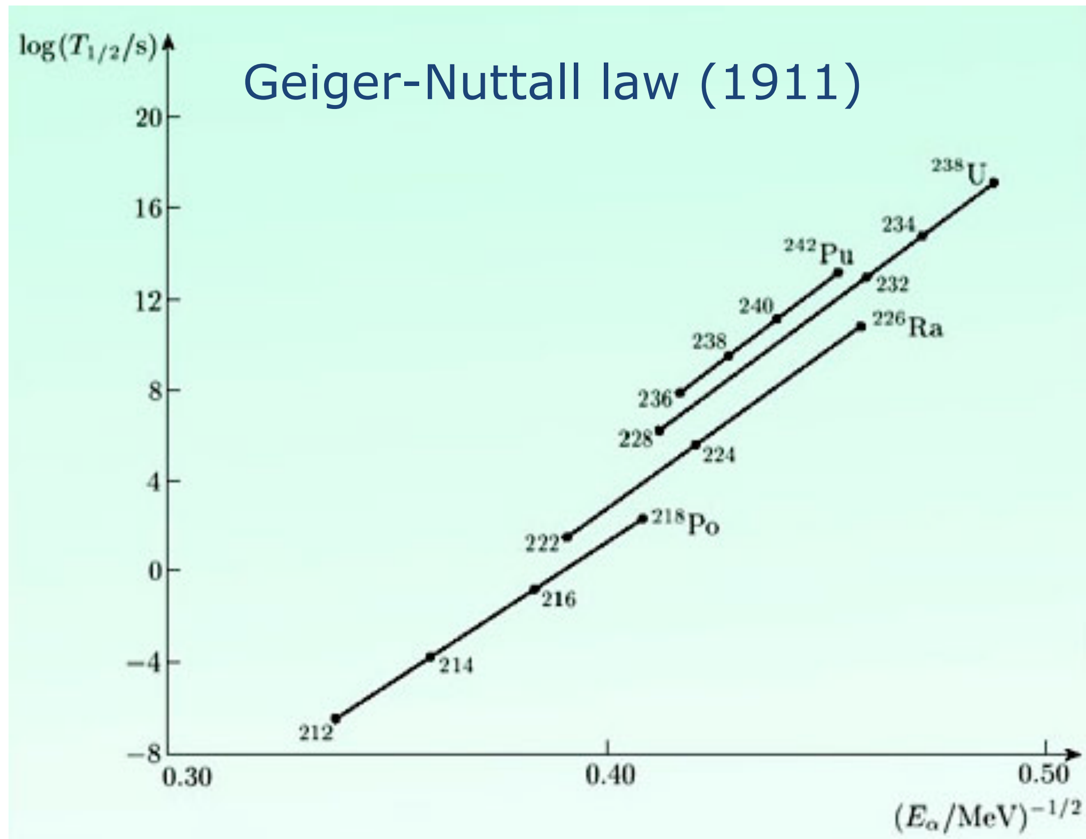
The theory of α decay

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



^{212}Po
E_α=8.78 MeV
E_B~ 25 MeV





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Antimatter

Special Relativity　　Quantum Mechanics

relativistic electron

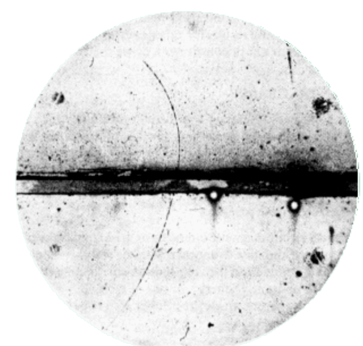
1929 : Dirac equation

The Dirac equation has 2 solutions ! { electron / ????

1930: P. Dirac invents the anti-electron

e^- electron | e^+ anti-electron

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



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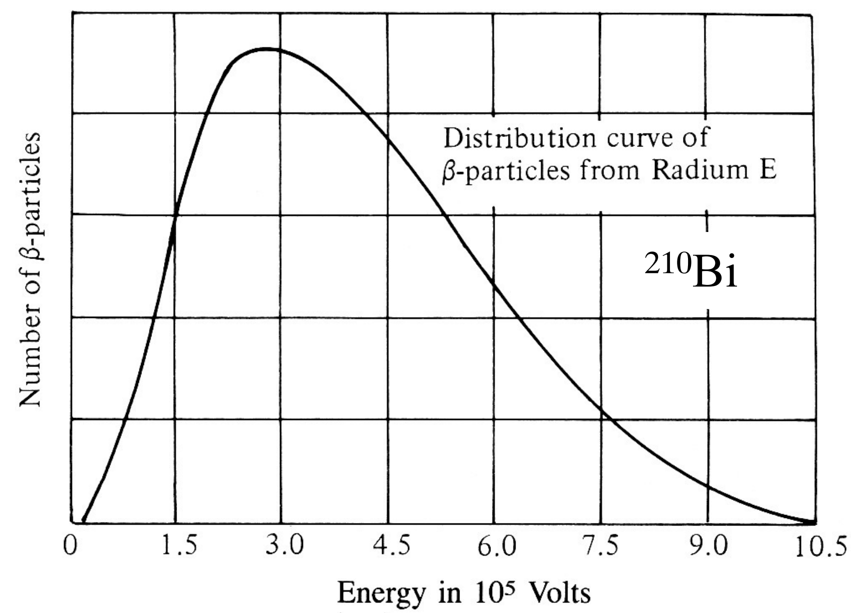
β decay and the neutrino hypothesis

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...!’

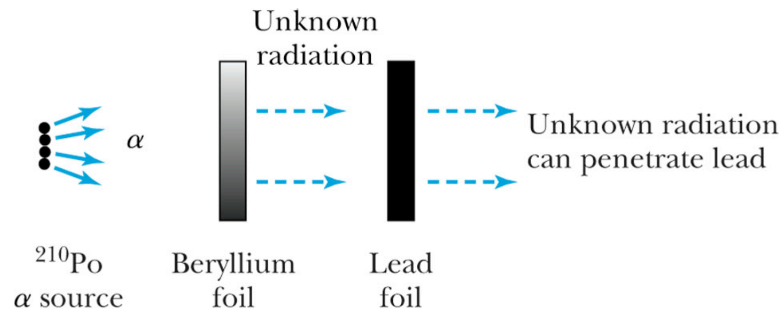
1927: Calorimetric experiment performed by C.D. Ellis and W.A. Wooster: average e^- energy < endpoint of β spectrum

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^-

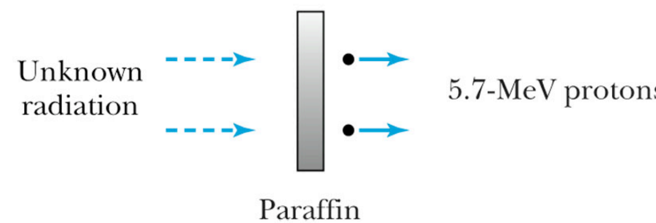
Discovery of the neutron

1930-32

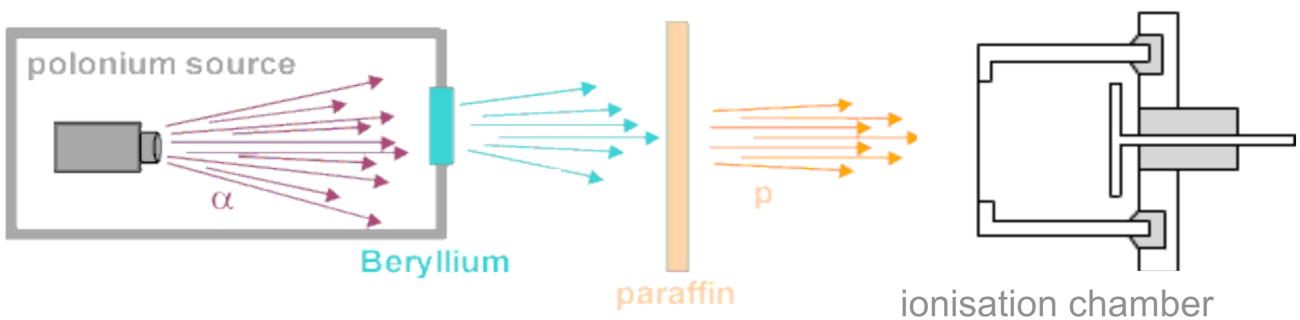
W. Bothe & H. Becker discover a strange reaction



I. Curie & F. Joliot observe the ejection of protons



James Chadwick



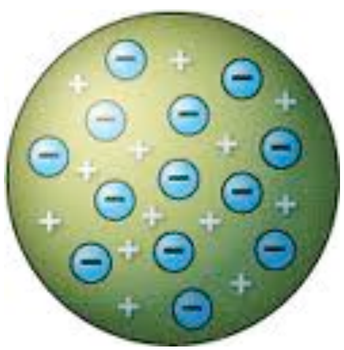
J. Chadwick shows that the mysterious radiation corresponds to a particle of mass ~1: the neutron

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

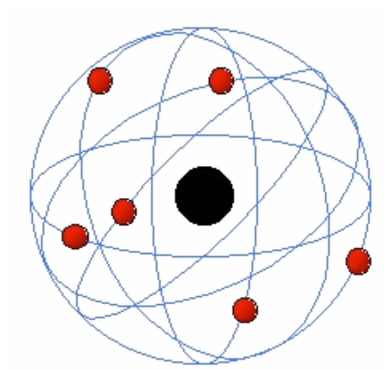
The nucleus is complete !

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

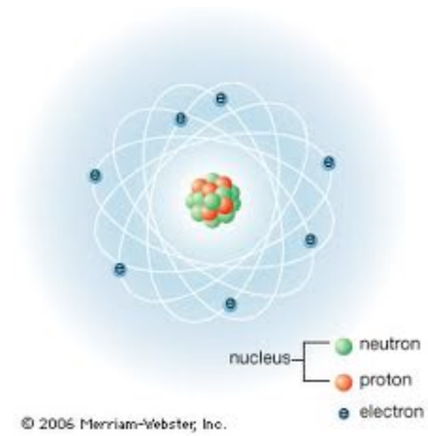
1898



1911



1932

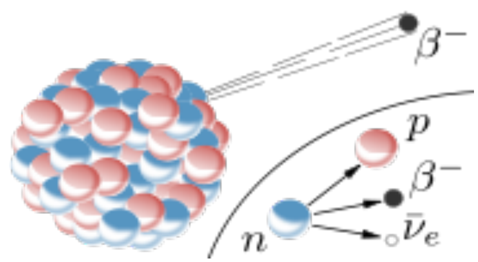


$$ {}^{A}_{Z}X_{N} $$

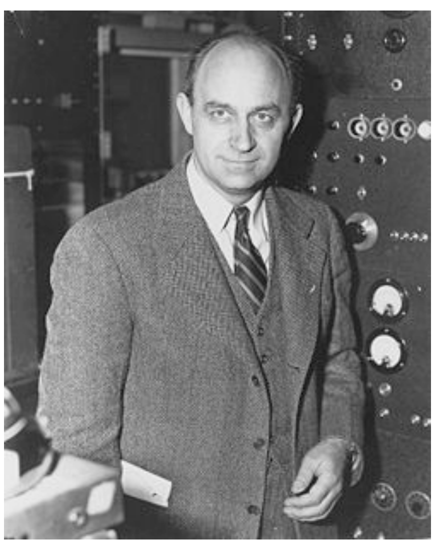
The presence of neutrons in the nucleus explains the phenomenon of isotopy and resolves some nuclear spin problems and the issue of e^- confinement

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



$$n \rightarrow p + e^{-} + \nu_e$$



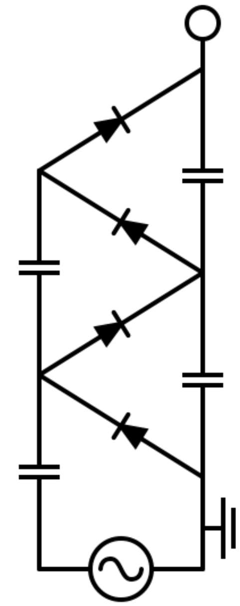
Enrico Fermi

In β-decay, the electrons are created at the time of the decay: a neutron decays into a proton with the emission of an electron and a particle, which he calls 'neutrino'

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



Cockroft-Walton voltage multiplier

Nature 129, Févier 1932, 242

Cockroft & Walton split the atom

1932: By bombarding Li with protons of energy **250 keV** , Cockroft and Walton observe the reaction:

$$p + Li \rightarrow 2\,\alpha$$

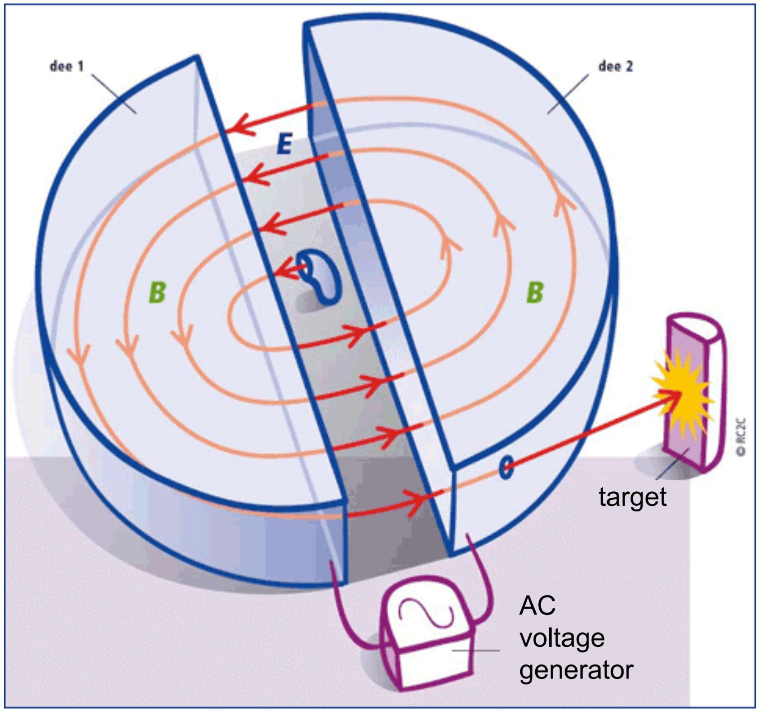
Li

The energy of 2 alpha particles is measured at **~17 000 keV**

First experimental confirmation of $E = mc^2$: Energy is preserved if $\mathbf{mc^2}$ is considered as a form of energy

Nature 129, Avril 1932, 649

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 , d~12 cm acceleration of protons up to 80 keV

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

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

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The nuclear interaction

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

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)

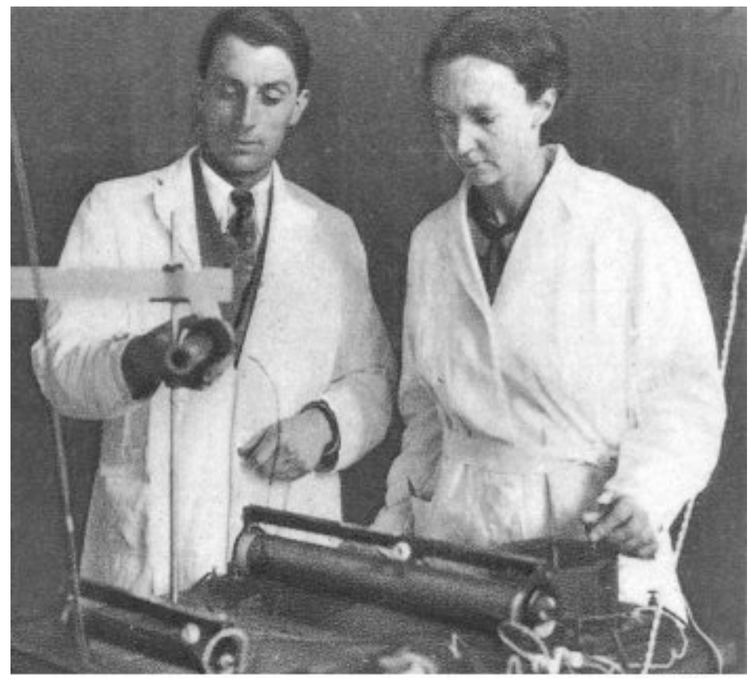
Artificial radioactivity

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 !



Library of Congress

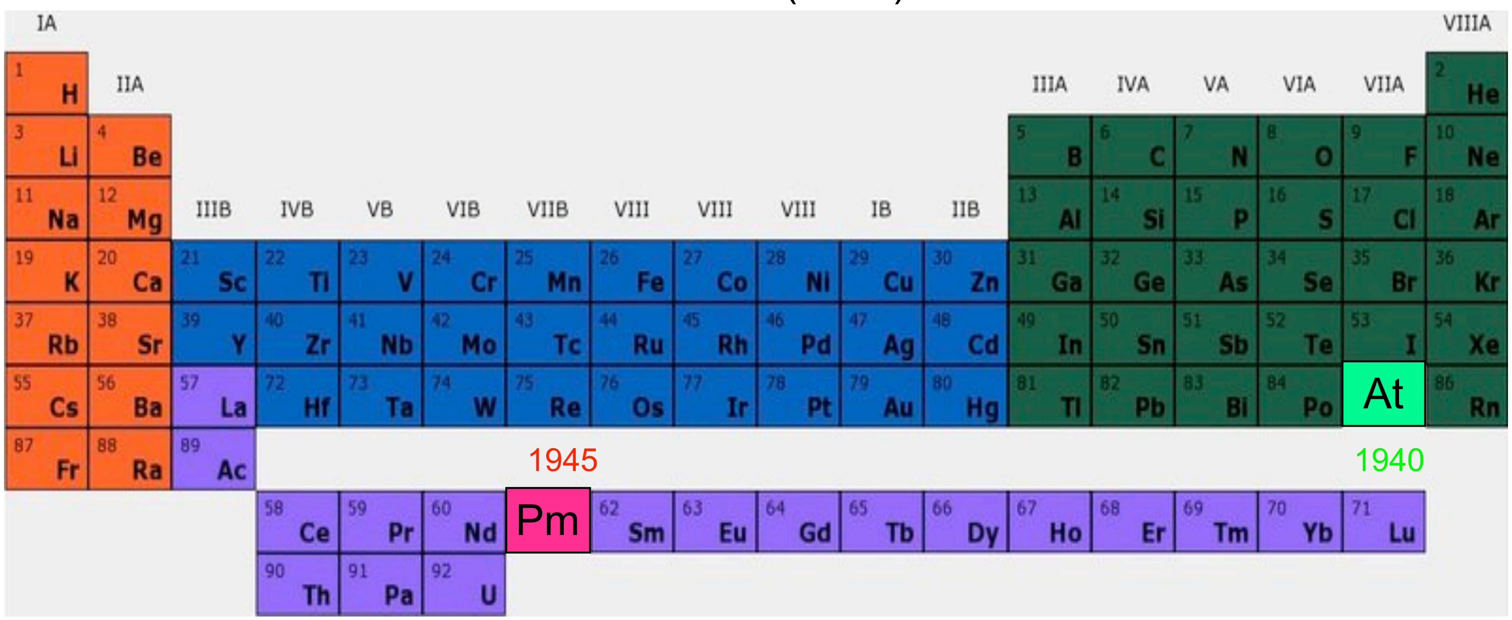
Irène Curie et
Frédéric Joliot

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

Artificial Element

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

Periodic Table (1939)



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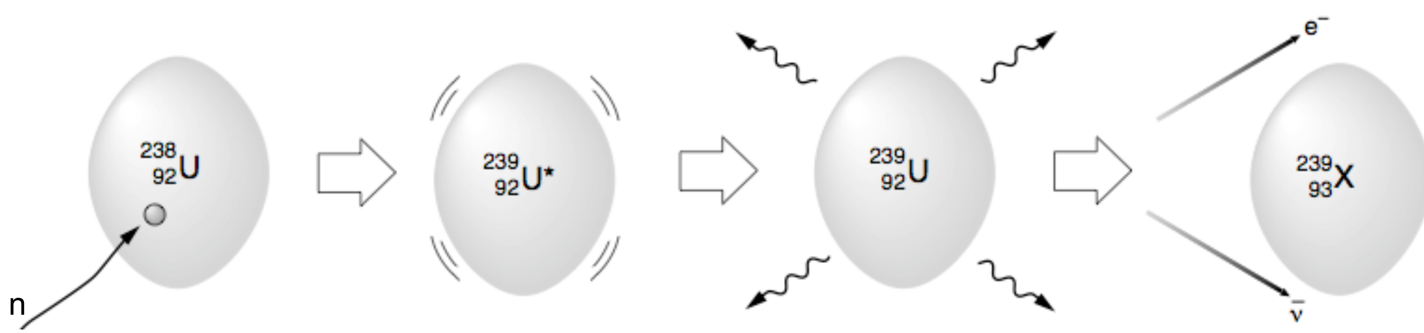
The era of the neutron

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, Transuranic element ?)

1938 O. Hahn et F. Strassmann look further into the French results by performing a detailed chemical analysis and come across a separation problem

Lise Meitner et Otto Hahn (1918)

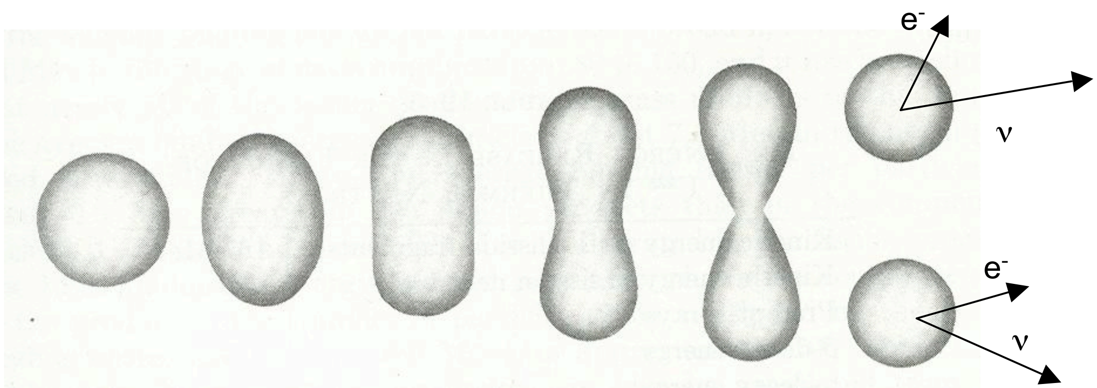
We must name Barium, Lanthanum and Cerium, what we called previously Radium, Actinium and Thorium. This is a difficult decision, which contradicts all previous nuclear physics experiments.'

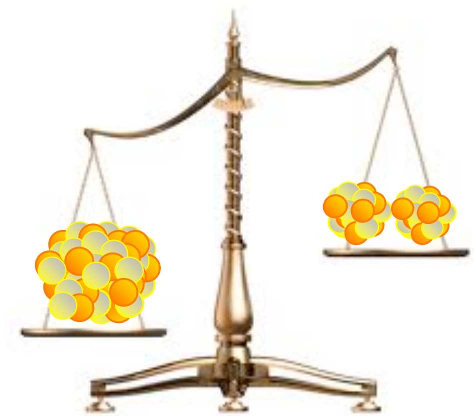
O. Hahn and F. Strassmann, Naturwiss 27 (1939) 11

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





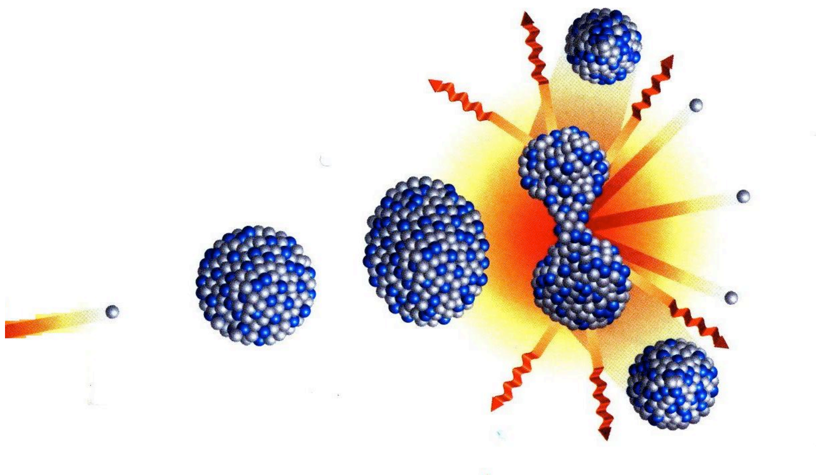
This hypothesis is immediately confirmed by O. Frisch and by others (F. Joliot)

O. Frisch, Nature 143 (1939) 276

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

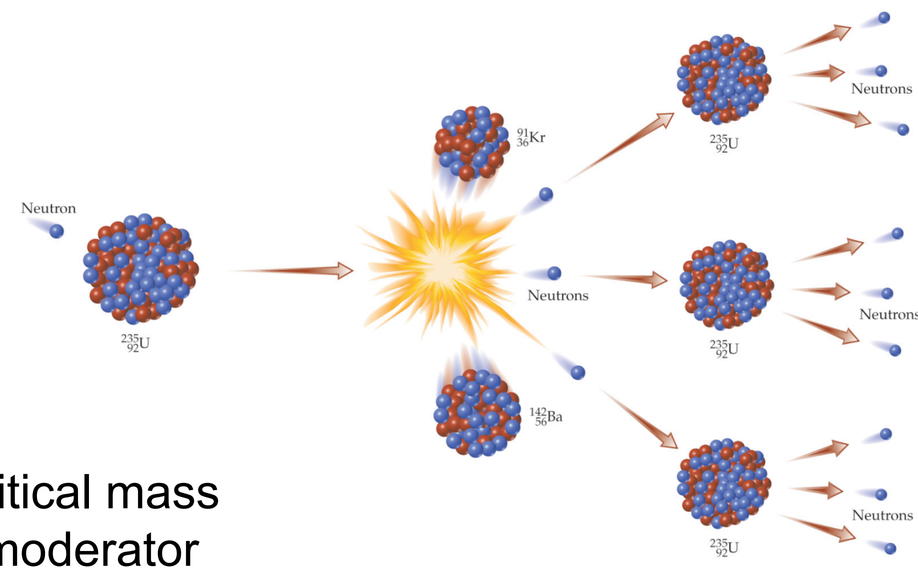
N. Bohr et A. Wheeler, Phys. Rev. 56 (1939) 426

Properties of fission



Each fission event produces neutrons

Hans Von Halban, Frédéric Joliot et Lew Kowarski, Nature 143 (1939) 470



F. Joliot sees the possibility of a chain reaction

Francis Perrin introduces the concept of critical mass and his group demonstrates the idea of a moderator

Patents are filed

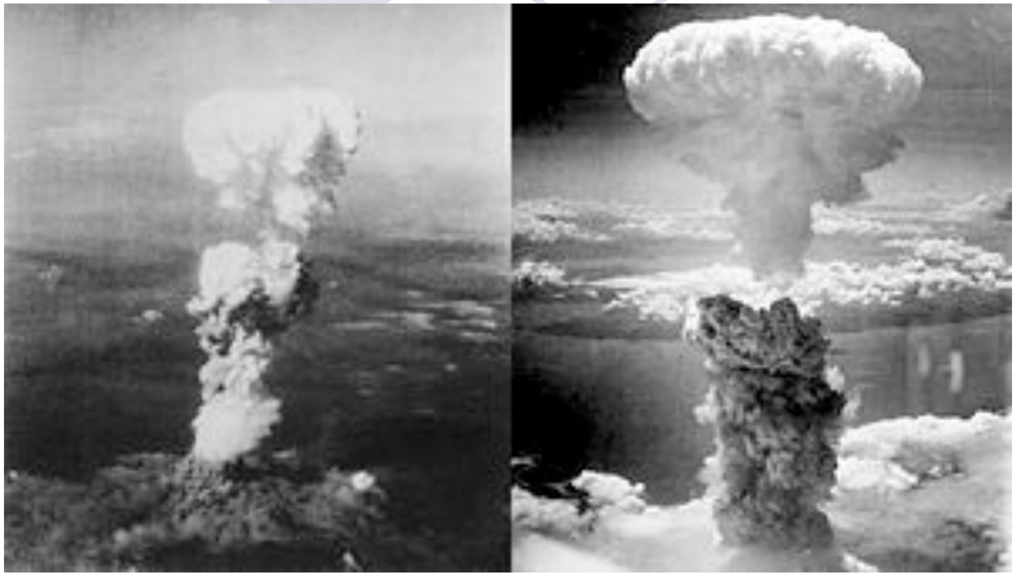
Manhattan Project and C_{hicago}P_{ile}-1

1939: Leo Szilard asks A. Einstein to sign a letter to president Franklin D. Roosevelt on the danger of nazi Germany developing an atomic bomb

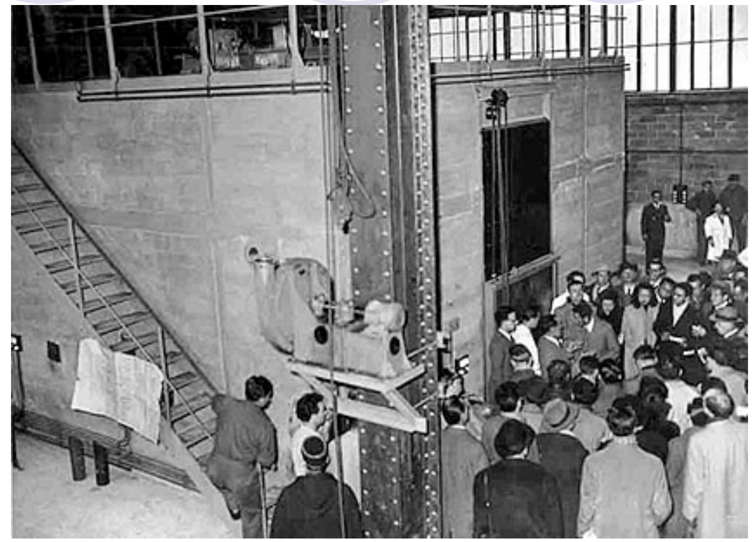
The first atomic pile is inaugurated in december 1942

The chain reaction is maintained for 28 minutes

Fission for war and peace....



Hiroshima & Nagasaki, 6 and 9 August 1945



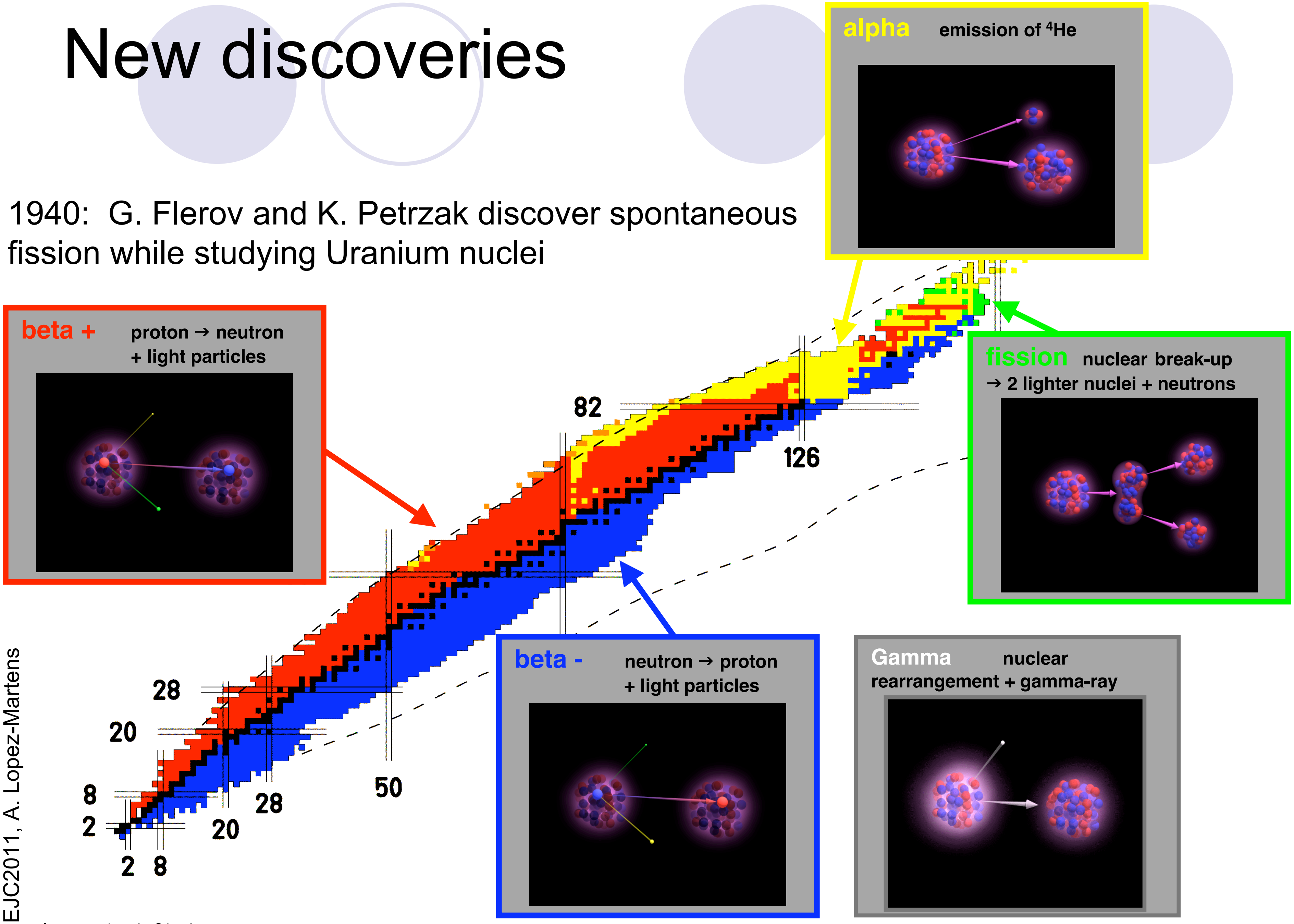
1948: Inauguration of the first French atomic pile: ZOE

1951: First production of nuclear electricity at EBR-I in Idaho (USA)

1954: First kWh from a nuclear power station in Obninsk AES-1 (USSR)

New discoveries

1940: G. Flerov and K. Petrzak discover spontaneous fission while studying Uranium nuclei



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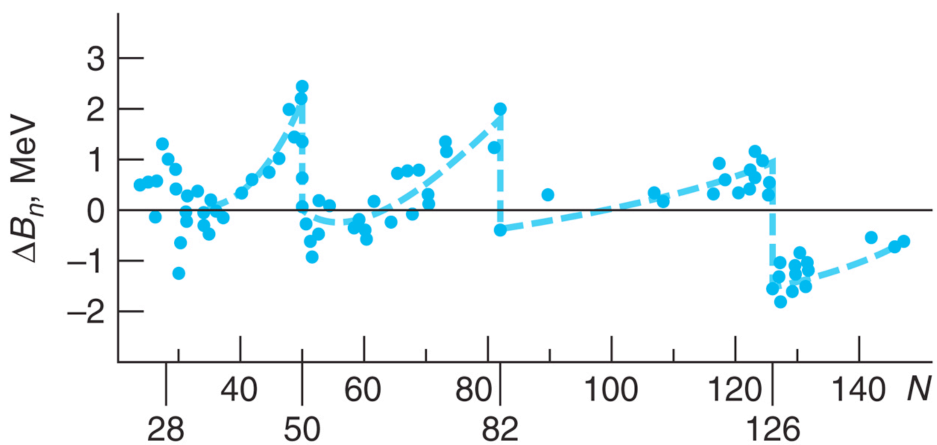
Images by J. Giovinazzo

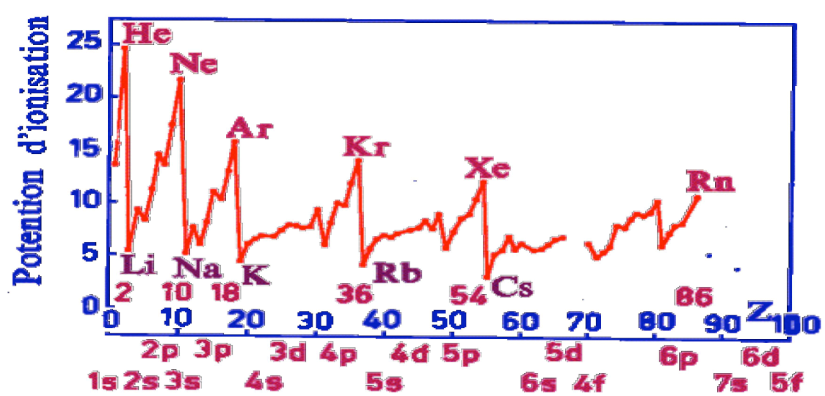
Magic numbers

Maria G. Mayer

M. Goeppert Mayer notices that nuclei with a number of neutrons and/or protons equal to 20, 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



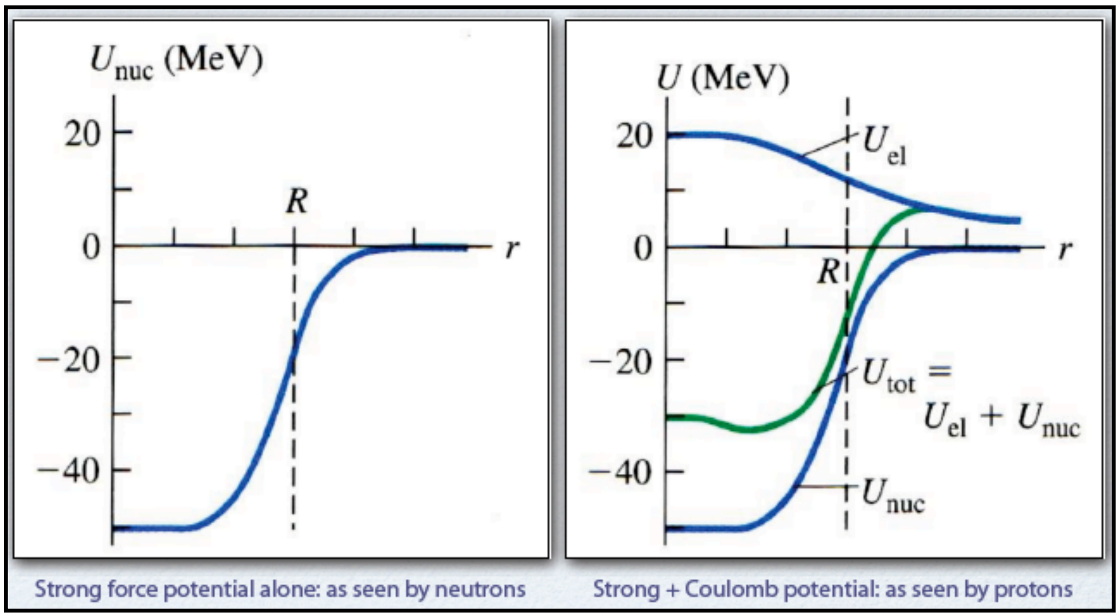


⇨ periodic structure of the nucleus ?

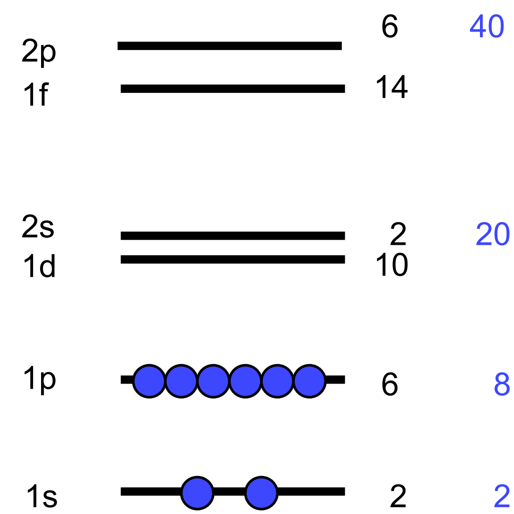
'On closed shells in nuclei', *M G. Mayer Phys. Rev. 74 (1948) 235*

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

mean nuclear potential felt by nucleons



energy levels



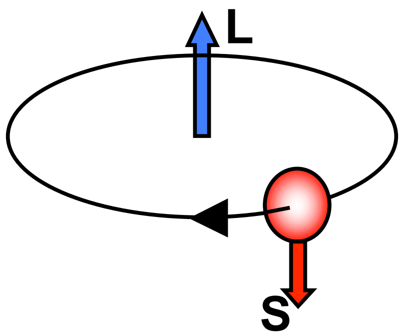
Total number of neutrons (or protons), which can be accommodated in each shell:

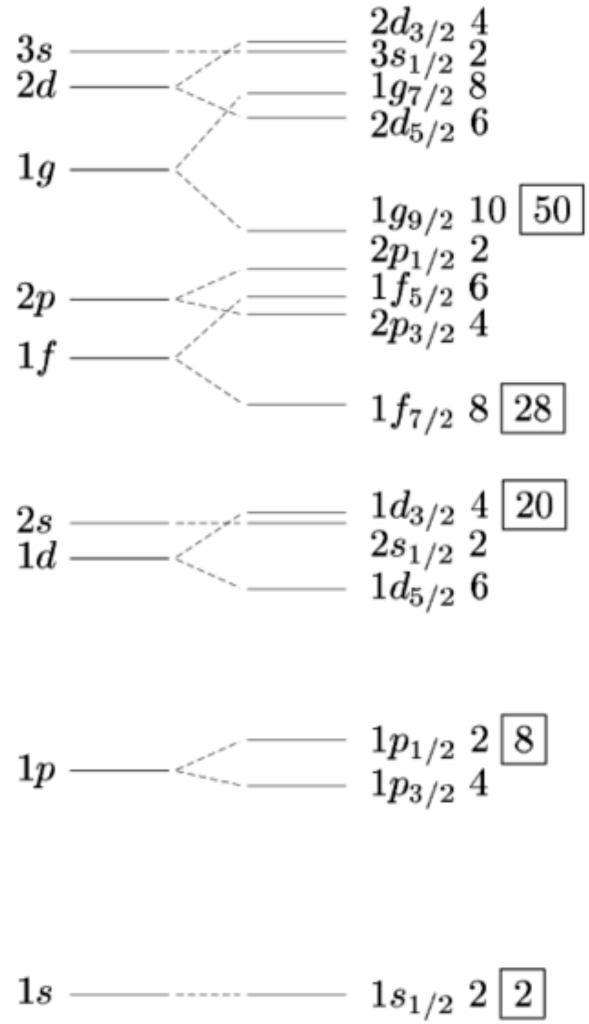
2, 8, 20, 40, 58, 92, 138

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

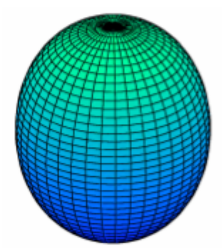


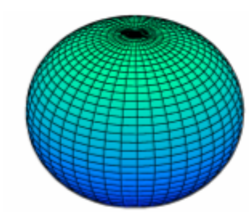


Hans Jensen

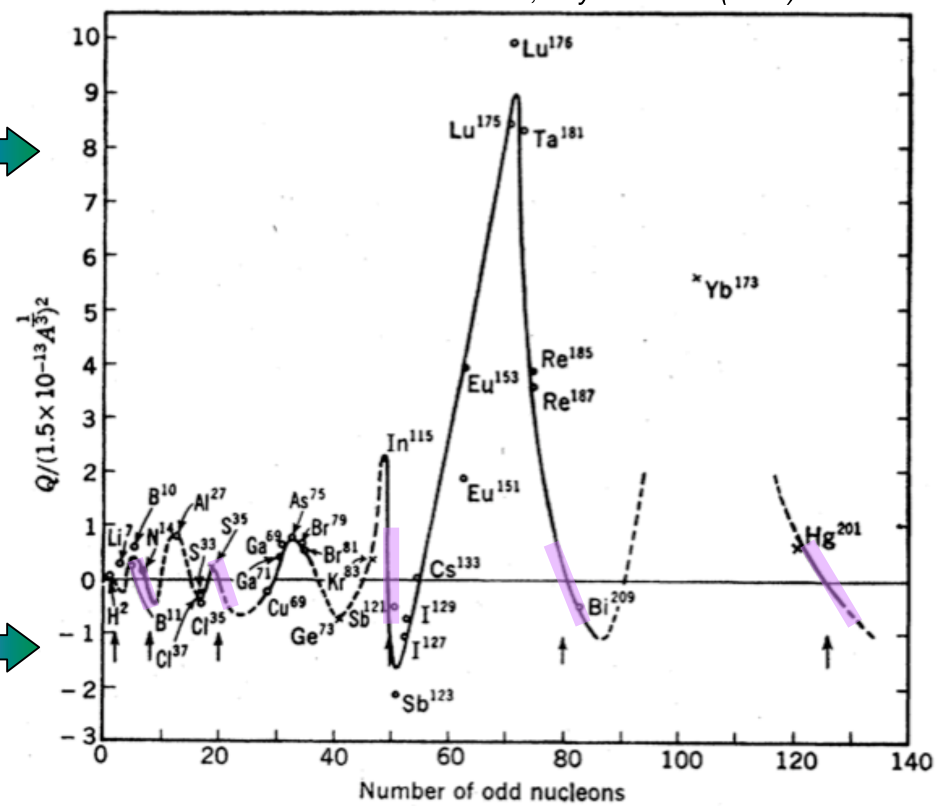
M.G. Mayer et H.D. Jensen 'Elementary Theory of Nuclear Shell Structure', 1955

Charge distribution within the nucleus





C.H. Townes et al., Phys. Rev. 76 (1949) 1415



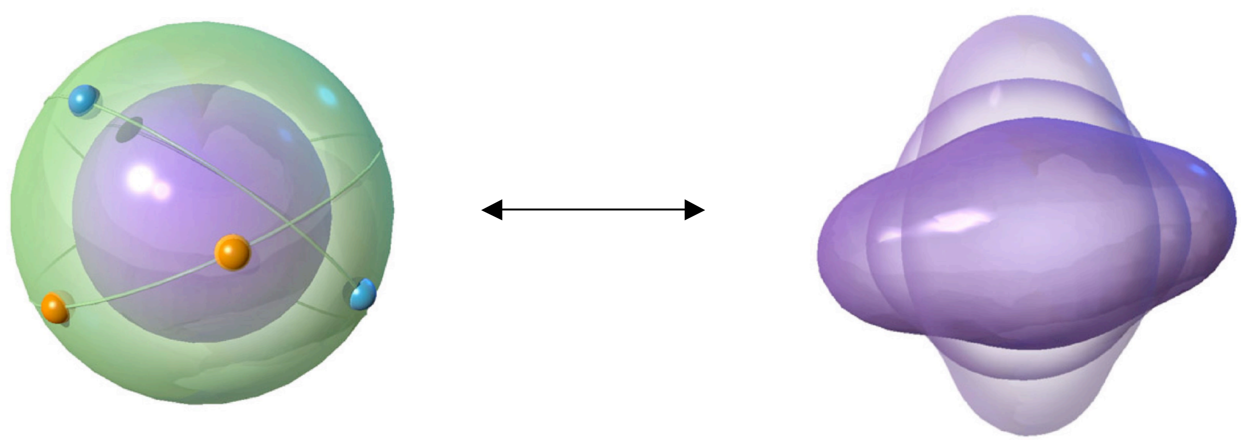
Certain moments are ~30 times larger than shell-model predictions !

And what if the nucleus was better off deforming itself ... ?

James Rainwater

Distortion of the liquid drop under the influence of the trajectories of the valence nucleons to gain in stability

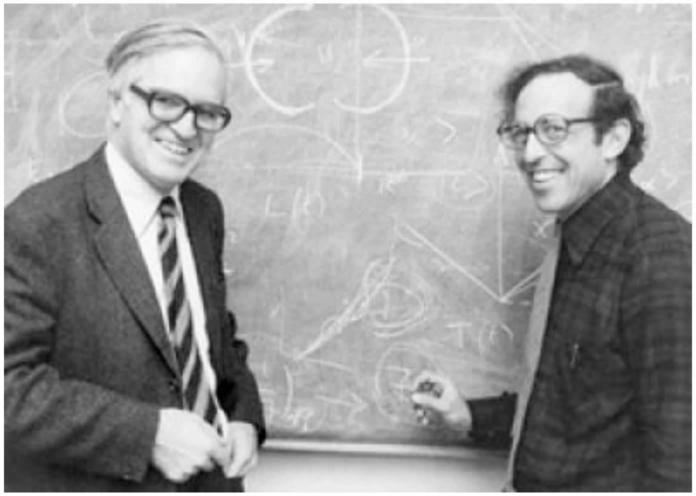
J. Rainwater, Phys. Rev. 79 (1950) 432



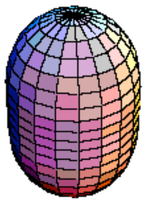
Single-particle and collective states of the nucleus

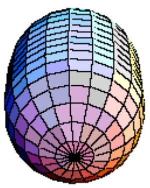
The unified model couples the oscillations and rotations of the liquid drop to the movement of the individual nucleons

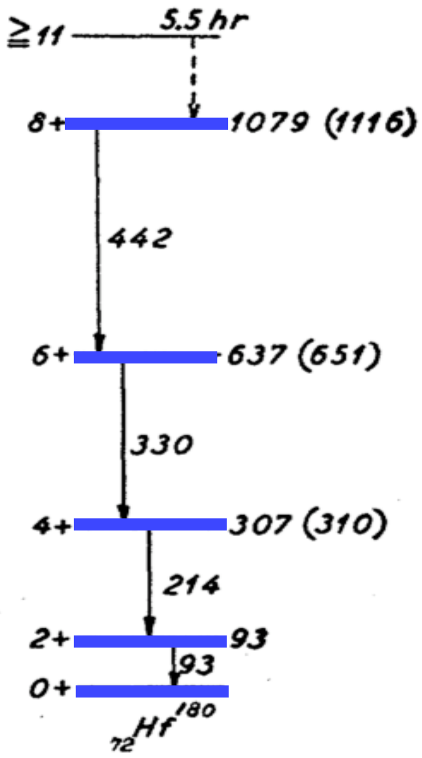
A. Bohr et B. Mottelson, Kgl. Danske Videnskab. Selskab, Mat-.-fys. Medd. 27 (1953) 16



Aage Bohr et Ben Mottelson

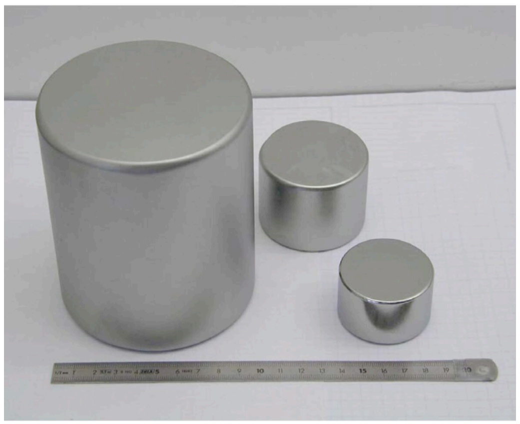




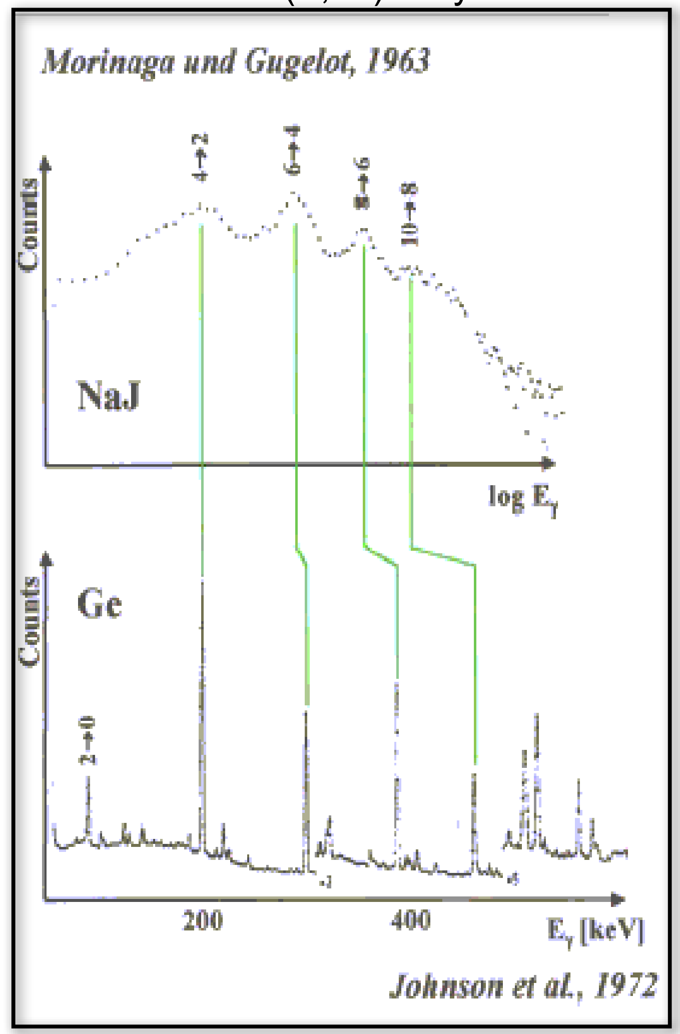


1950-1970: detection and acceleration developments

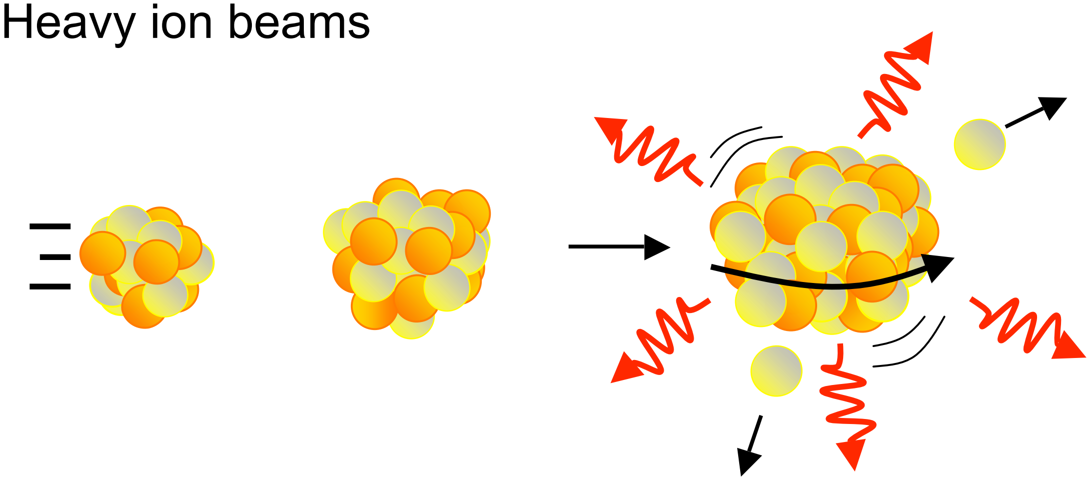
Scintillators & semi-conductors



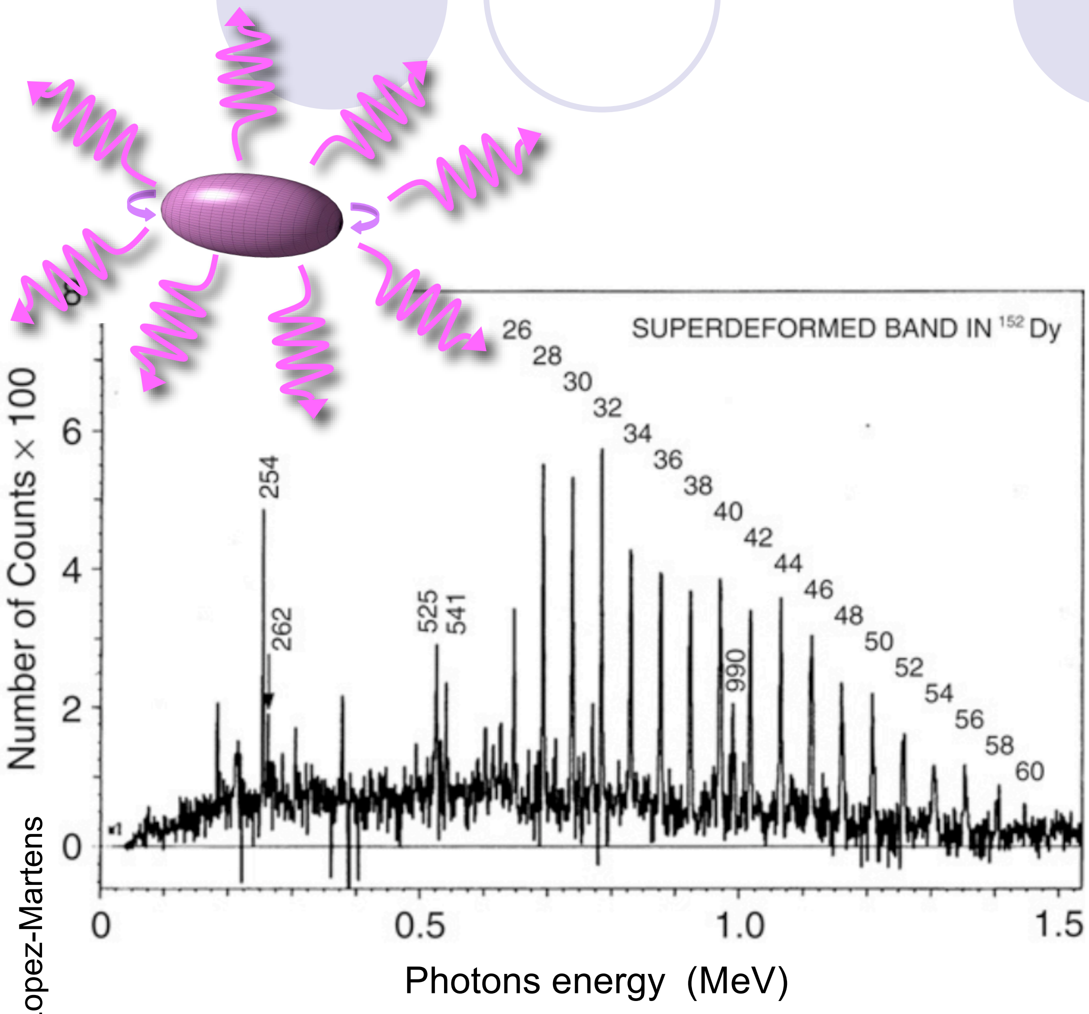
^{160}Gd(α,4n)^{160}Dy



Heavy ion beams

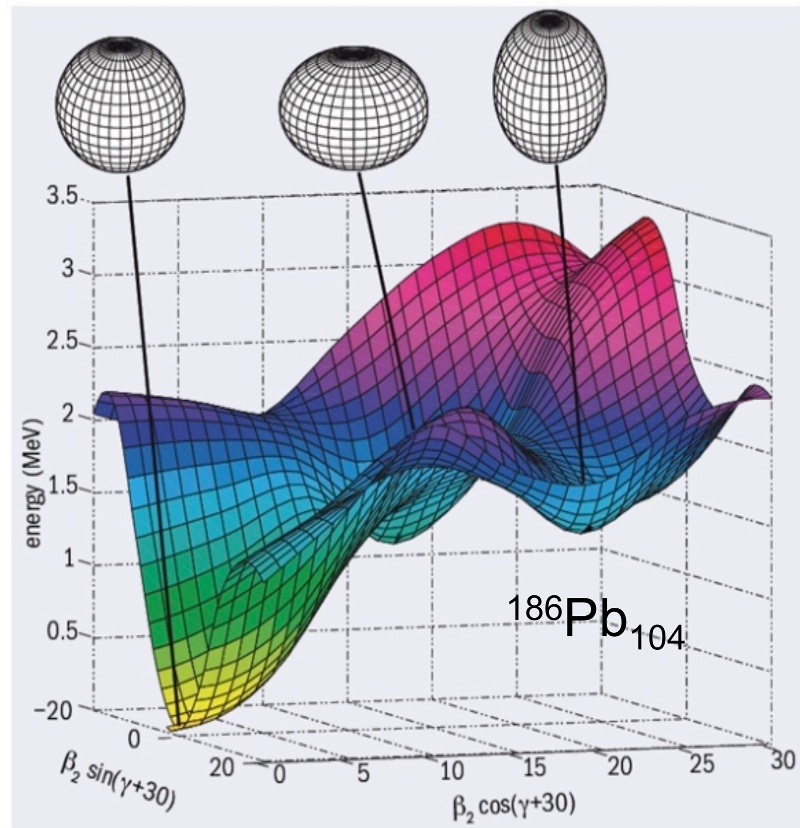


Extreme and multiple shapes



P.J. Twin et al., Phys. Rev. Lett. 57 (1986) 811
T. Lauritsen et al., Phys. Rev. Lett. 88 (2002) 042501

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



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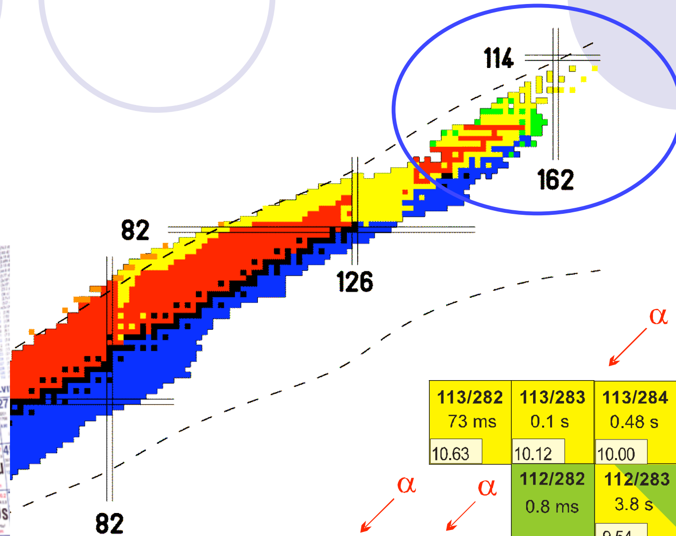
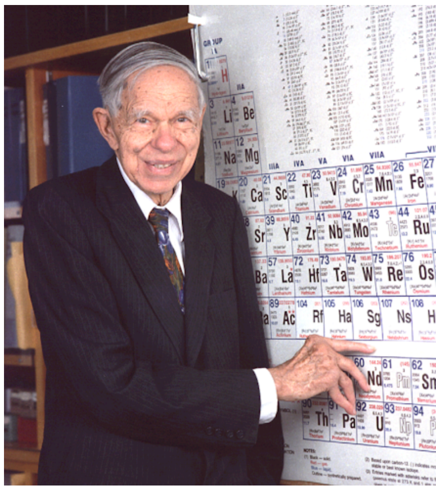
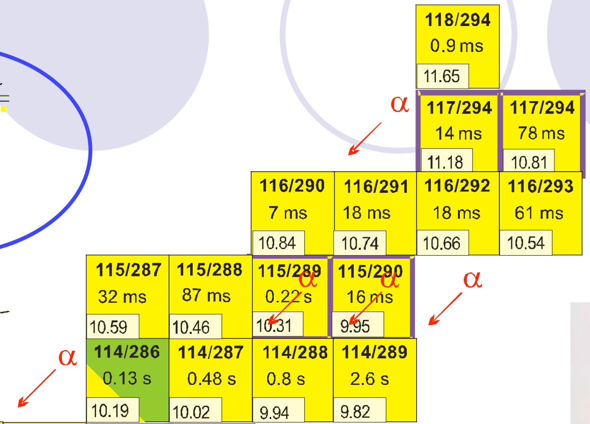
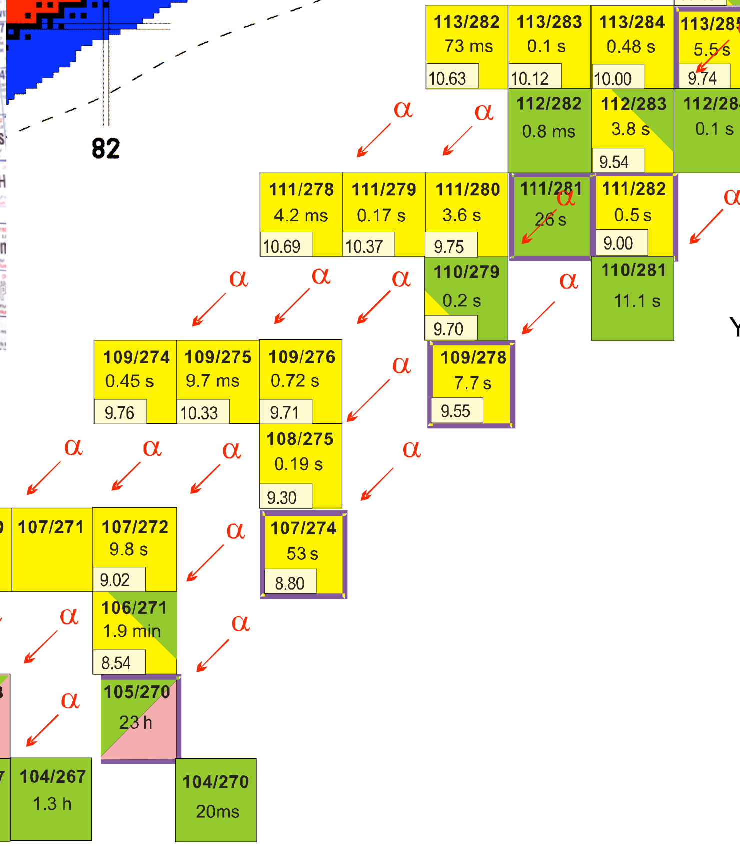
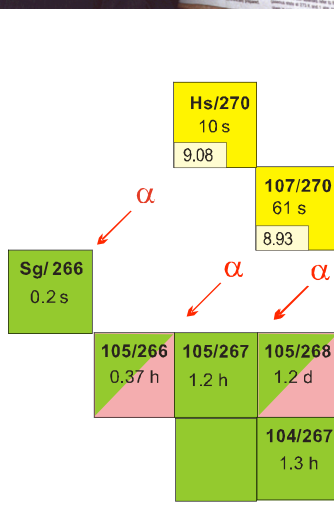
Extreme elements



Glenn Seaborg



Yuri Oganessian

Y. Oganessian et al., Phys. Rev. Lett. 104, 142502 (2010)

Sigurd Hofmann

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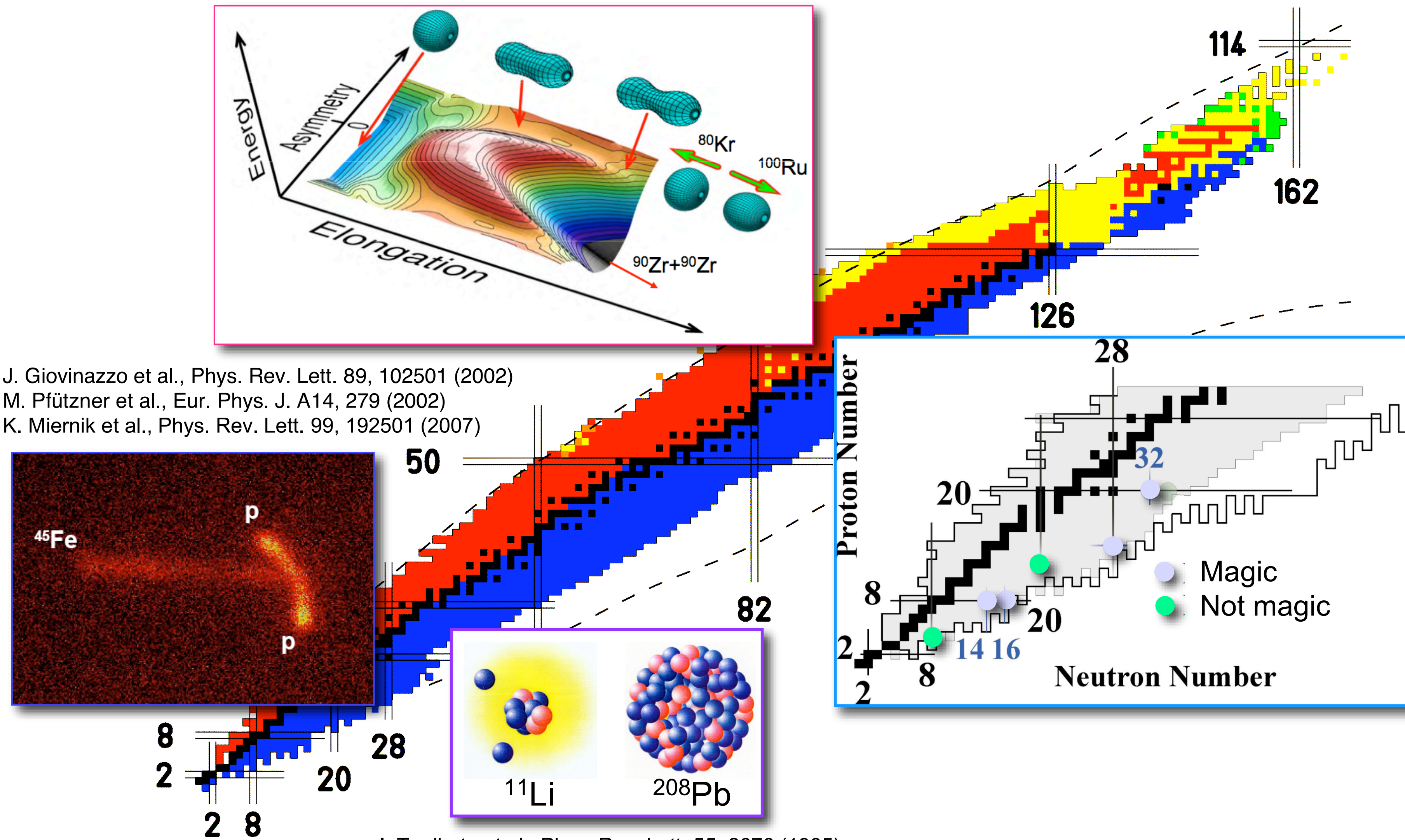
New features

A. Andreyev et al., Phys. Rev. Lett. 105 (2010) 252502

J. Giovinazzo et al., Phys. Rev. Lett. 89, 102501 (2002)
M. Pfützner et al., Eur. Phys. J. A14, 279 (2002)
K. Miernik et al., Phys. Rev. Lett. 99, 192501 (2007)



I. Tanihata et al., Phys. Rev. Lett. 55, 2676 (1985)

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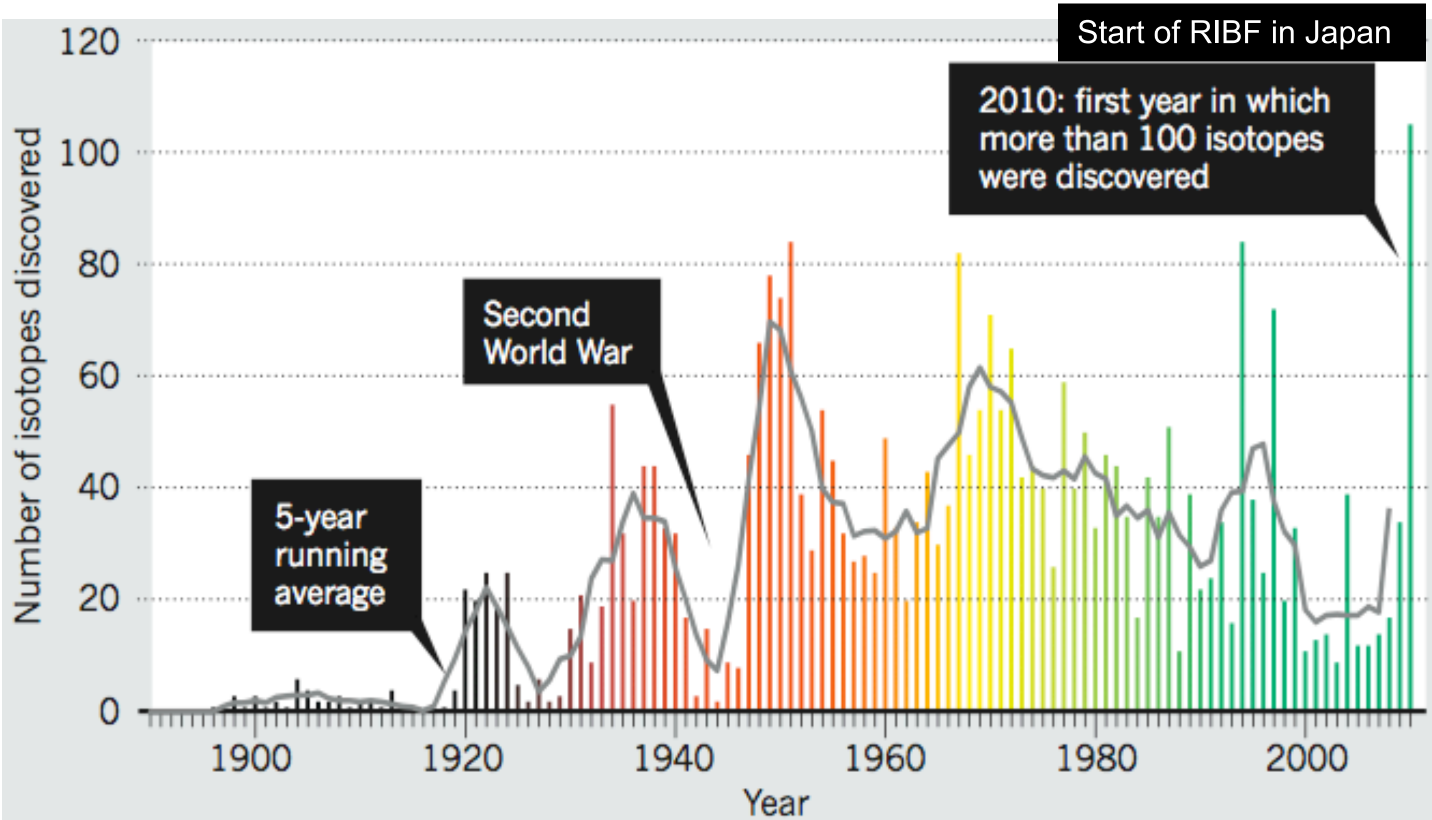
Future

First stable and radioactive beams at the next-generation facilities SPIRAL2, RIA & FAIR



M. Thoennessen et B. Sherrill, Nature 473 (2011) 25

The future looks bright !