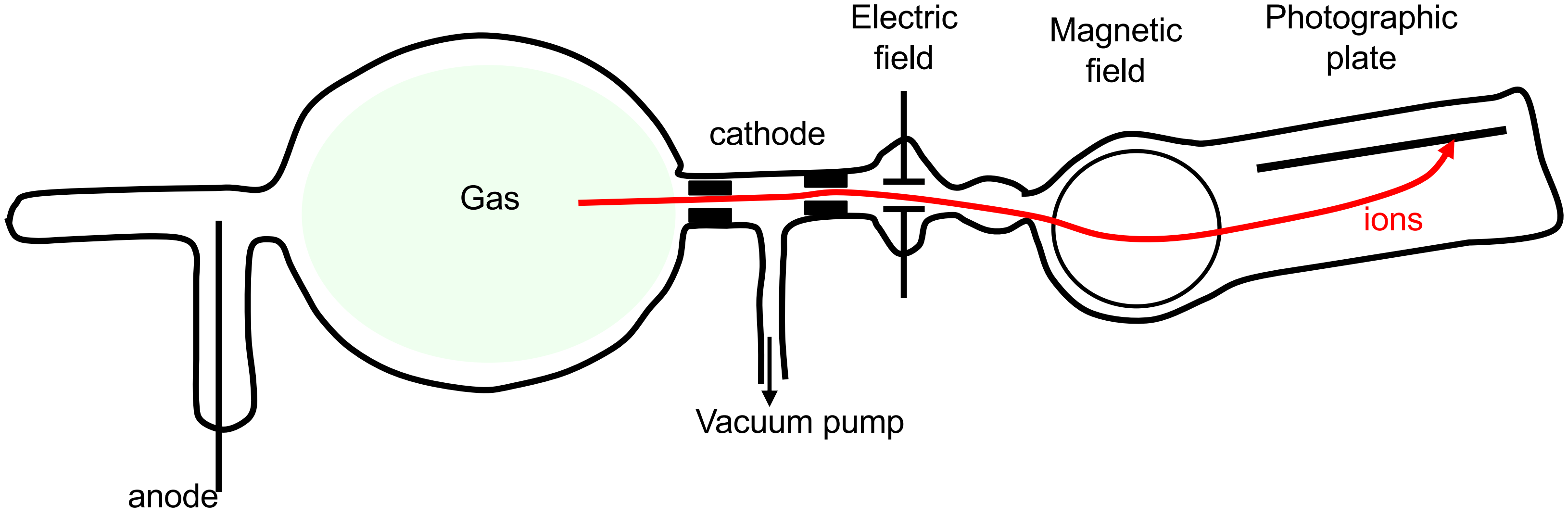
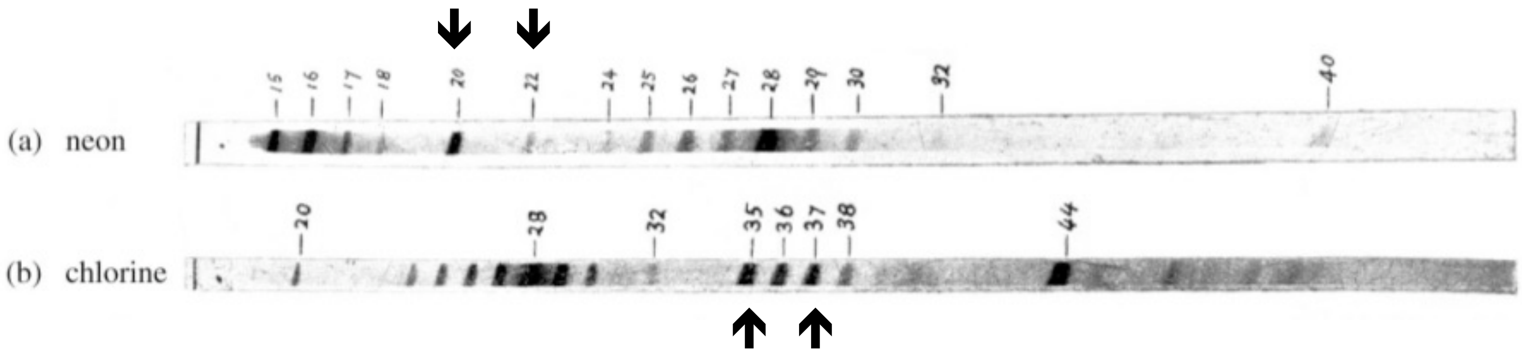
Part 2 – Nuclear Mass, Stability & Interaction

The beginnings of mass spectrometry



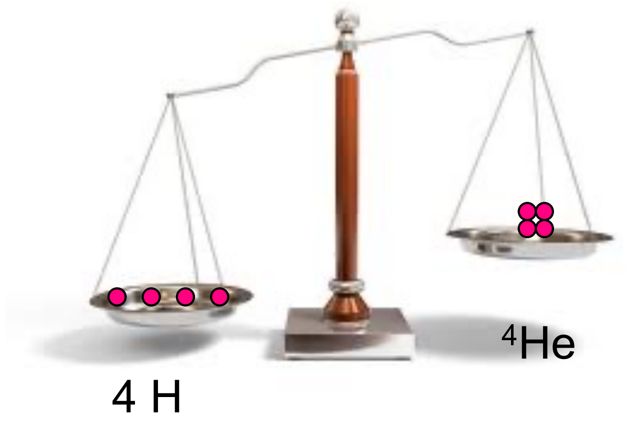
Francis Aston

1919: With the first mass spectrometer, F. Aston provided experimental proof of the concept of isotopes



He measures isotopic abundances and observes that the relative masses of isotopes ($M(^{16}O) = 16$) are integers, with the exception of H (1.008).

Mass excess

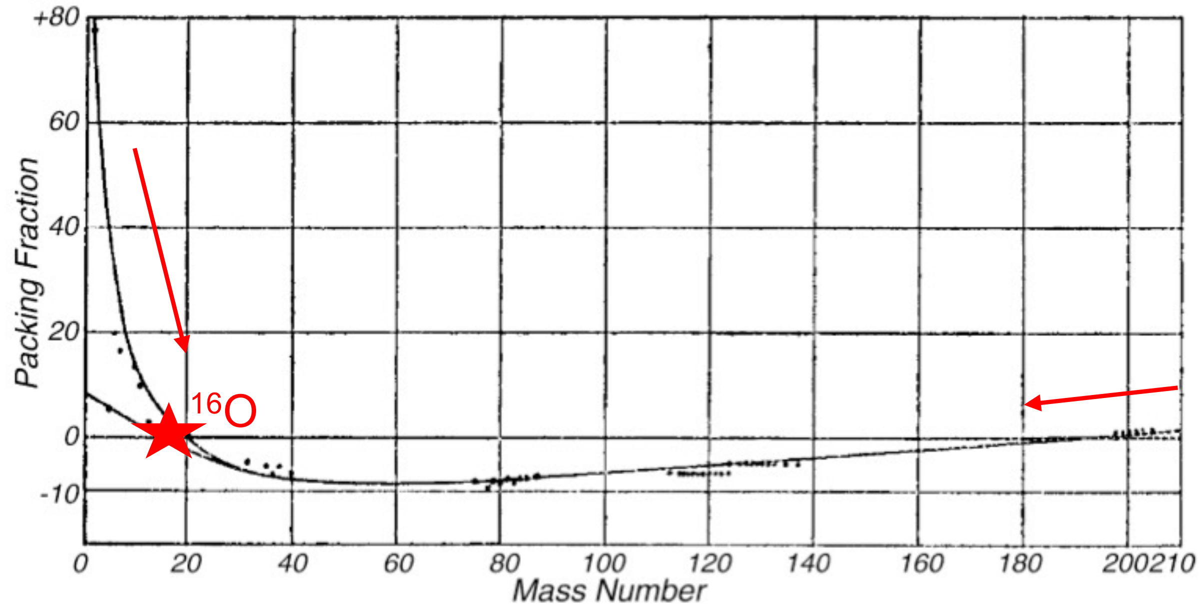


F. Aston proposes that mass is lost to form nuclei

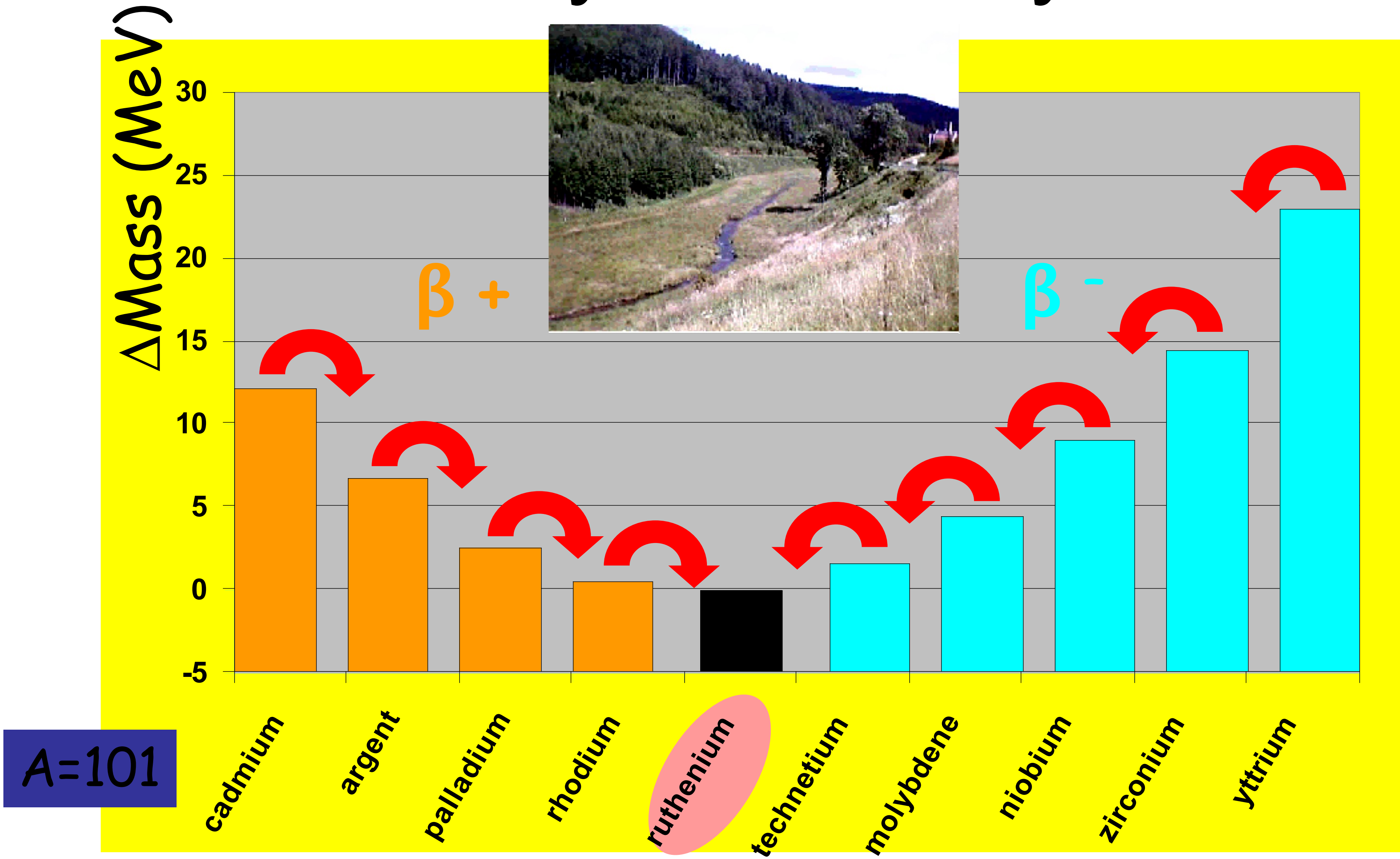
A. Eddington et J. Perrin suggest that the transformation of H into He is the source of the sun's energy

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

'packing fraction'= 10 000 (M – A)/A



Valley of Stability

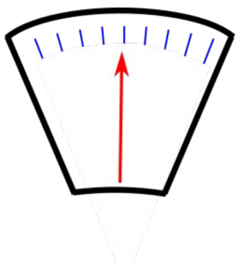


protons	48	44	39
neutrons	53	57	62

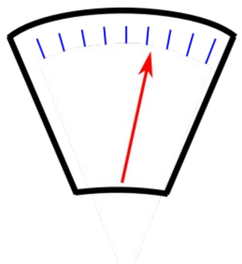
Towards high-precision mass measurement...

Resolution ~ $1/10^8$

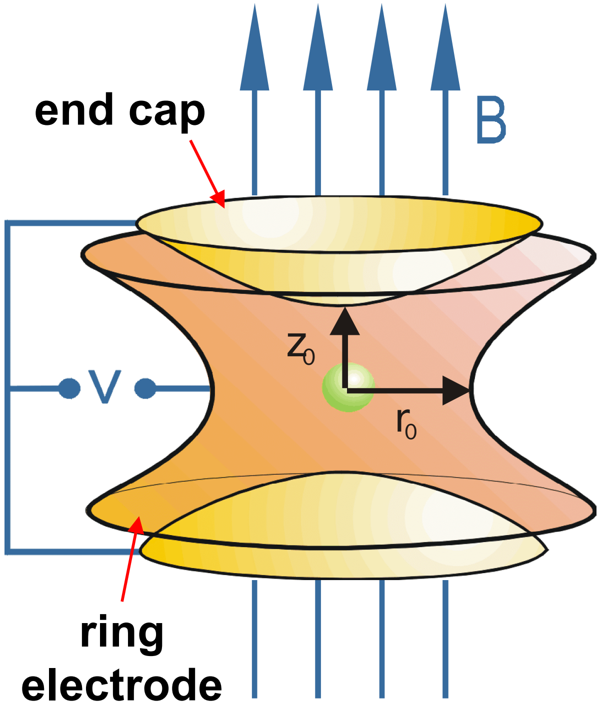
Airbus A380-800F:
252.2 tons (empty)

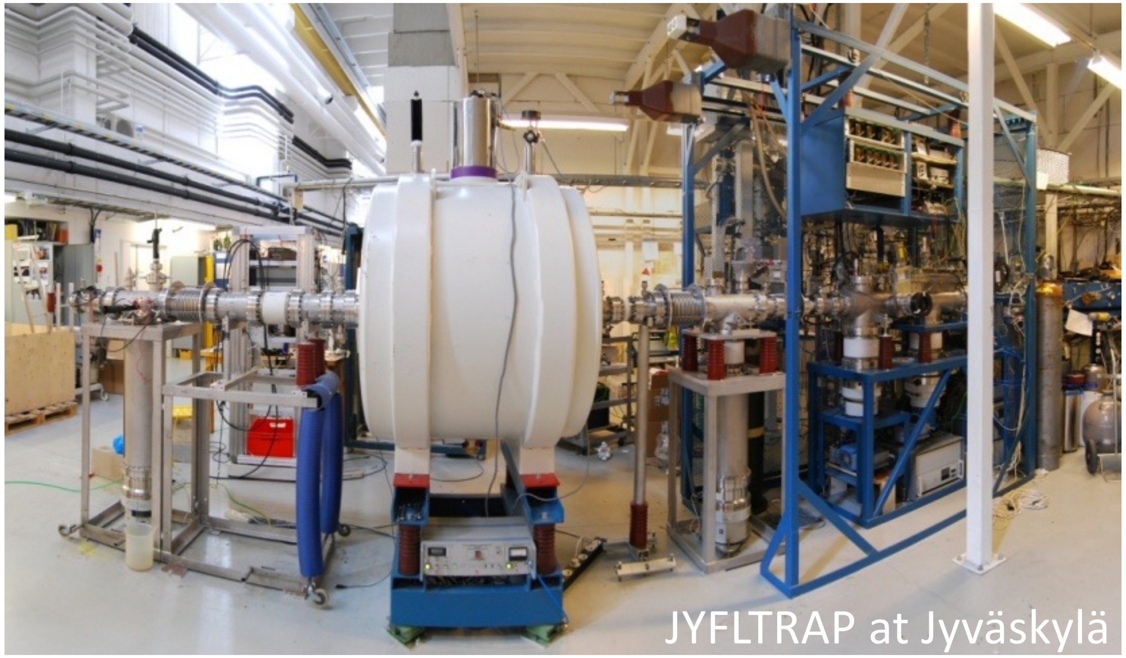


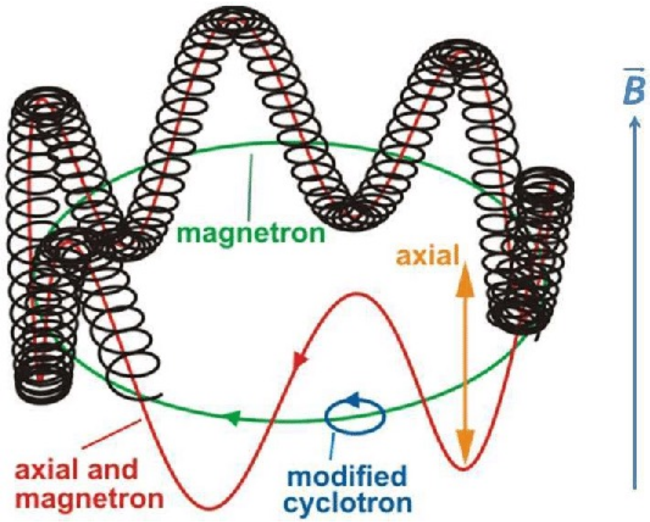
Airbus A380-800F +
1 mini-carambar (4 g)



Mass measurements with traps







PENNING trap

- Intense homogeneous magnetic field
- weak 3D quadrupole electric field

Cyclotron frequency $f_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B$

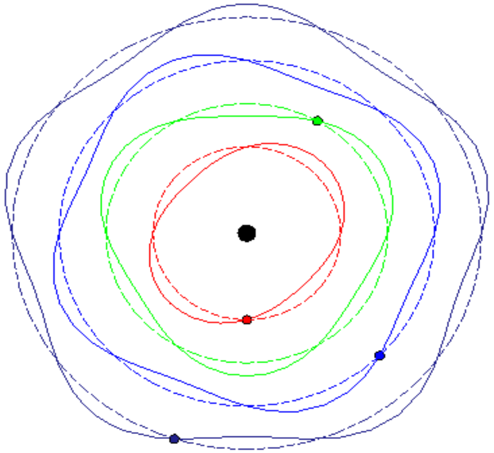
$f_c(^{133}Cs^+)/f_c(^{255}Lr^{2+}) = 0.95969174(6)$

E. Minaya et al., Science 337 (2012) 1207

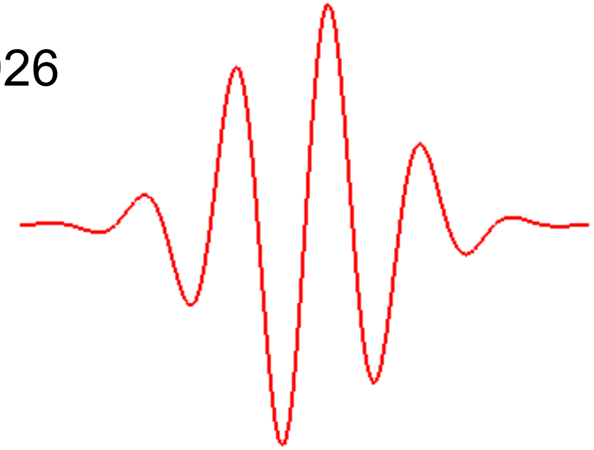
Quantum mechanics and the wave function

1924

L. de Broglie



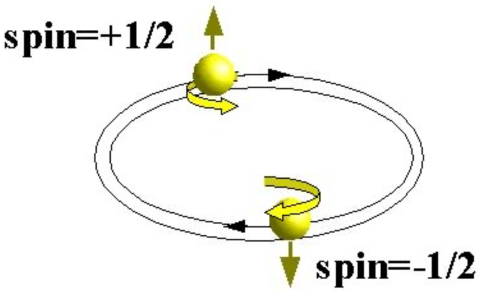
1926



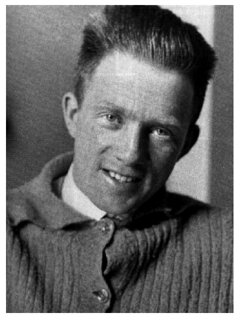
E. Schrödinger

1924-1925

W. Pauli



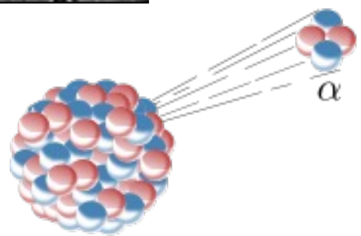
M. Born



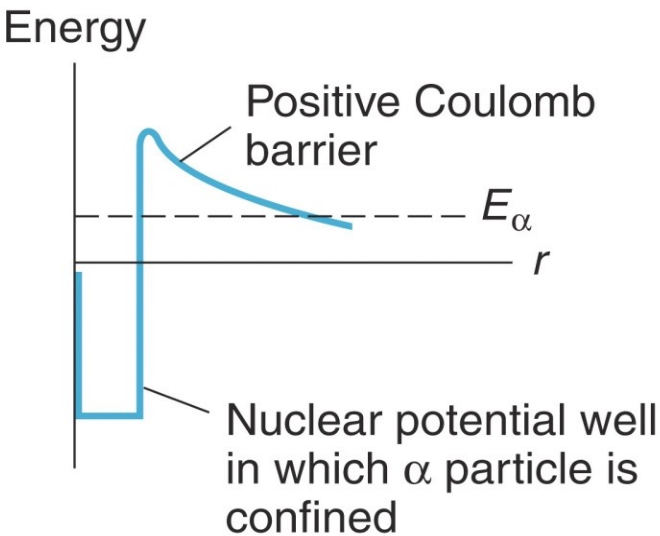
W. Heisenberg

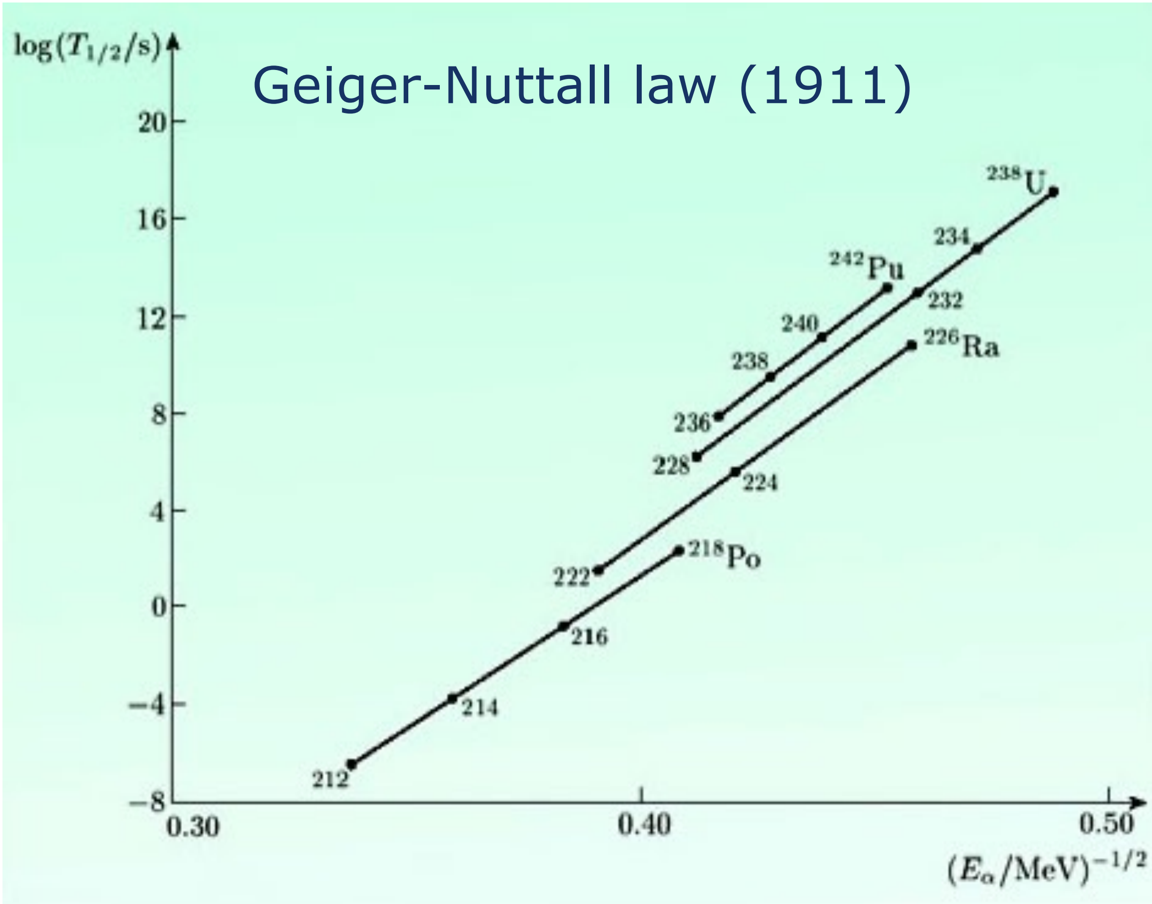
The theory of α decay

1928: G. Gamow proposes a model for α decay based on the new quantum mechanics *Z. Physik* ***5****1, 204 (1928)*



^{212}Po
E_{α}=8.78 MeV
E_B~ 25 MeV





Antimatter

Special relativity

Quantum mechanics

Relativistic electron

Paul Dirac

1928 : Dirac equation

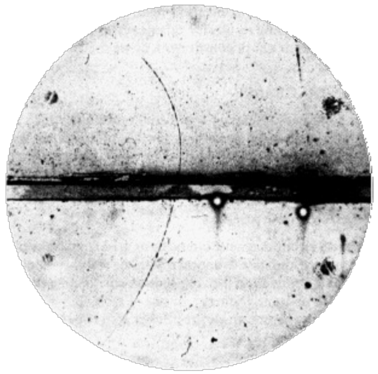
The Dirac equation has 2 solutions !

- electron
- ????

1931: P. Dirac invents the anti-electron

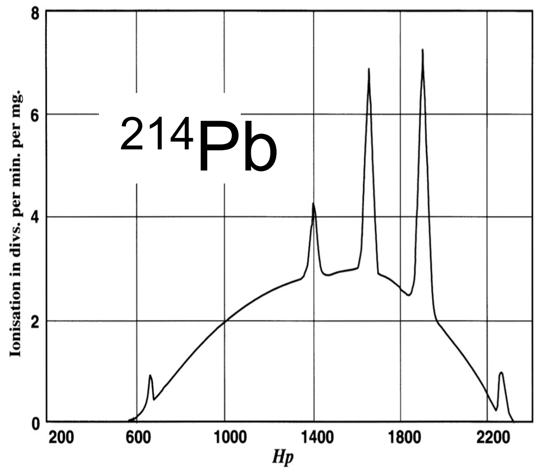
e^- | e^+
electron | anti-electron

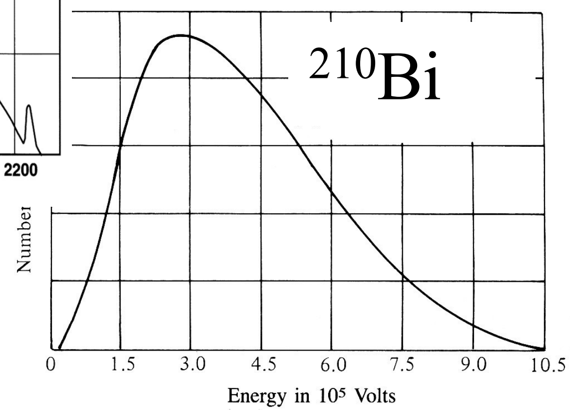
1932 : C. Anderson discovers the anti-electron and calls it positron



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...!'

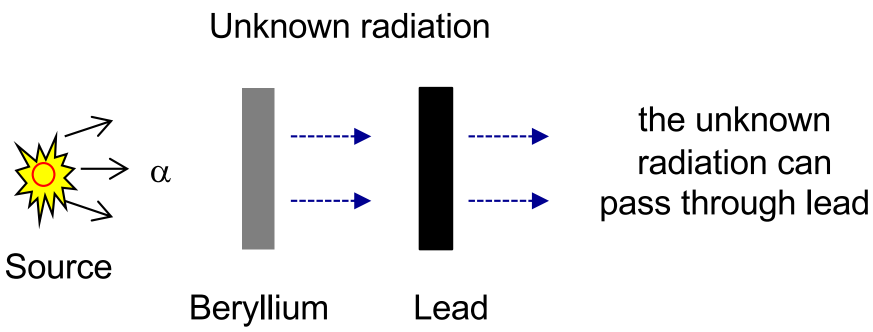
1927: Calorimetric experiment performed by C.D. Ellis and W.A. Wooster: average e^- energy < endpoint of β spectrum

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^-

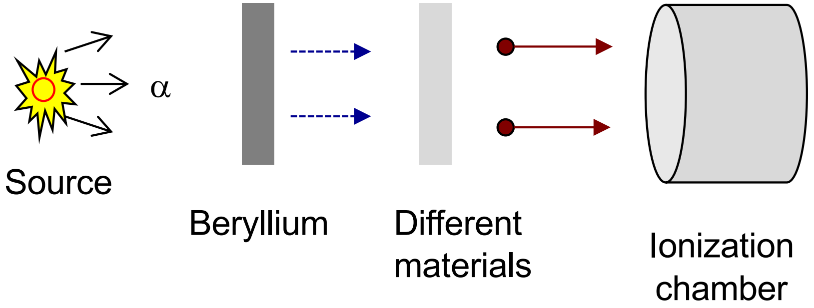
Discovery of the neutron

1930-32

W. Bothe & H. Becker discover a strange reaction



James Chadwick

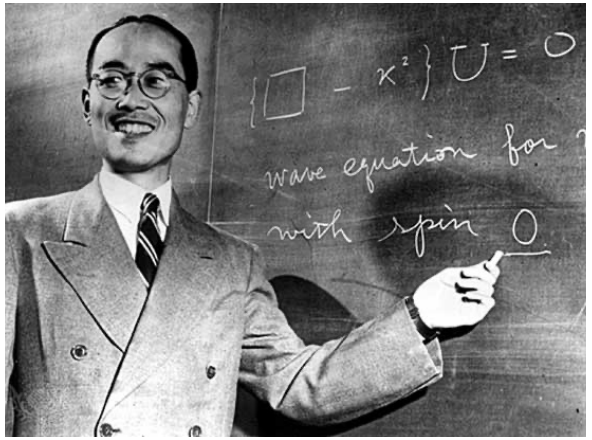


J . Chadwick shows that the mysterious radiation corresponds to a particle of mass ~1: the neutron

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

Consequences of the discovery

1932: D. Ivanenko, W. Heisenberg and E. Majorana propose models of the nucleus composed of Z protons and N neutrons. Heisenberg introduces isospin : the proton and the neutron are 2 two states of the same particle, which exchange charge



Hideki Yukawa

1935: Yukawa goes further than Heisenberg and proposes that the nucleons exchange a new particle:
the meson

What mass for the meson ?

Uncertainty principle: $\Delta E\, \Delta t \geq \hbar/2$

Because of its mass, the meson cannot exist for longer than

$$\Delta t \sim \hbar/2\,\Delta E = \hbar/2mc^2$$

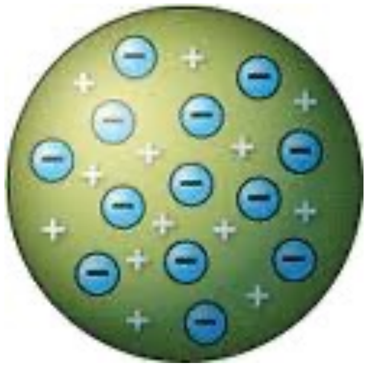
The meson must travel the distance between a proton and a neutron (~1 fm) in Δt

$$1fm \sim c\Delta t = \hbar c/2mc^2 \quad \Rightarrow \quad mc^2 \sim 100 \text{ MeV}$$

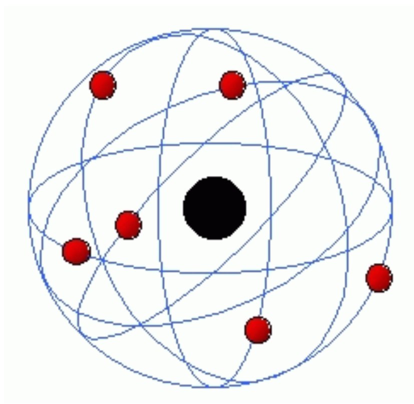
The meson was discovered in 1947 with a mass of ~140 MeV

The nucleus is complete !

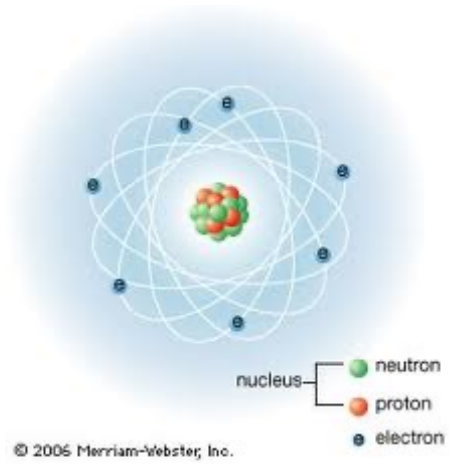
1898



1911



1932

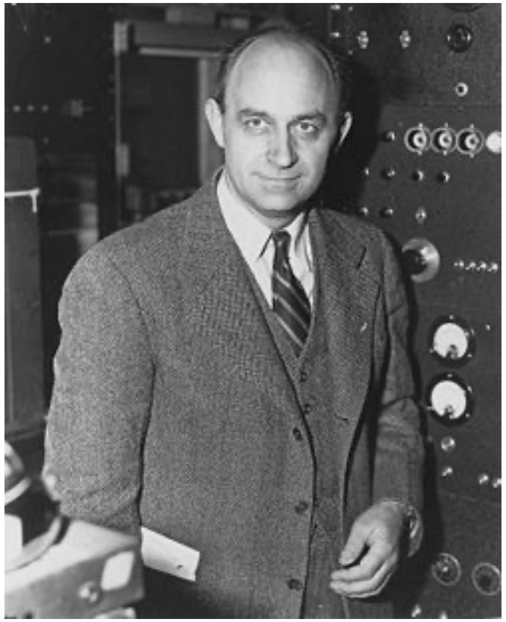


$$ {}^{A}_{Z}X_{N} $$

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

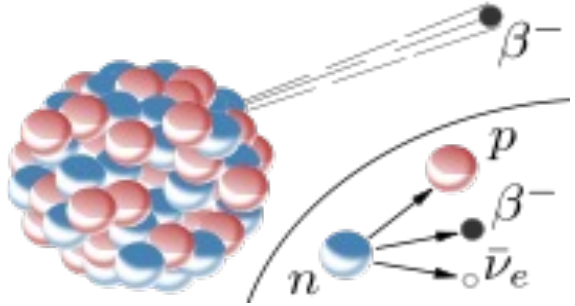
Origin of the β-decay electrons ?

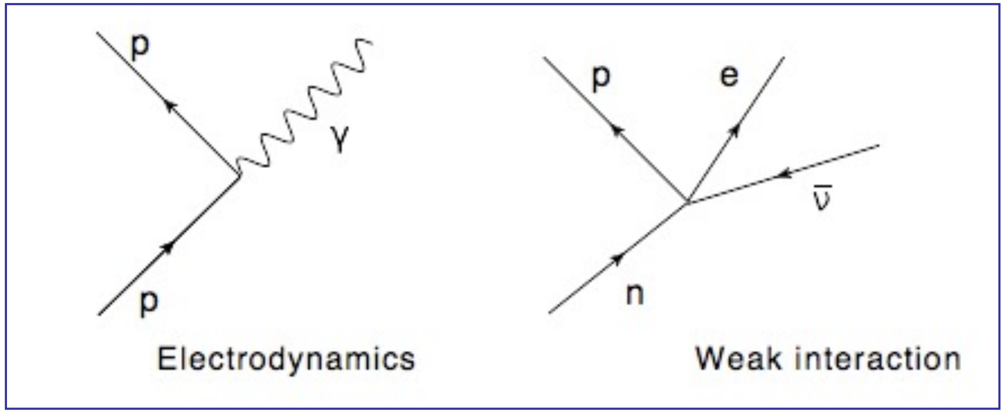
1934: E. Fermi suggests the existence of a new force, the weak force, and derives a theory for β decay



Enrico Fermi

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





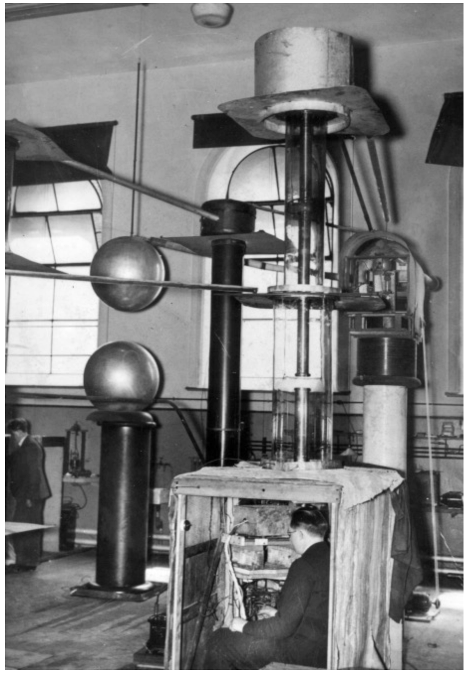
Fermi's analogy

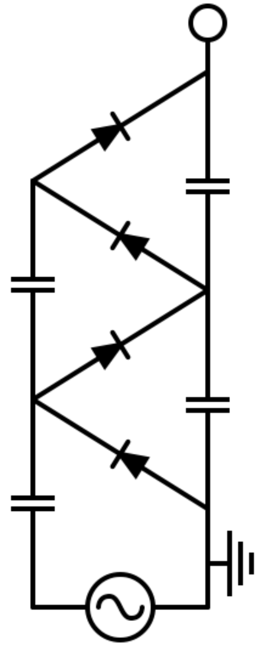
He submits this theory to the journal Nature—but the paper is rejected on the grounds that it contained "speculations too far removed from reality."

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





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:

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

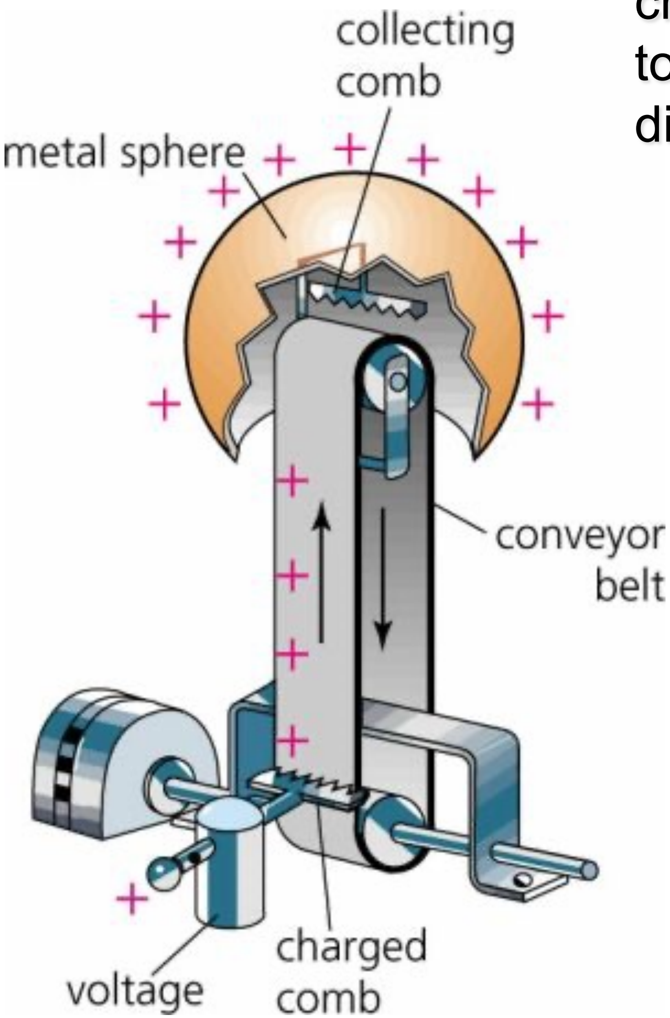
The energy of 2 alpha particles is measured at **~17 000 keV**

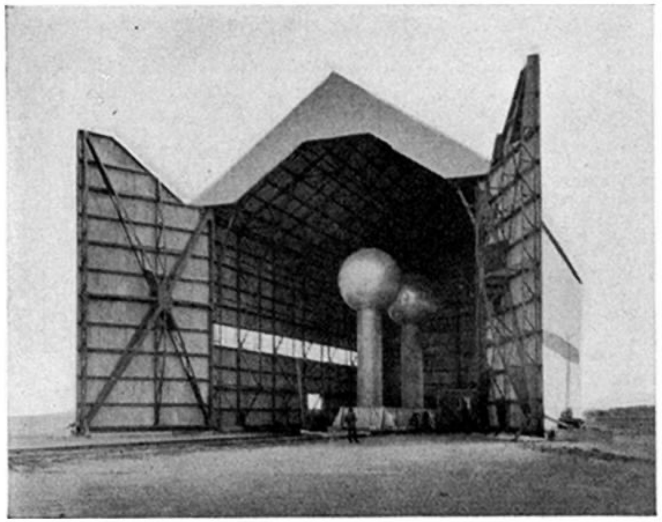
First experimental confirmation of $E = mc^2$: Energy is preserved if $\mathbf{mc^2}$ is considered as a form of energy

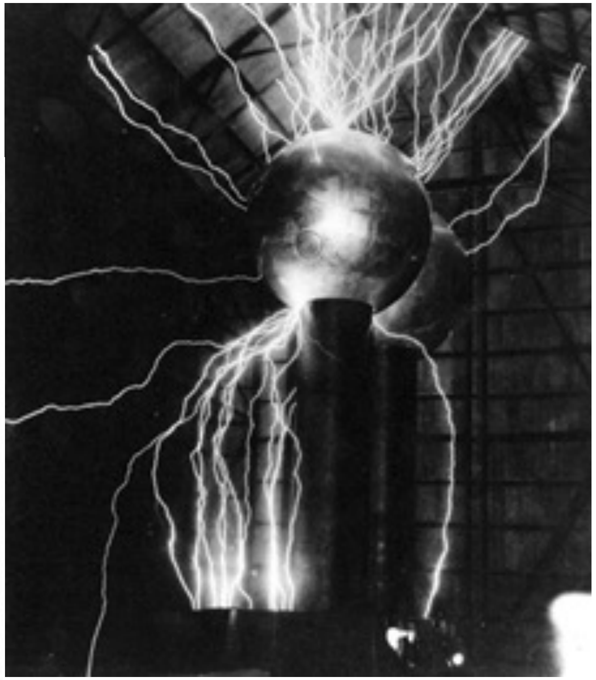
Nature 129, Avril 1932, 649

Van de Graaff generator

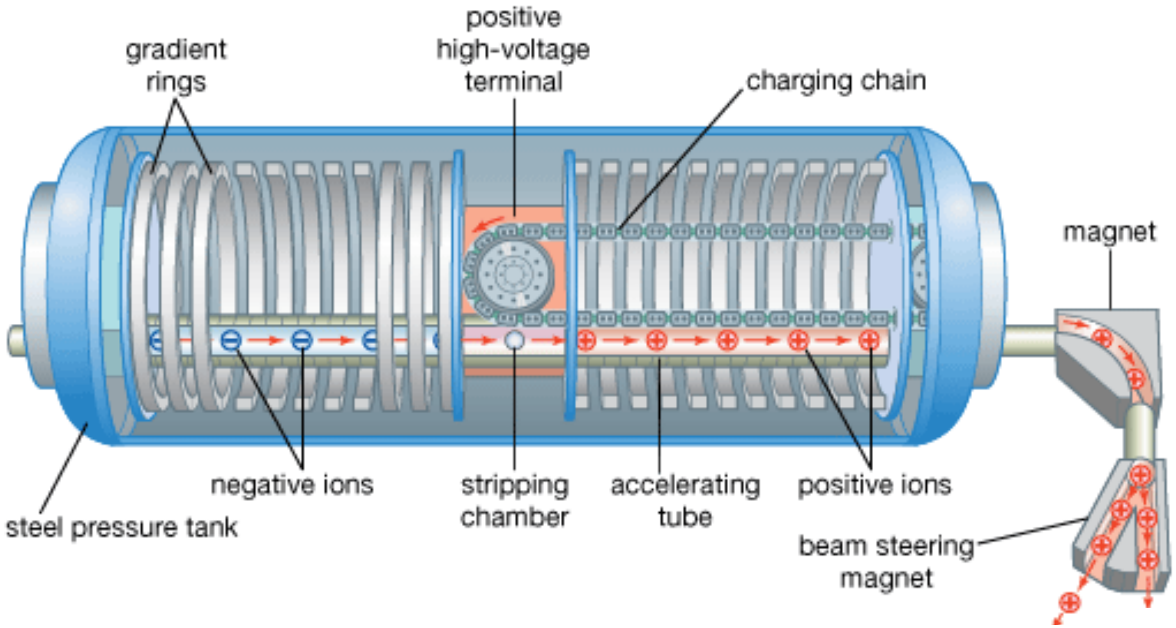
1929: **R. Van de Graaff** invents another type of accelerator in which charges are mechanically transported to a terminal to create a potential difference



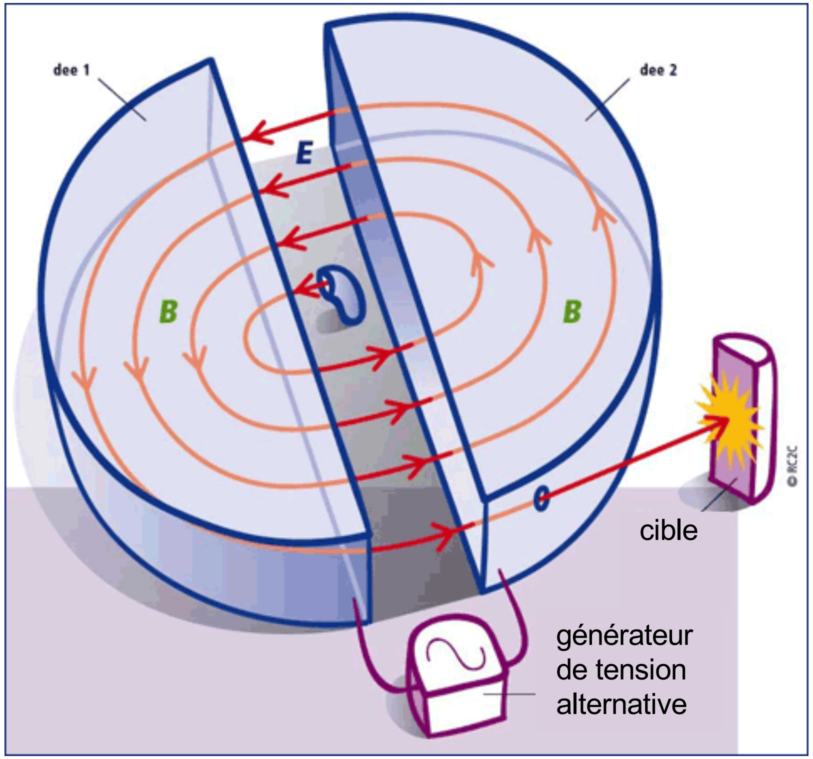




Tandem of IJCLab



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)

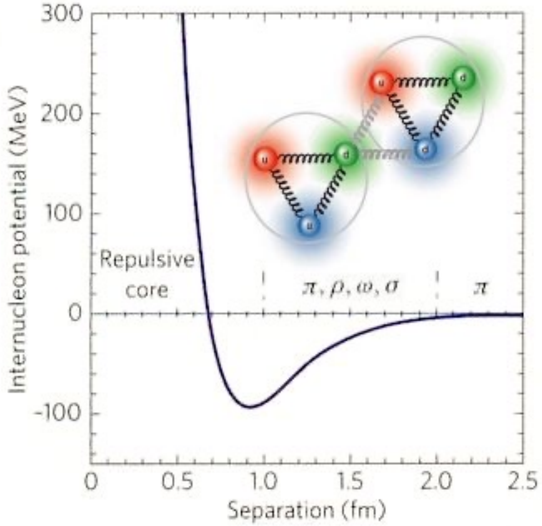
1st cyclotron in 1931, V=1.8KV , d~12 cm acceleration of protons up to 80 keV

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

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

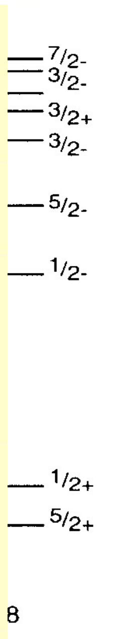
The nuclear interaction

- strong attractive interaction, repulsive at very short distances
- Short range
- ~independent of the type of nucleon: n-n, n-p, p-p



Modern Nuclear Chemistry, W. Loveland et al.,

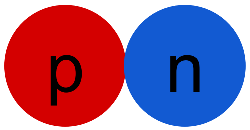
A	*Nucleus*	*Total Binding Energy (MeV)*	*Coulomb Energy (MeV)*	*Net nuclear binding energy (MeV)*
3	^{3}H	-8.486	0	-8.486
	^{3}He	-7.723	0.829	-8.552
13	^{13}C	-97.10	7.631	-104.734
	^{13}N	-94.10	10.683	-104.770
23	^{23}Na	-186.54	23.13	-209.67
	^{23}Mg	-181.67	27.75	-209.42
41	^{41}Ca	-350.53	65.91	-416.44
	^{41}Sc	-343.79	72.84	-416.63



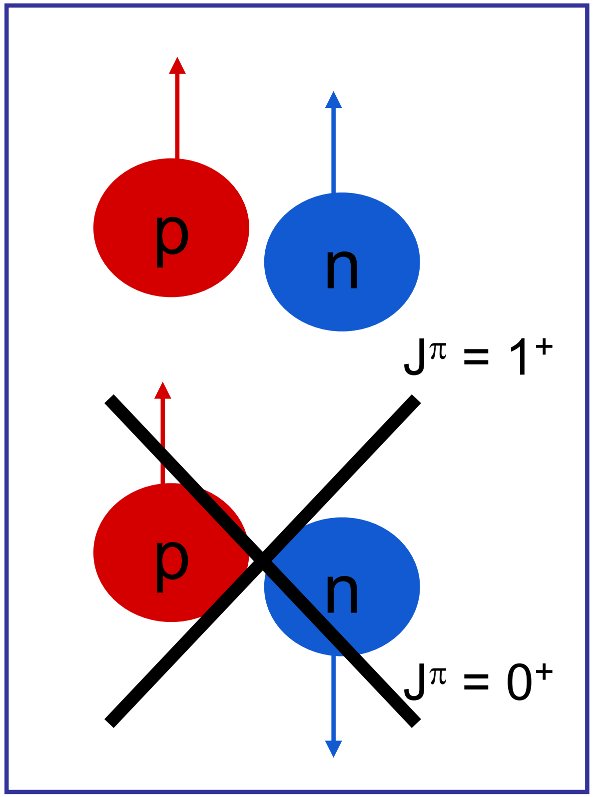
The nuclear interaction

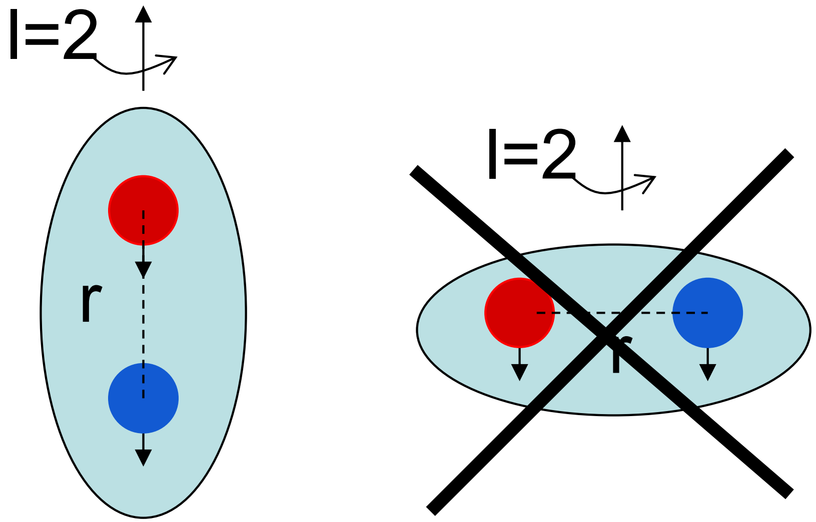
- dependent on the orientations and relative positions of the nucleon spins

deuteron



Weak binding energy B=2.2 MeV
$J^{\pi} = 1^{+}$
$\mu_d = 0.8574\ \mu_N$ (μ_p=+2.7928 μ_N, μ_n=-1.9130 μ_N)
Weak positive electric quadrupole moment: $Q = 0.2859\ e.fm^2$

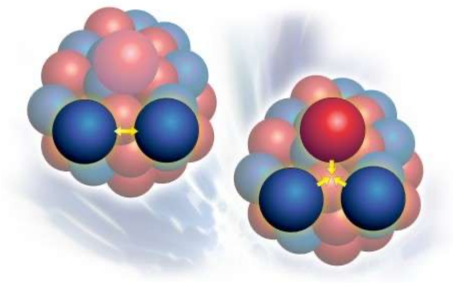




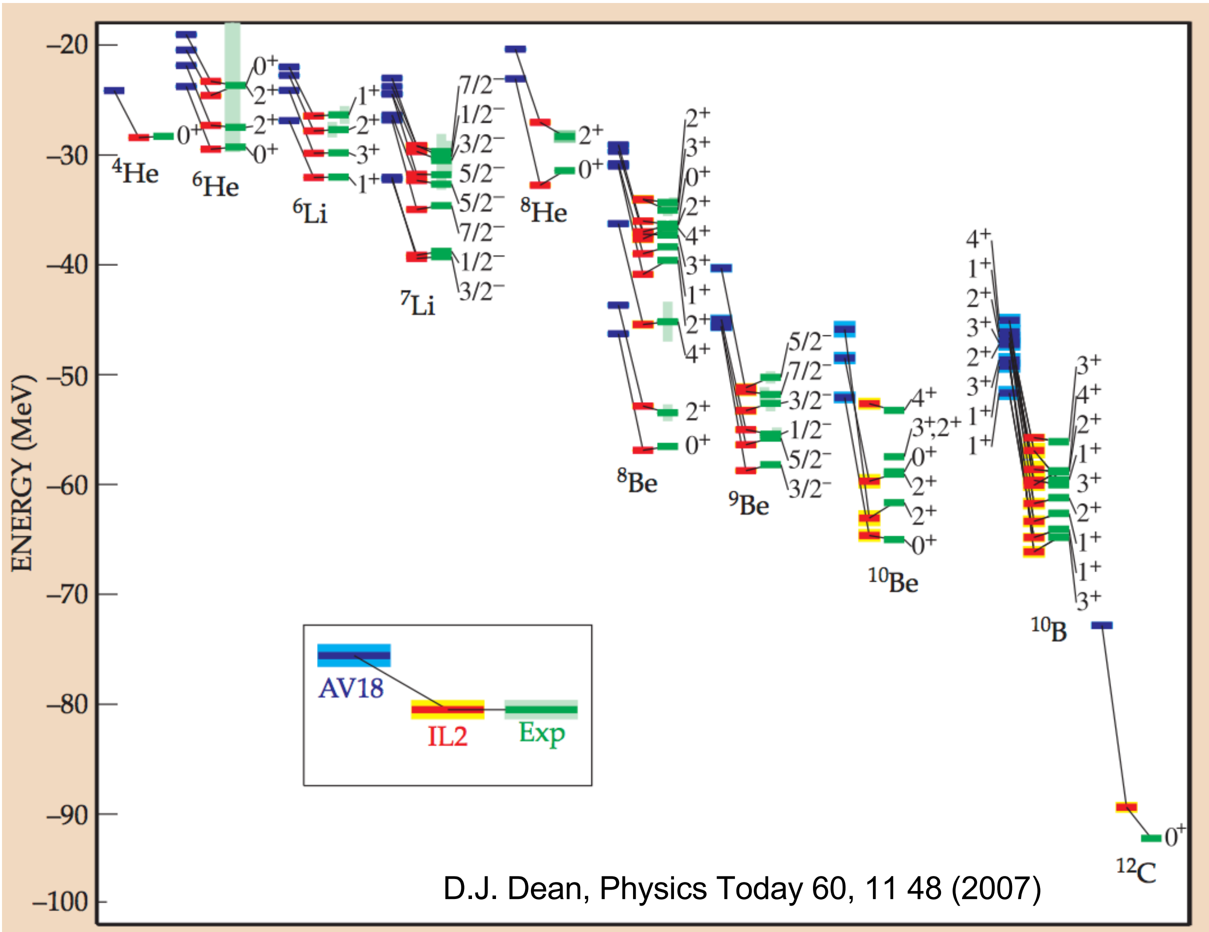
Q > 0 Q < 0

⇨ spin-spin term and tensor term in the N-N force

The nuclear interaction



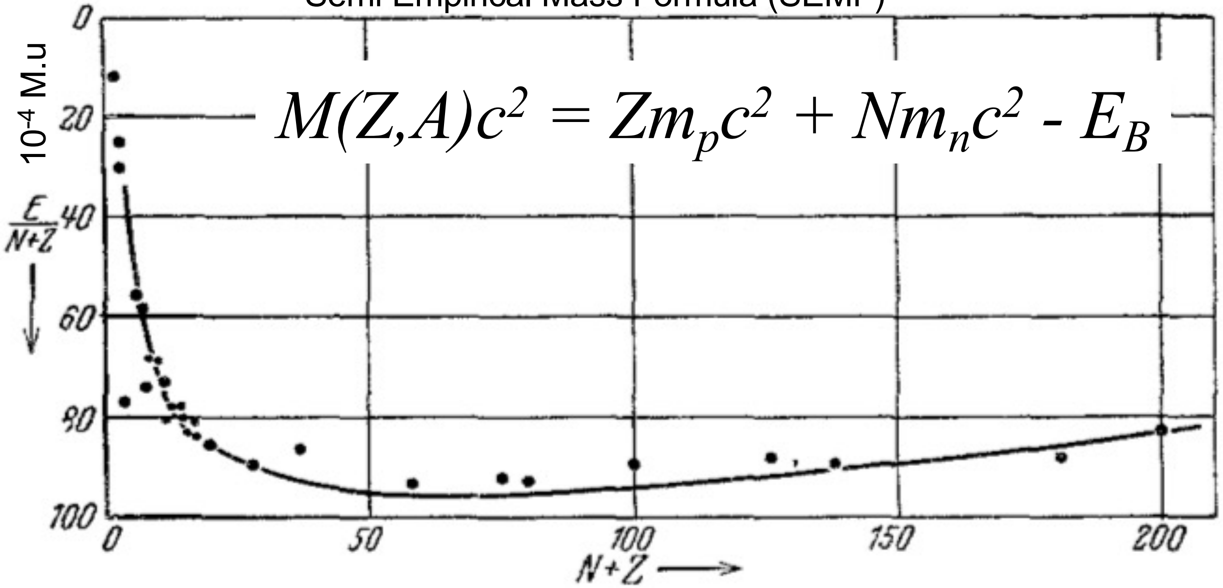
Importance of 3-body forces N-N-N



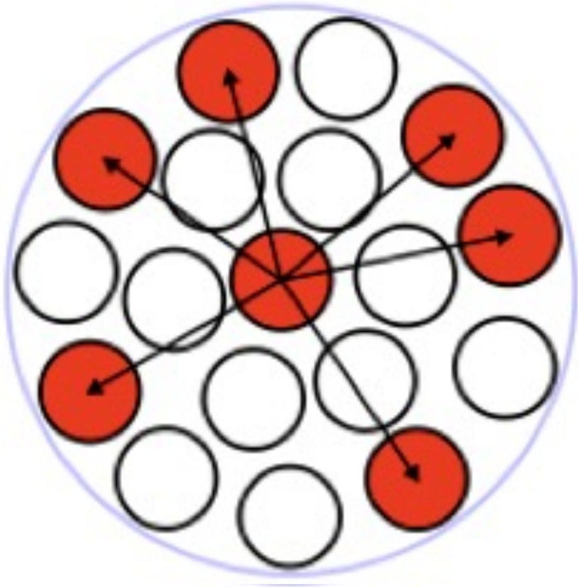
The liquid drop

The nuclear force is similar to the force, which binds water molecules within a liquid drop *W. Heisenberg, Congrès de Solvay 1933 d'après une idée originale de G. Gamow (Proc. Roy. Soc. 126 (1930) 637)*

Semi Empirical Mass Formula (SEMF)



C.F. v. Weiszäcker, Z. Phys. 96 (1935) 431

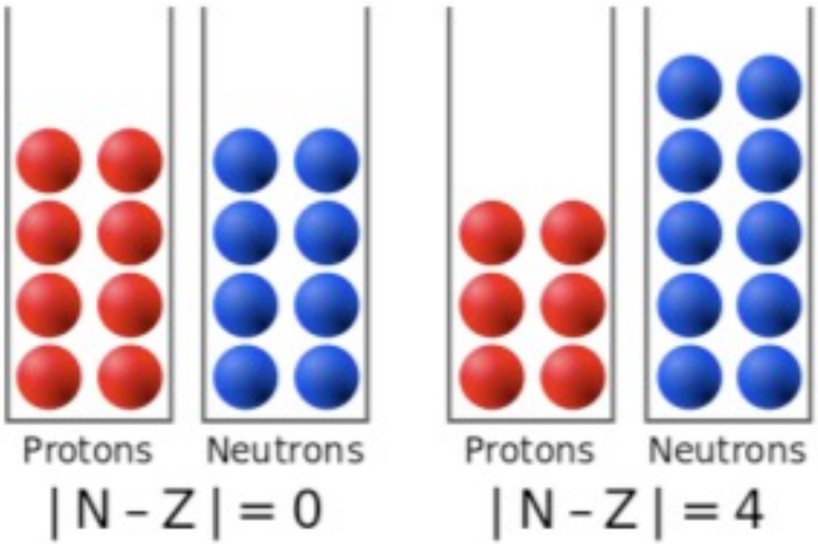


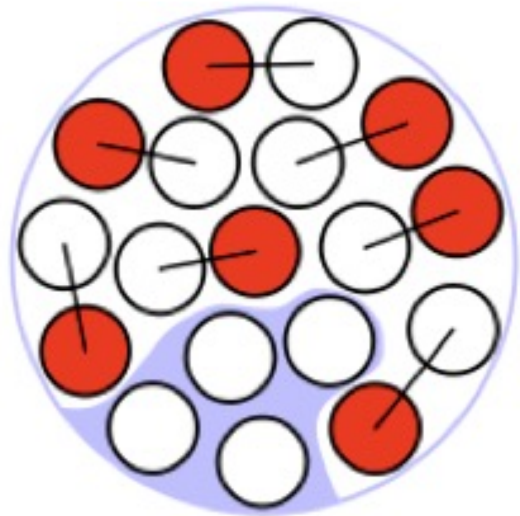
Volume term	Surface term	Coulomb term	Asymmetry term	Pairing term

$$B(A,Z) = a_v A - a_s A^{2/3} - a_c Z^2 A^{-1/3} - a_a (A-2Z)^2 A^{-1} - \delta$$

Asymmetry term

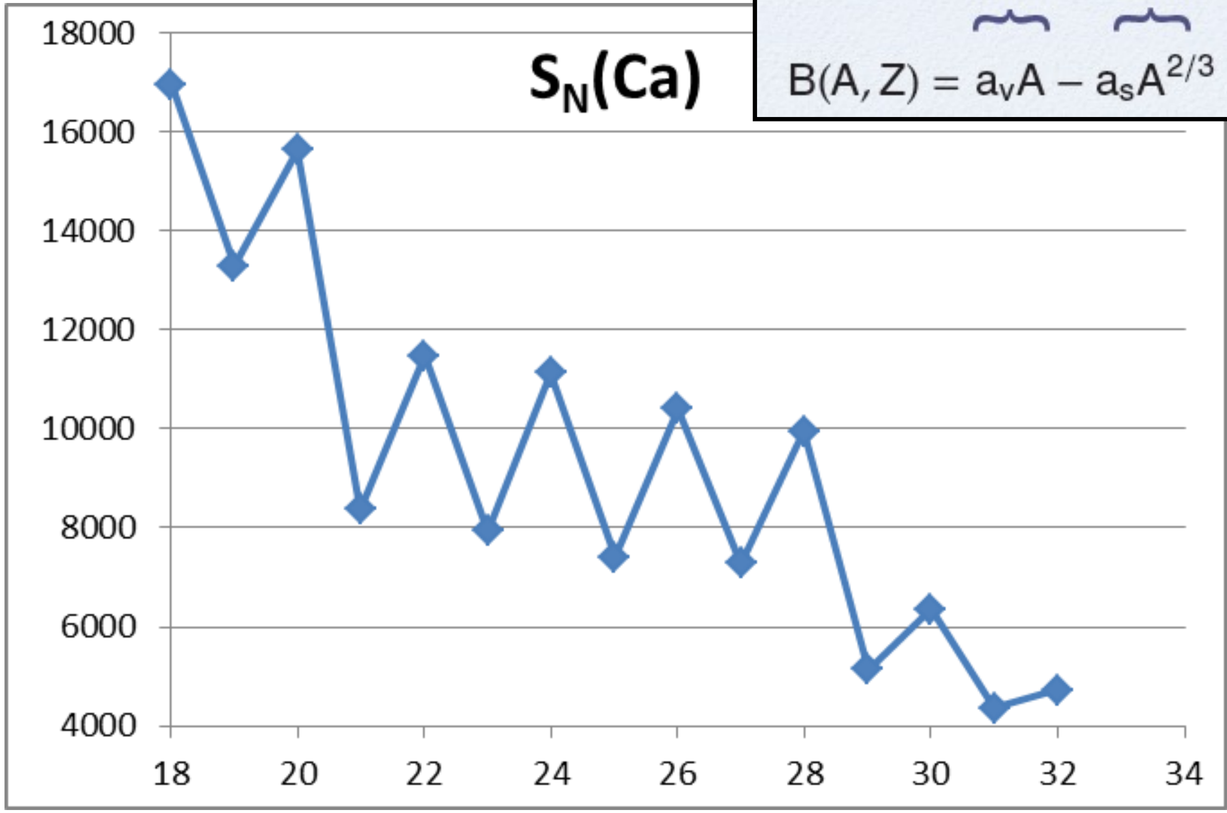
$$B(A,Z) = \overbrace{a_v A}^{\text{Volume term}} - \overbrace{a_s A^{2/3}}^{\text{Surface term}} - \overbrace{a_c Z^2 A^{-1/3}}^{\text{Coulomb term}} - \overbrace{a_a (A-2Z)^2 A^{-1}}^{\text{Asymmetry term}} - \overbrace{\delta}^{\text{Pairing term}}$$

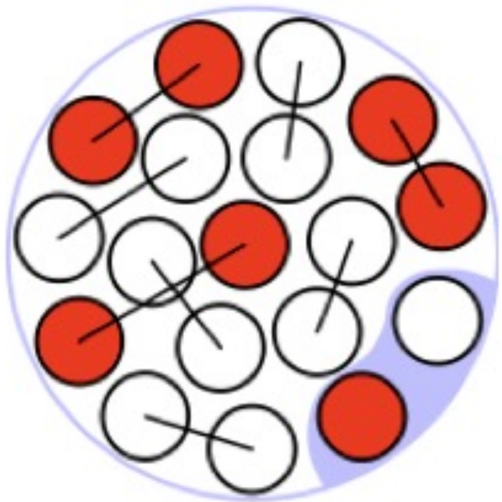




Pairing term

$$B(A,Z) = \overbrace{a_v A}^{\text{Volume term}} - \overbrace{a_s A^{2/3}}^{\text{Surface term}} - \overbrace{a_c Z^2 A^{-1/3}}^{\text{Coulomb term}} - \overbrace{a_a (A-2Z)^2 A^{-1}}^{\text{Asymmetry term}} - \overbrace{\delta}^{\text{Pairing term}}$$





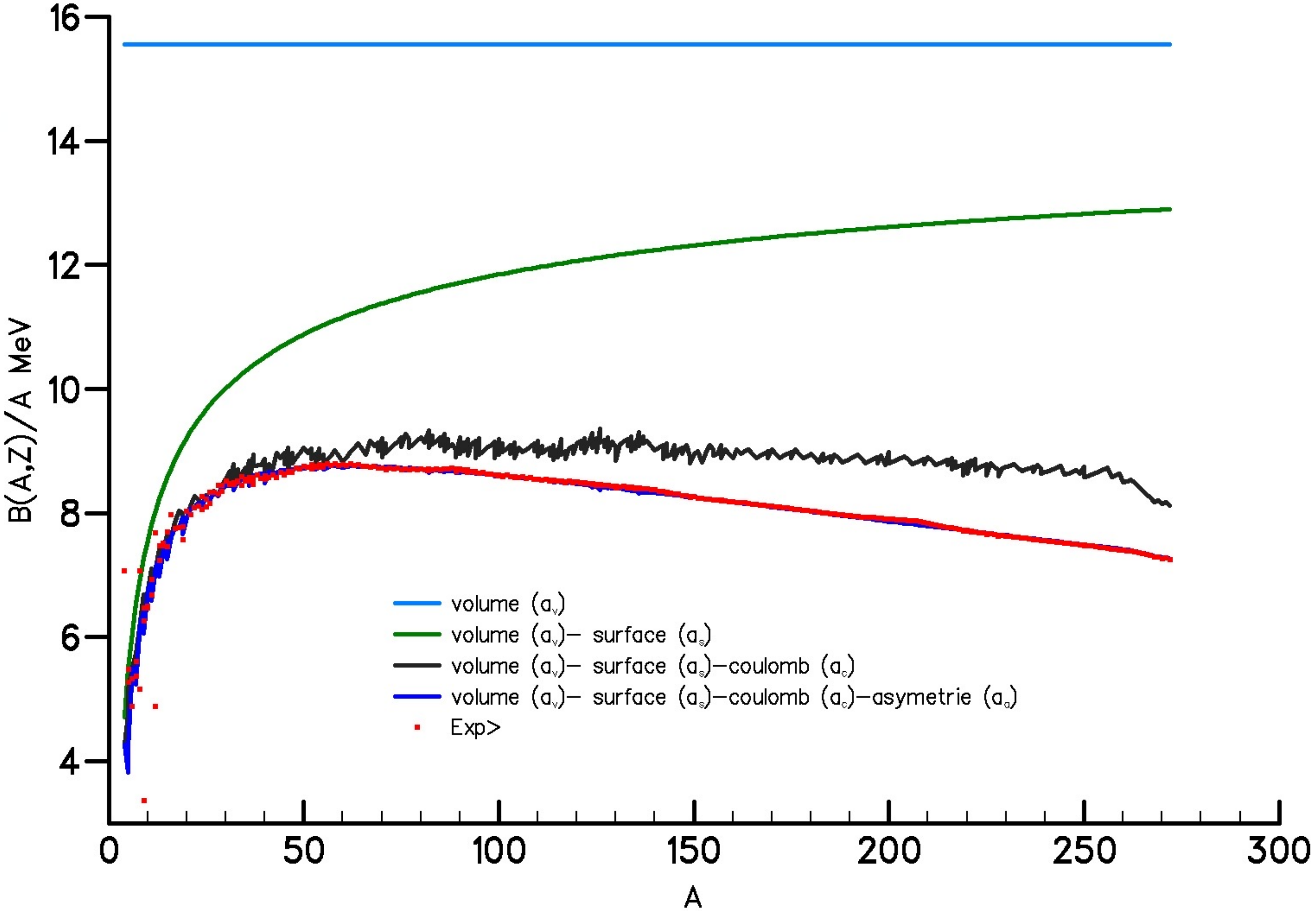
$$\begin{aligned} \delta &= +a_p A^{-1/2} && \text{for both N \& Z odd} \\ &= 0 && \text{for N even, Z odd / Z even, N odd} \\ &= -a_p A^{-1/2} && \text{for both N \& Z even} \end{aligned}$$

Application to data

Wapstra (1971):

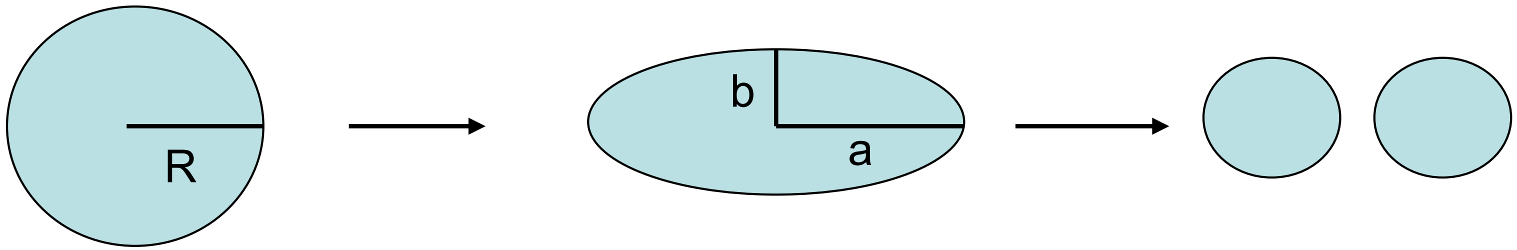
$a_v = 15.85$ MeV
$a_s = 18.34$ MeV
$a_c = 0.71$ MeV
$a_A = 23.21$ MeV
$a_p = 12$ MeV

For A > 20, accuracy generally better than 0.1 MeV
(i.e. error < 1% of total mass)



Stability of the liquid drop

Competition between the Coulomb repulsion between protons, which tends to deform the nucleus, and the surface tension, which tends to keep it spherical



$V = 4/3\pi R^3$

$S = 4\pi R^2$

$a = R(1+\varepsilon)$

$b = R(1+\varepsilon)^{-1/2}$

$\varepsilon = \sqrt{1 - \frac{b^2}{a^2}}$

$V = 4/3\pi a b^2$

$S = 4\pi R^2(1 + 2/5\varepsilon^2 + \ldots)$

$-a_s A^{2/3} - a_c Z^2 A^{-1/3}$

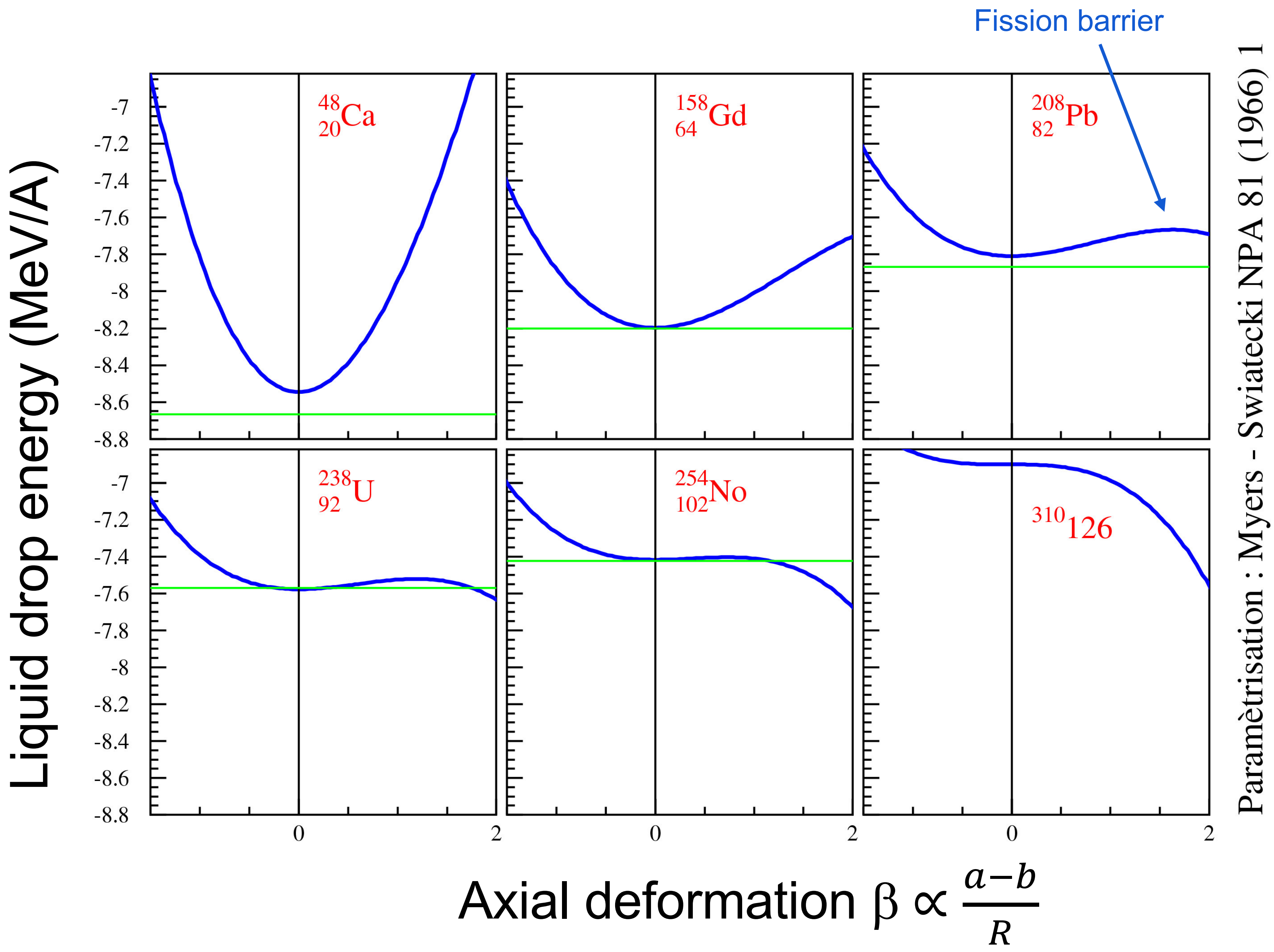
$a_s A^{2/3}(1 + 2/5\varepsilon^2 + \ldots) - a_c Z^2 A^{-1/3}(1 - 1/5\varepsilon^2 + \ldots)$

If $\Delta E = BE(\varepsilon) - BE(\varepsilon=0) > 0$, i.e $1/5 a_c Z^2 A^{-1/3} > 2/5 a_s A^{2/3}$:

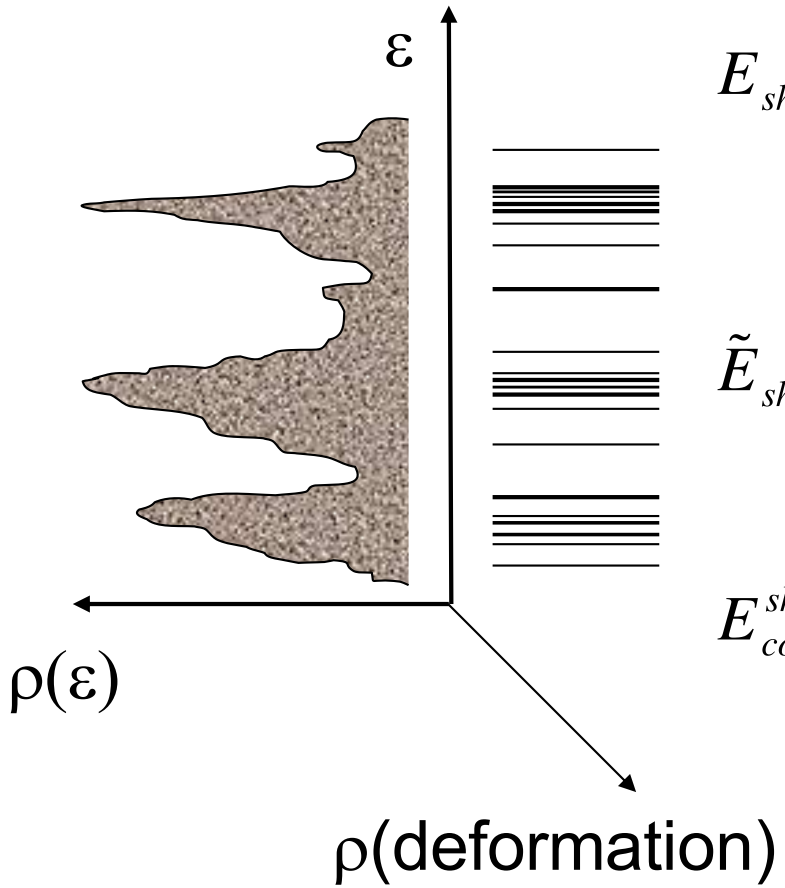
=> the nucleus gains binding energy if it deforms

=> spontaneous fission

Stability of the liquid drop



Quantum shell correction



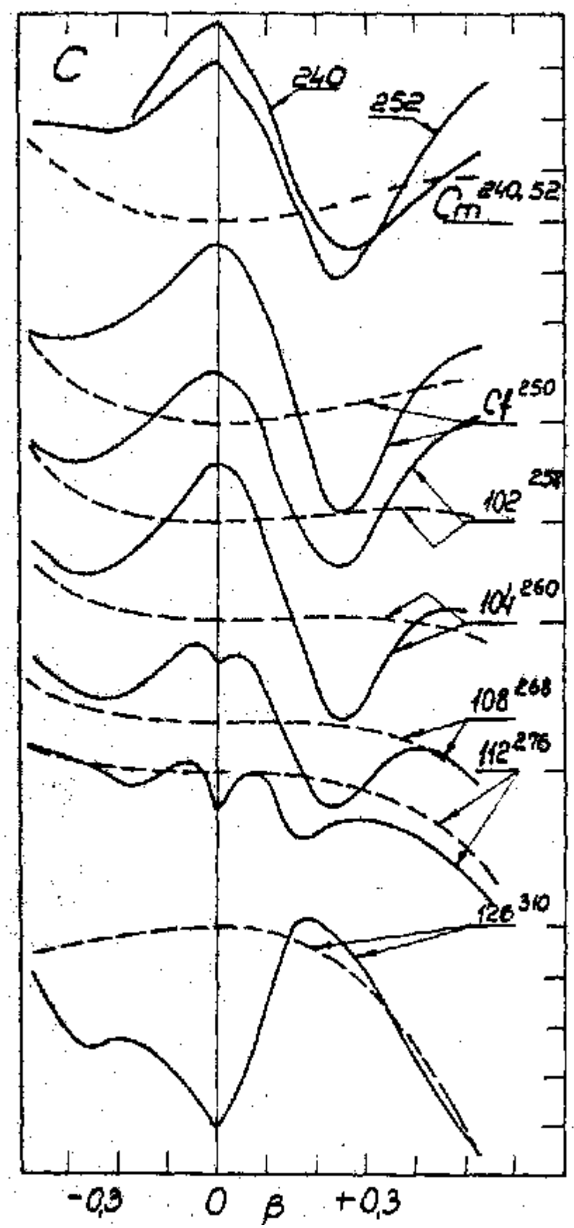
Density of states

$$E_{shell} = \sum \varepsilon_\nu = \int_{-\infty}^{\varepsilon_F} \rho(\varepsilon)\,d\varepsilon$$

Smoothed density

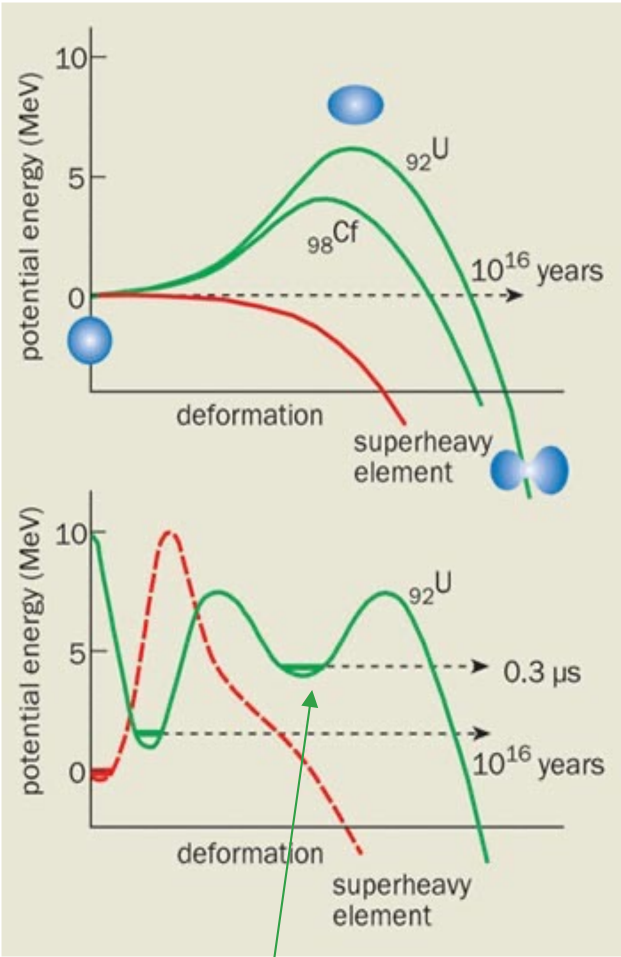
$$\tilde{E}_{shell} = \int_{-\infty}^{\tilde{\varepsilon}_F} \tilde{\rho}(\varepsilon)\,d\varepsilon$$

$$E^{shell}_{corr} = E_{shell} - \tilde{E}_{shell}$$



V.M. Strutinski, Nucl. Phys. A 95 (1967) 420

Fission isomers



Superdeformed nucleus

First observation of a spontaneously-fissioning isomer : ^{242}Am

S. Polikanov *et al.* Sov.Phys.JETP **15** (1962)

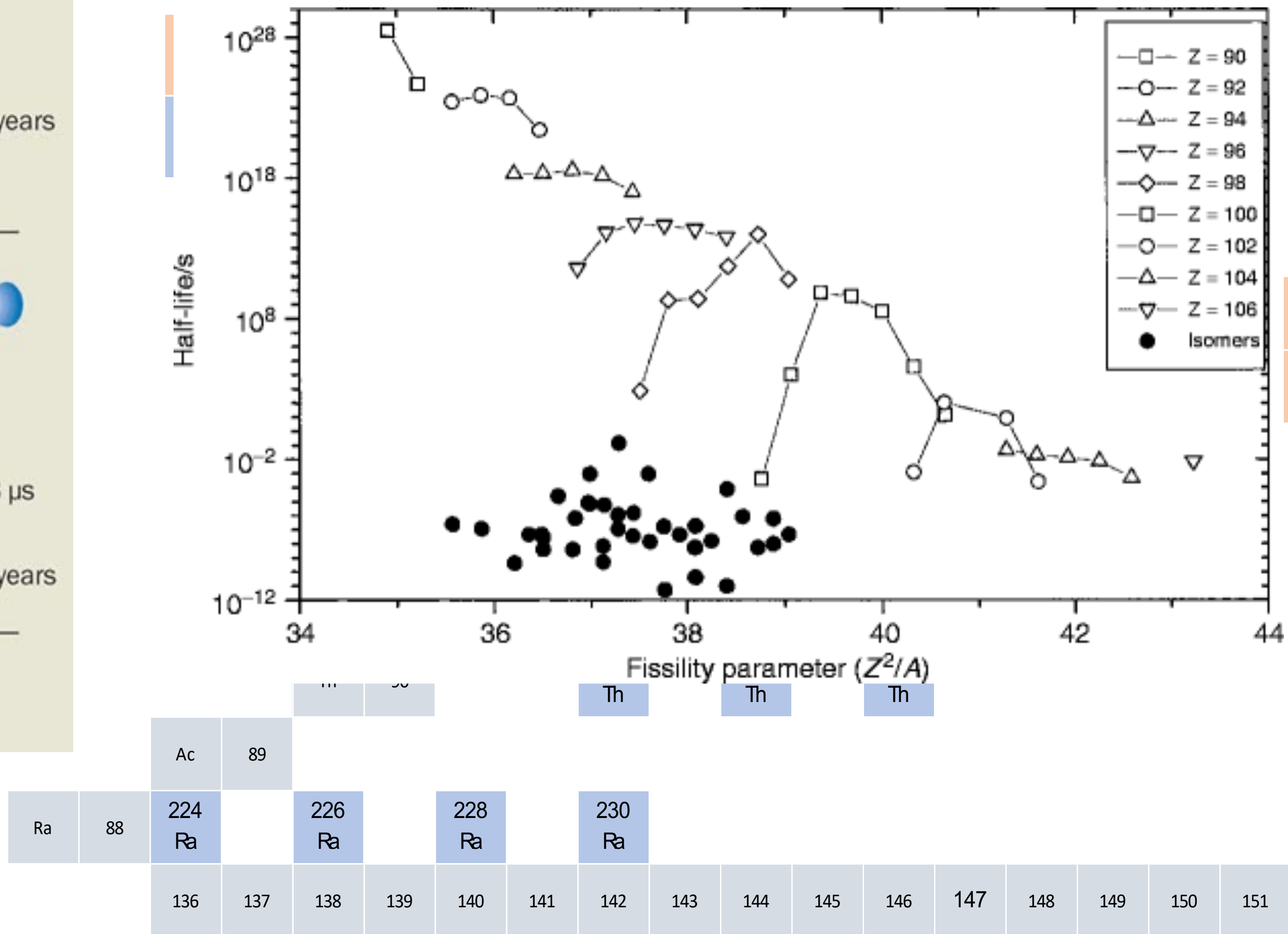


Image by J.N. Wilson

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 !

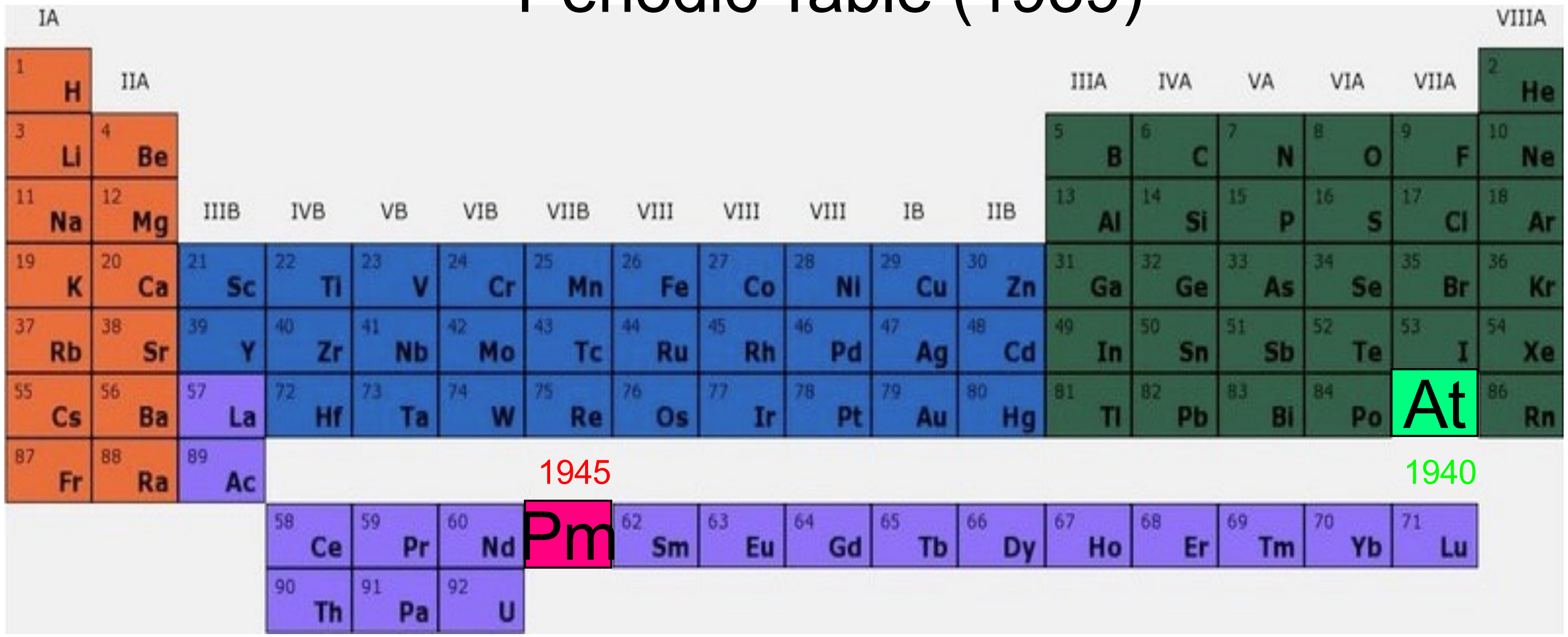
Irène Curie et
Frédéric Joliot

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, which they call Technetium

Periodic Table (1939)



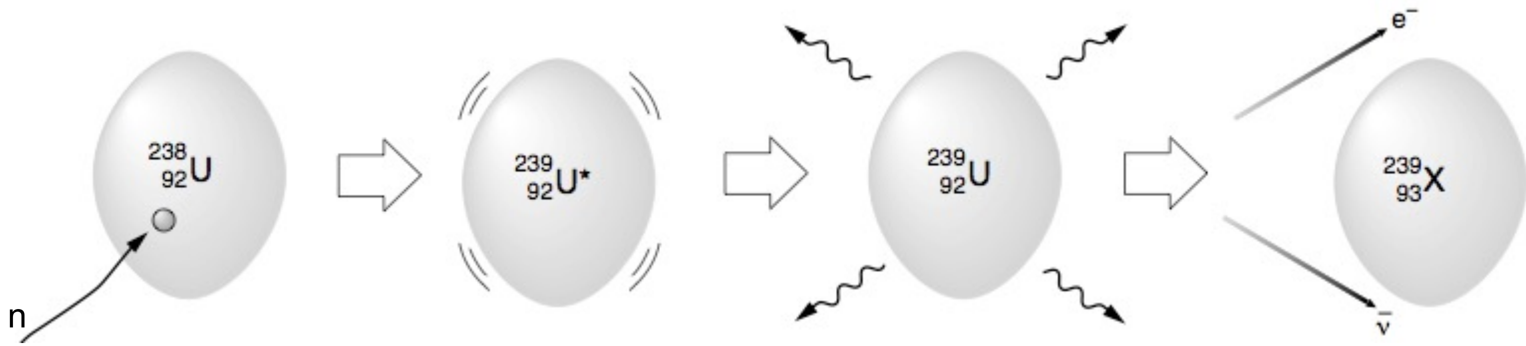
The era of the neutron

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...

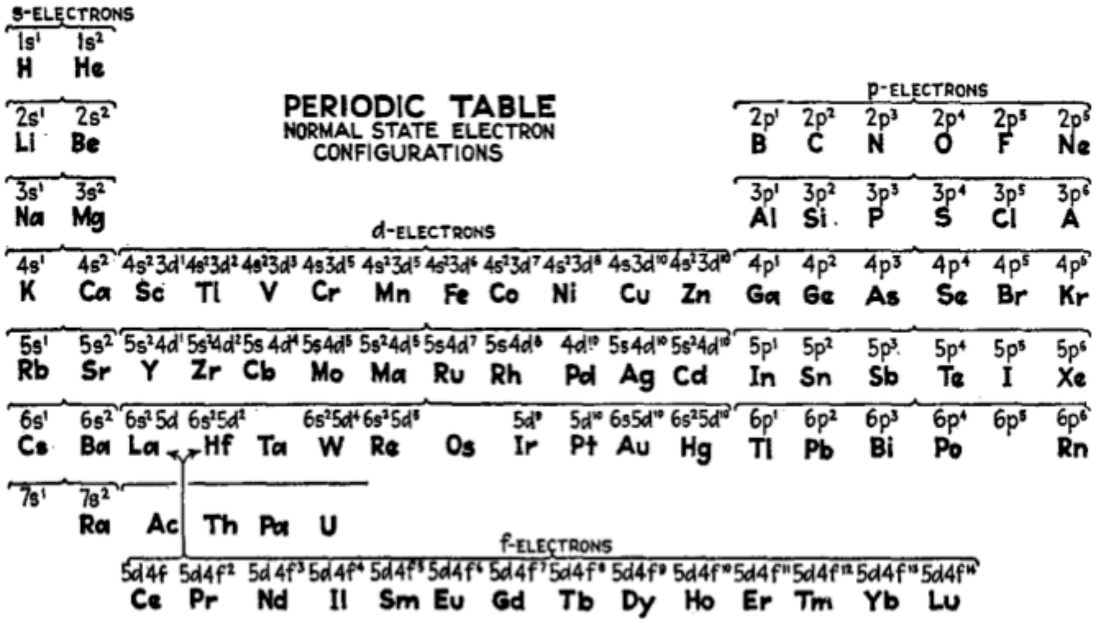
1935-1938: Otto Hahn, Lise Meitner and Fritz Strassmann discover a great number of new transuranium radio-isotopes (up to Z=96)

Irène Curie end Pavel Savitch claim to have produced a substance similar to Lanthanum

Lise Meitner et Otto Hahn (1918)

...m and Cerium, what we called ... Thorium. This is a difficult decision, ...uclear physics experiments.

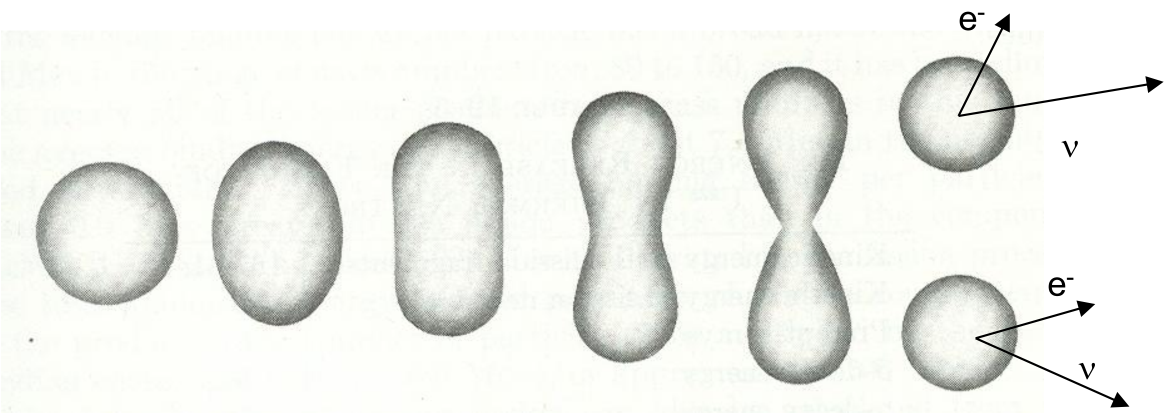
...hn and F. Strassmann, Naturwiss 27 (1939) 11

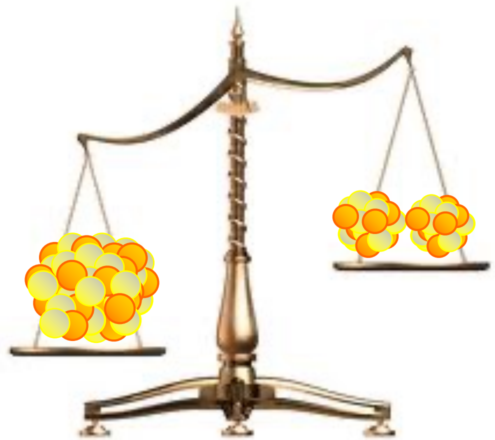


Fission

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





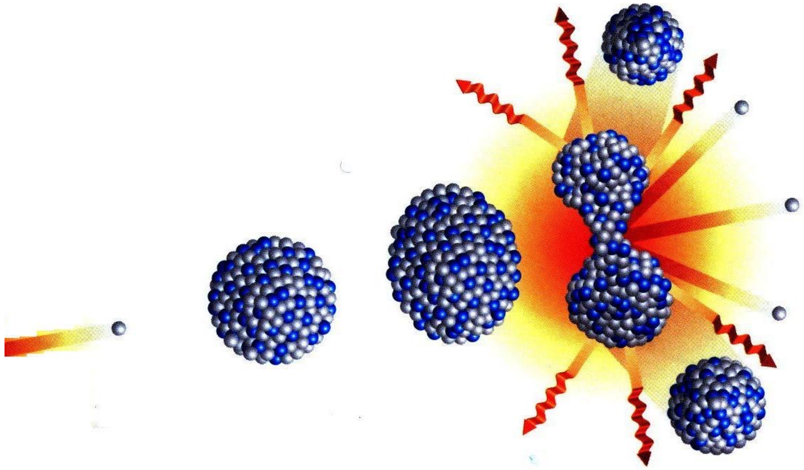
This hypothesis is immediately confirmed by O. Frisch and by others (F. Joliot)

O. Frisch, Nature 143 (1939) 276

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

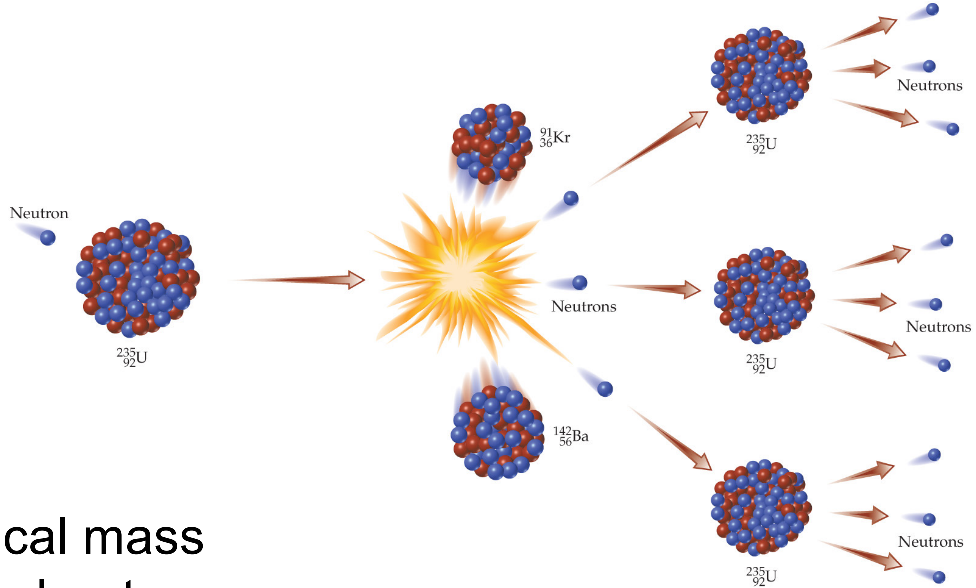
N. Bohr et A. Wheeler, Phys. Rev. 56 (1939) 426

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

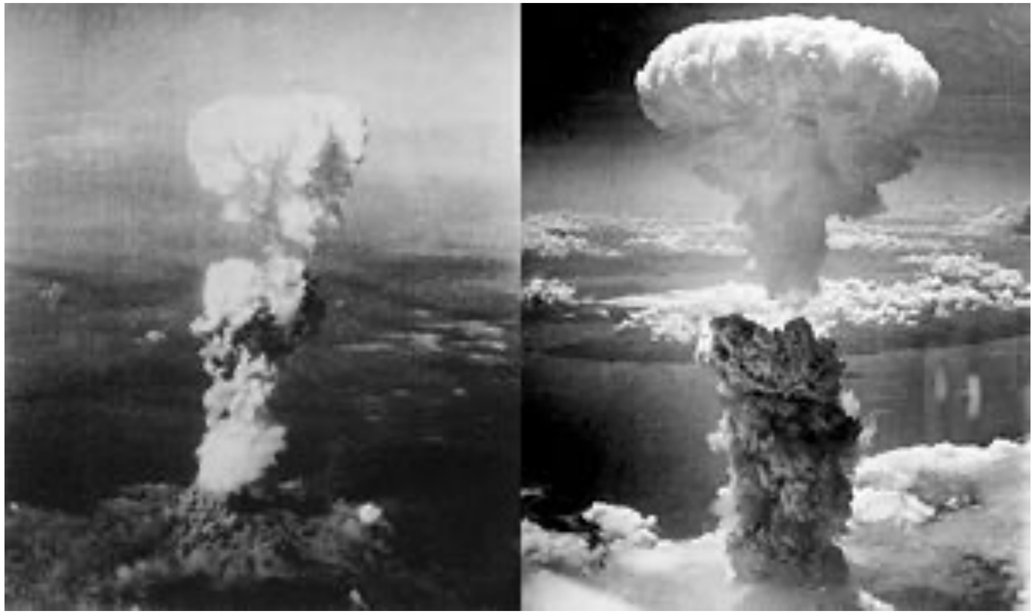
Manhattan Project and C_{hicago}P_{ile}-1

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

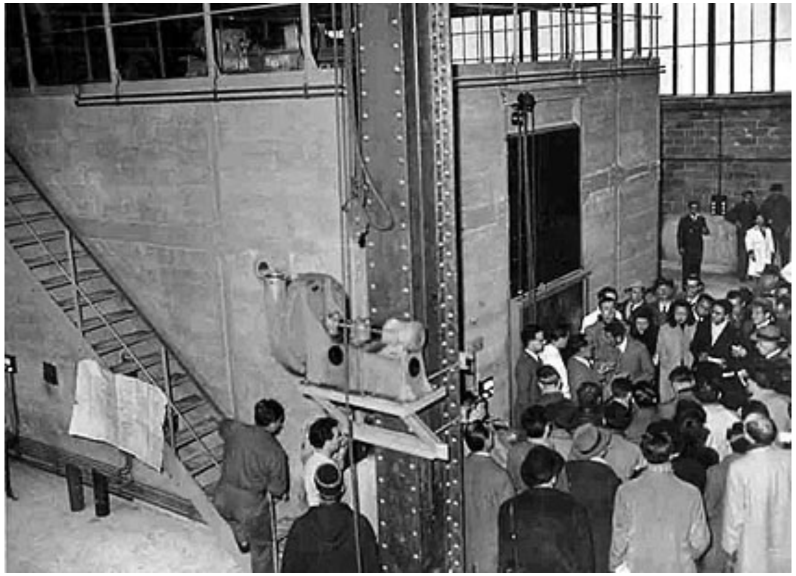
The first atomic pile is inaugurated in december 1942

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)

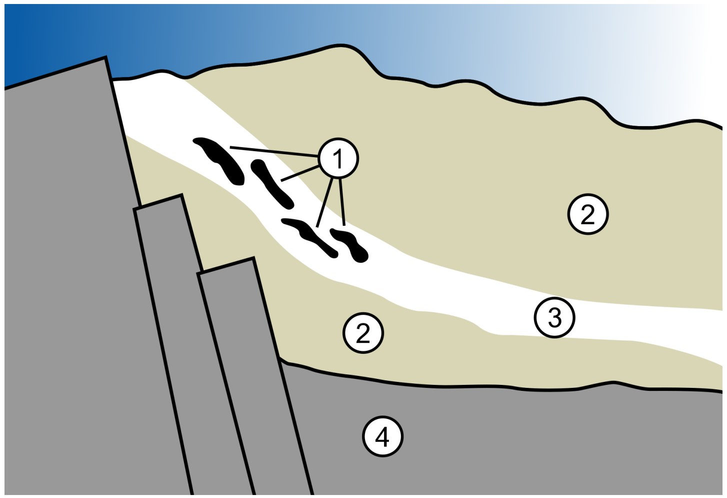
1954: First kWh from a nuclear power station in Obninsk AES-1 (USSR)

Oklo natural reactor

Discovered in 1972 in a uranium mine in Gabon (an abnormal deficit of ^{235}U, later confirmed by traces of fission products)

A combination of circumstances:

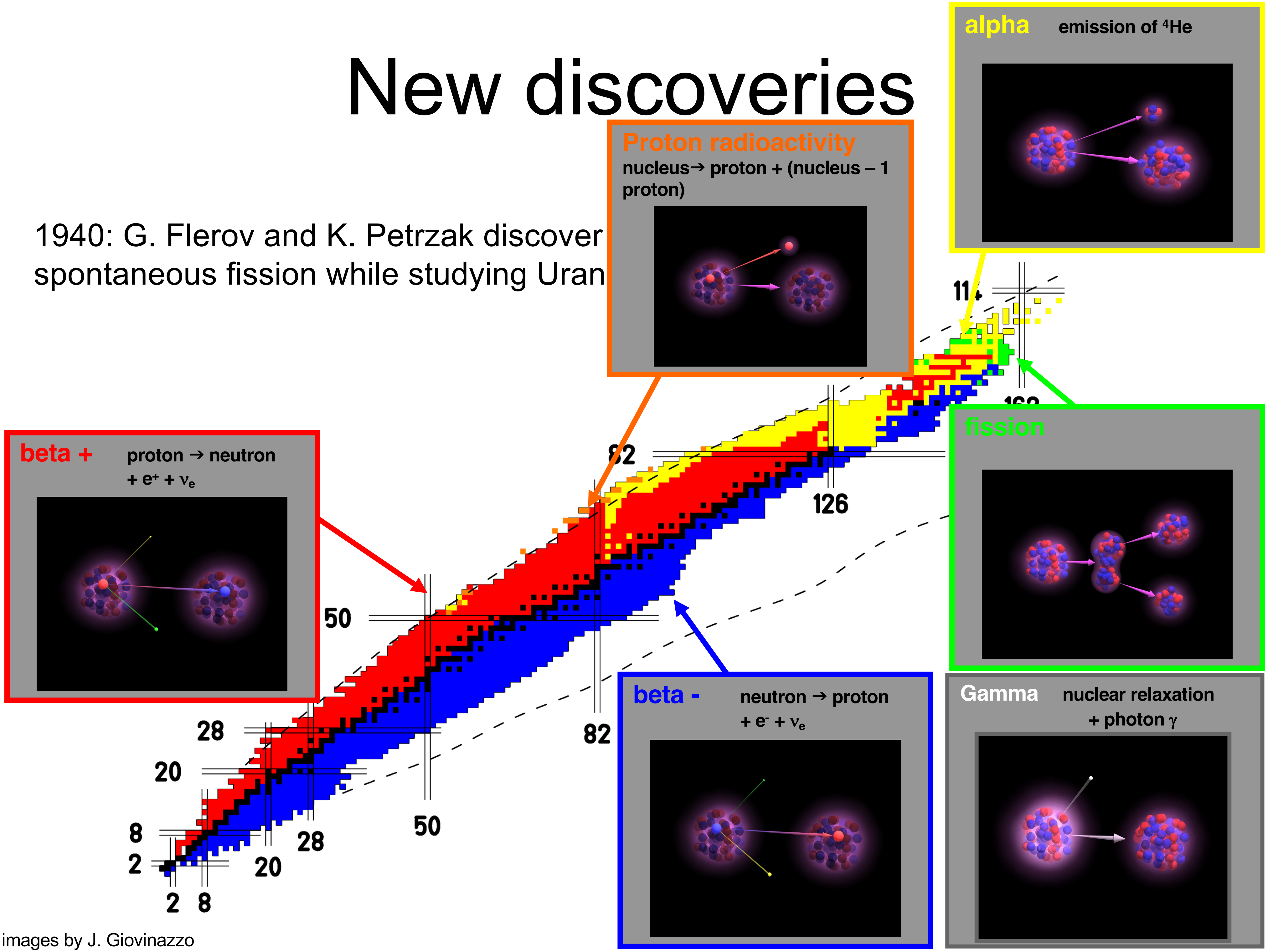
- U-rich zone
- Sufficient concentration of 235U (higher concentration 2 billion years ago: 3.8% instead of 0.7%)
- Presence of a moderator to sustain the reaction: water
- Absence of neutron-absorbing metals/minerals



These reactors operated for hundreds of thousands of years in cycles of approximately 2.5 hours.

New discoveries

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



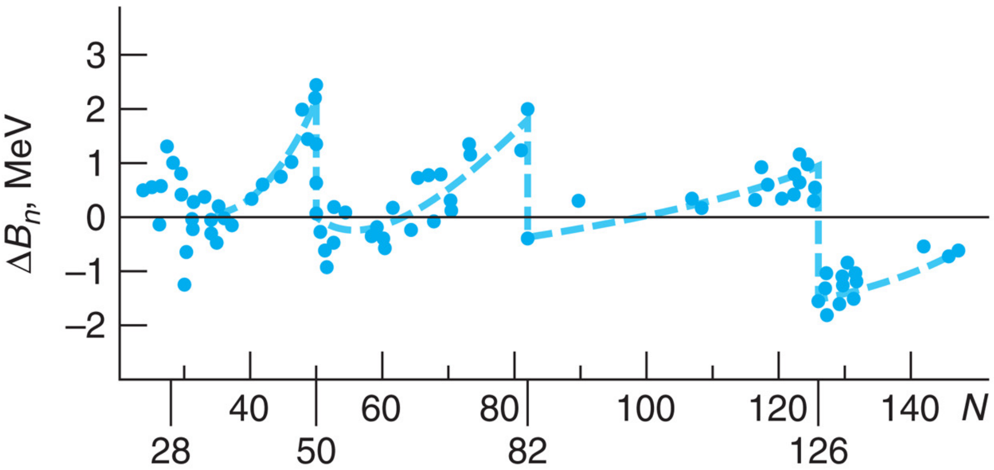
images by J. Giovinazzo

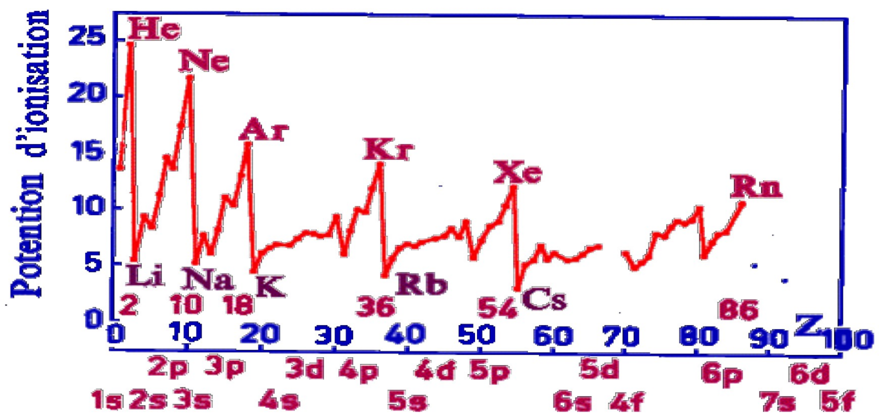
Magic numbers

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



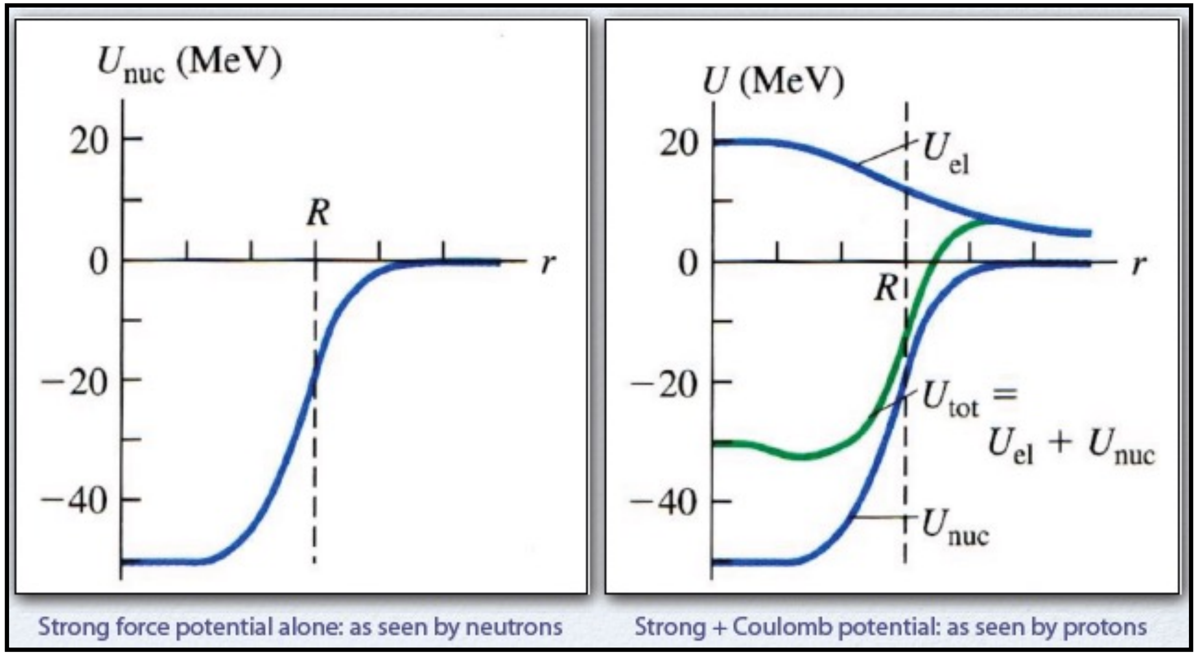


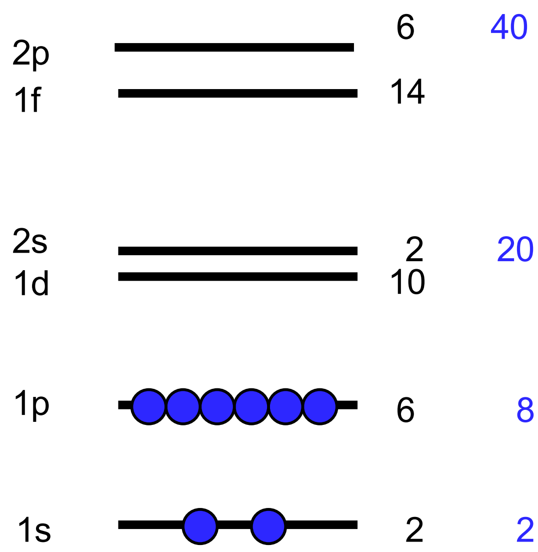
⇨ periodic structure of the nucleus ?

‘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





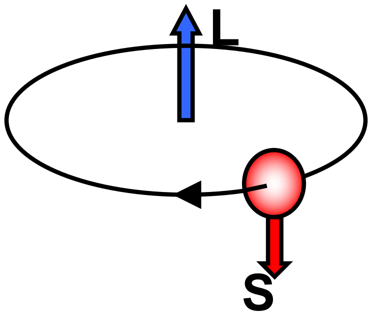
Total number of neutrons (or protons), which can be accommodated in each shell

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

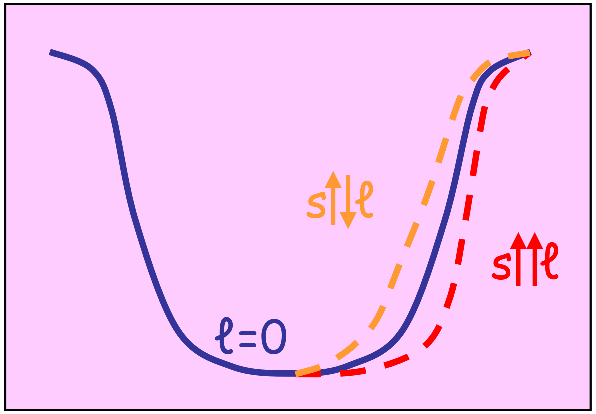
The question which solves the problem

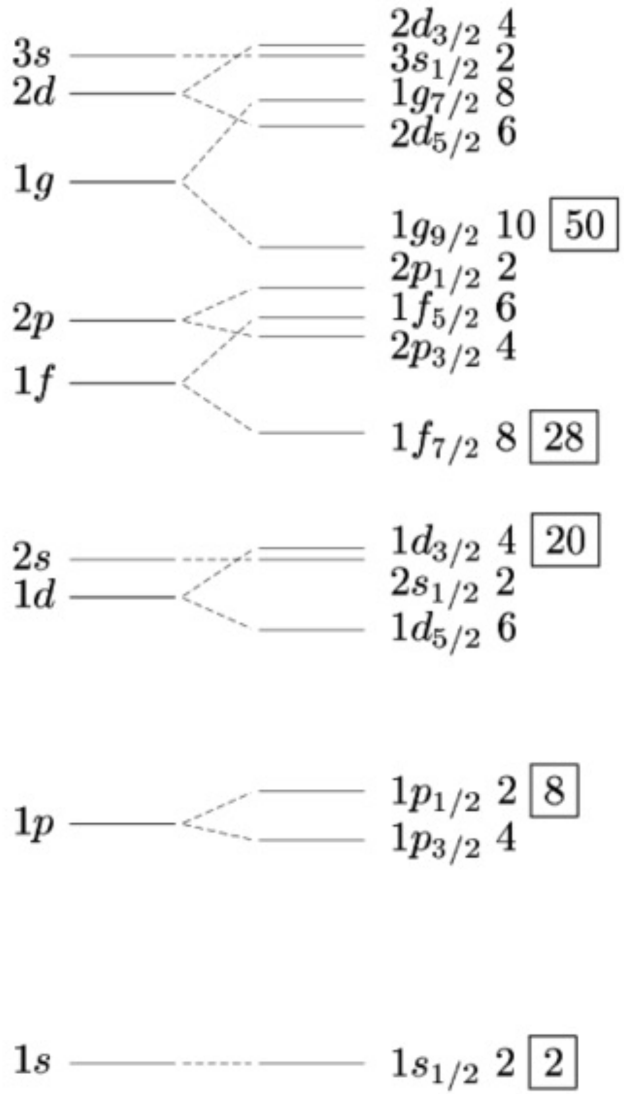
Thanks are due to Enrico Fermi for the remark, "Is there any indication of spin-orbit coupling?" which was the origin of this paper.

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



Hans Jensen



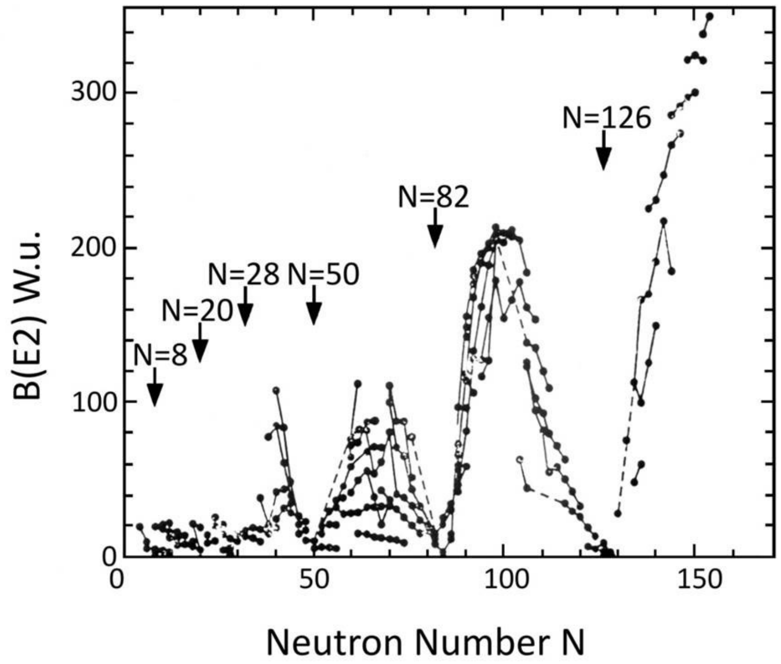


M.G. Mayer et H.D. Jensen 'Elementary Theory of Nuclear Shell Structure', 1955

Success of the Shell Model

Properties of magic nuclei:

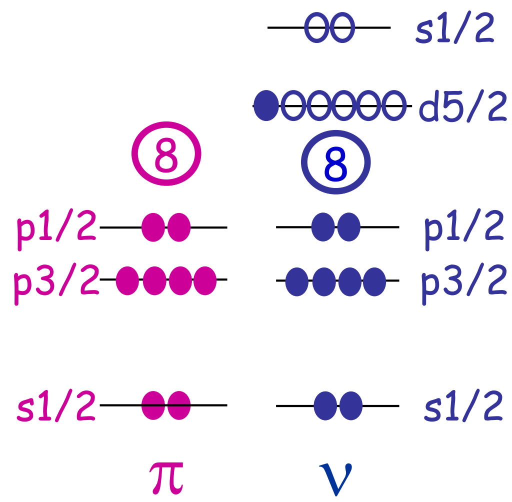
* $J^\pi=0^+$
* 1st excited state at high energy
* Low excitability



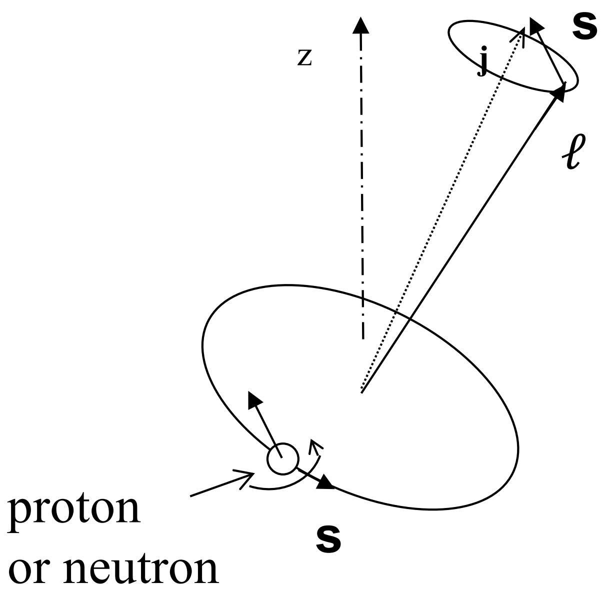
Properties of nuclei with +/- 1 nucleon with respect to a magic nucleus:

* J^π (nucleus) = J^π (last nucleon/hole)

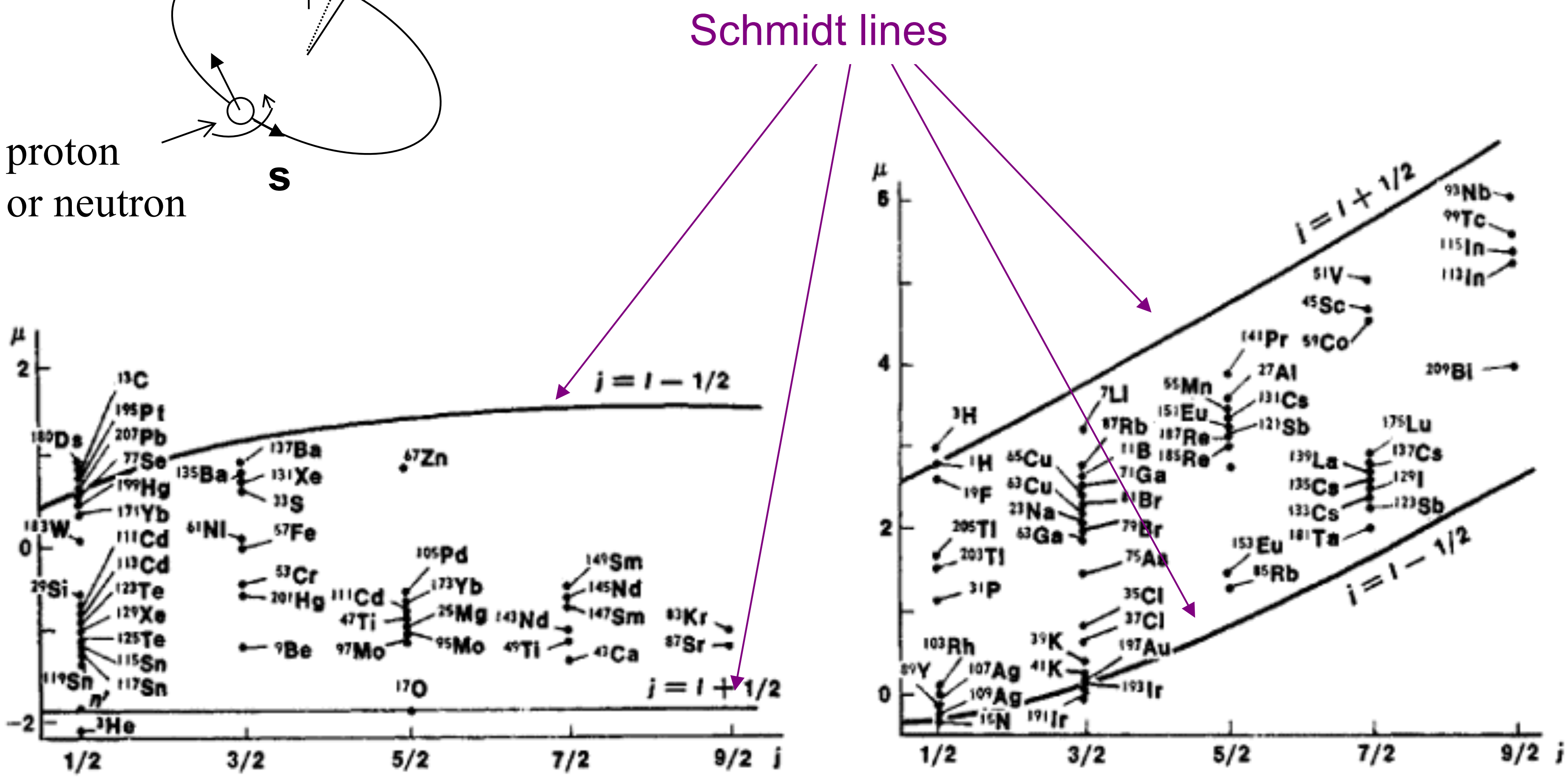
^{17}O:
- Ground state: $5/2^+$
- 1^{st} excited state: $1/2^+$



Nuclear magnetic moments



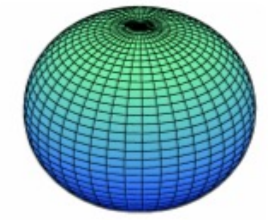
$$\vec{\mu} = g^l \vec{l} + g^s \vec{s}$$



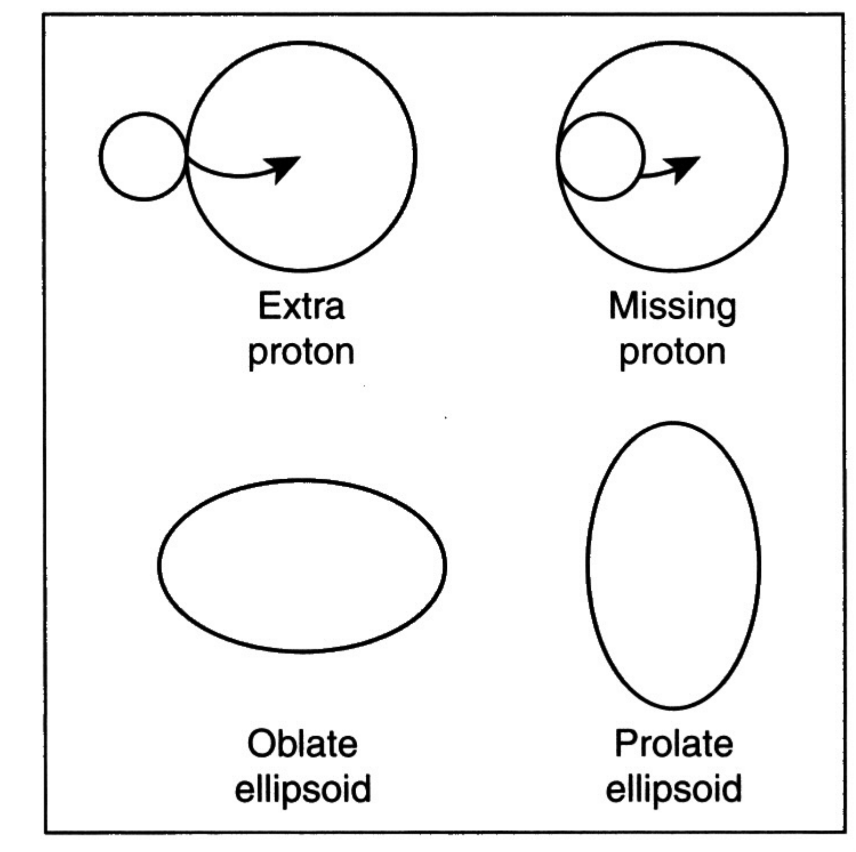
neutron célibataire

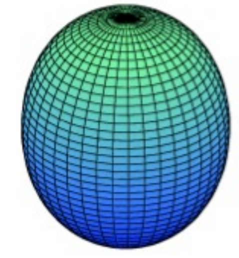
proton célibataire

Electric quadrupole moments



$$Q < 0$$





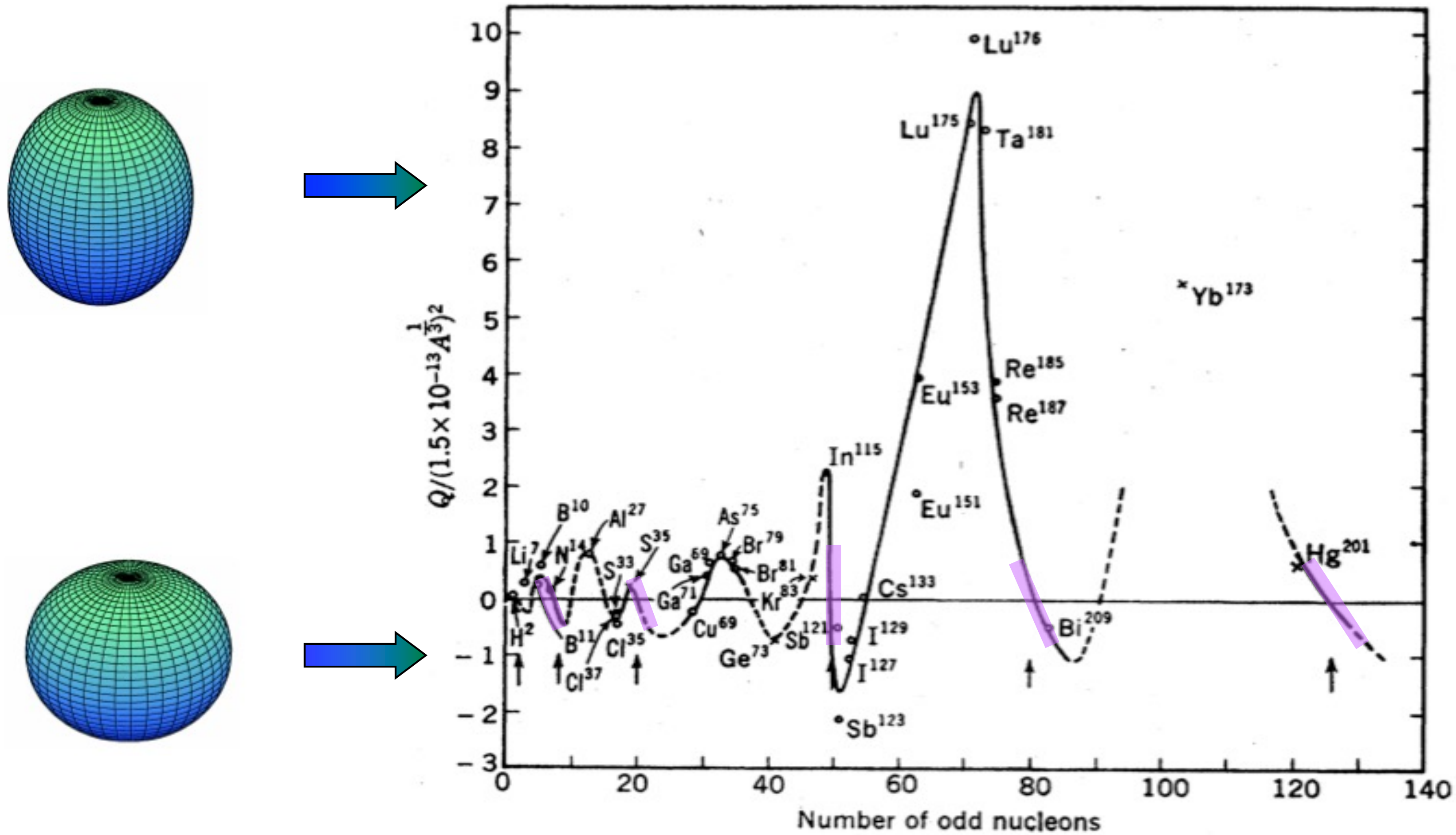
$$Q > 0$$

$$\langle Q \rangle = -\frac{2j-1}{2(j+1)} \langle r_j^2 \rangle$$

$$\langle Q \rangle (hole) = -\langle Q \rangle (particle)$$

Experimental charge distributions

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



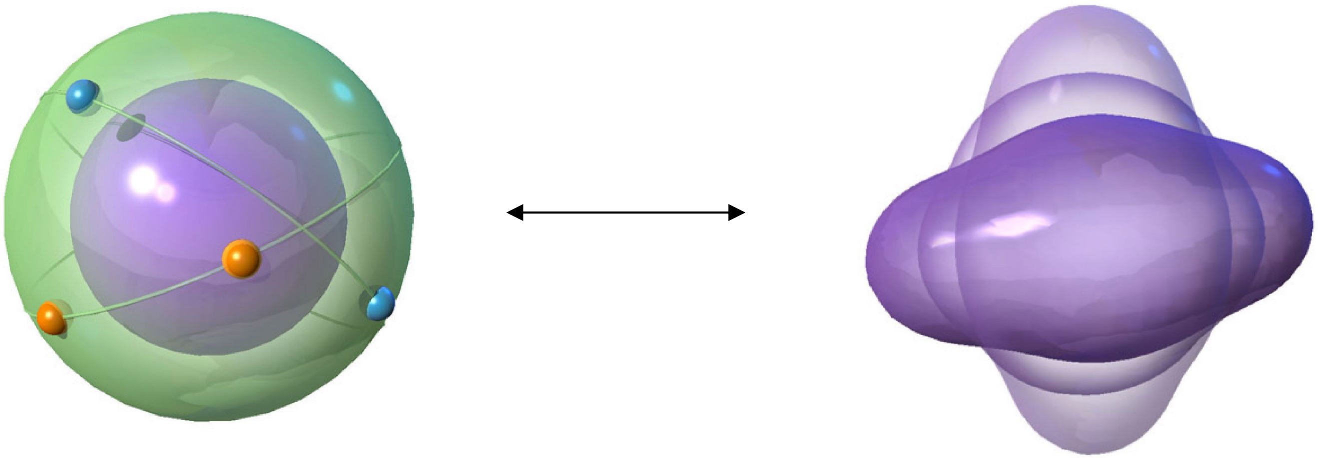
Certain moments are ~30 times larger than shell-model predictions !

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

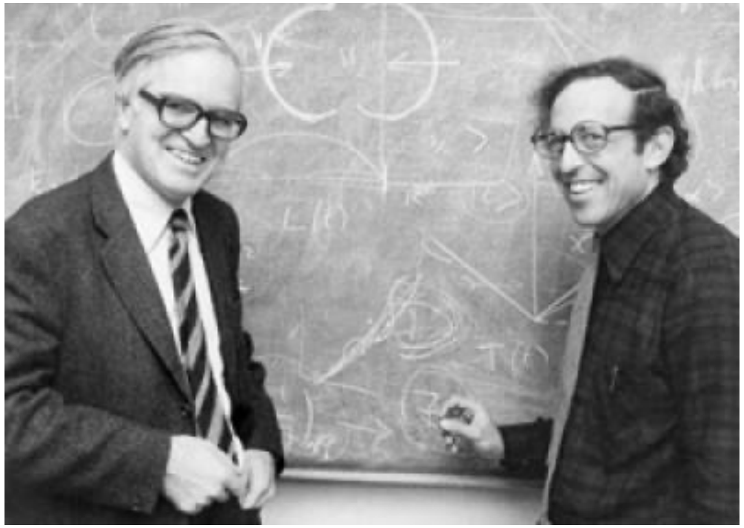
J. Rainwater, Phys. Rev. 79 (1950) 432



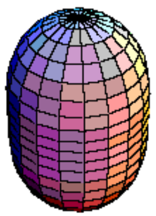
Single-particle and collective states of the nucleus

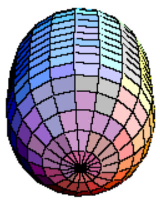
The unified model couples the oscillations and rotations of the liquid drop to the movement of the individual nucleons

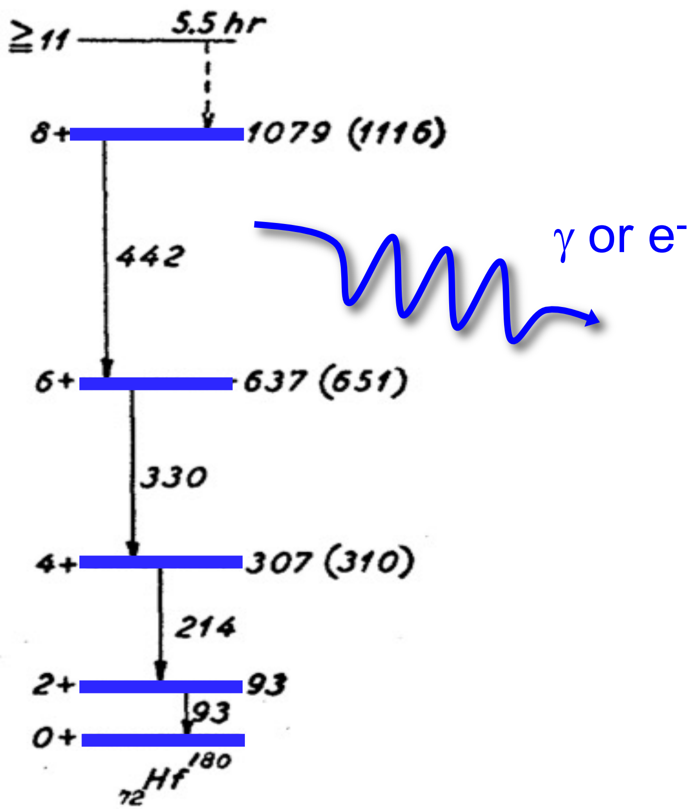
A. Bohr et B. Mottelson, Kgl. Danske Videnskab. Selskab, Mat-.-fys. Medd. 27 (1953) 16



Aage Bohr et Ben Mottelson



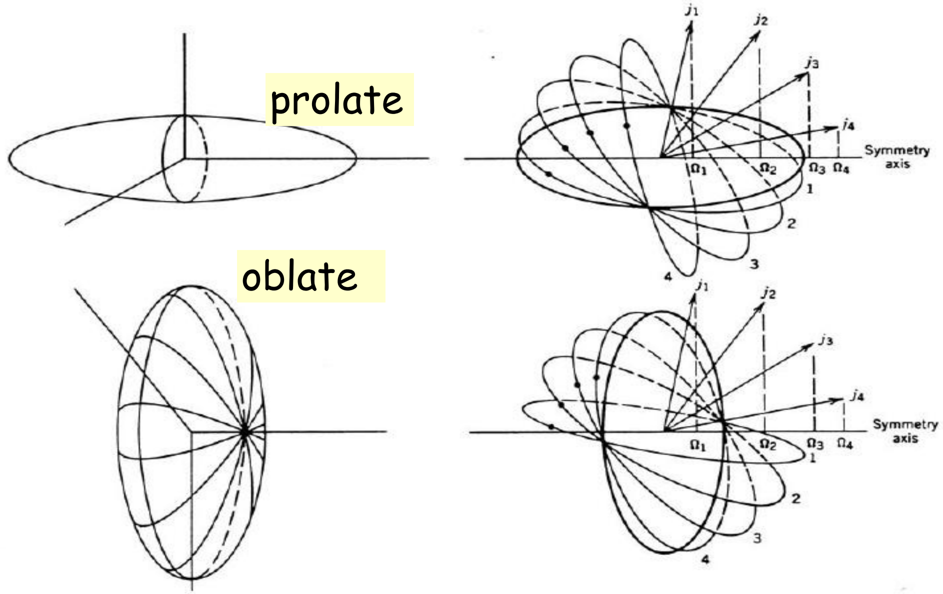


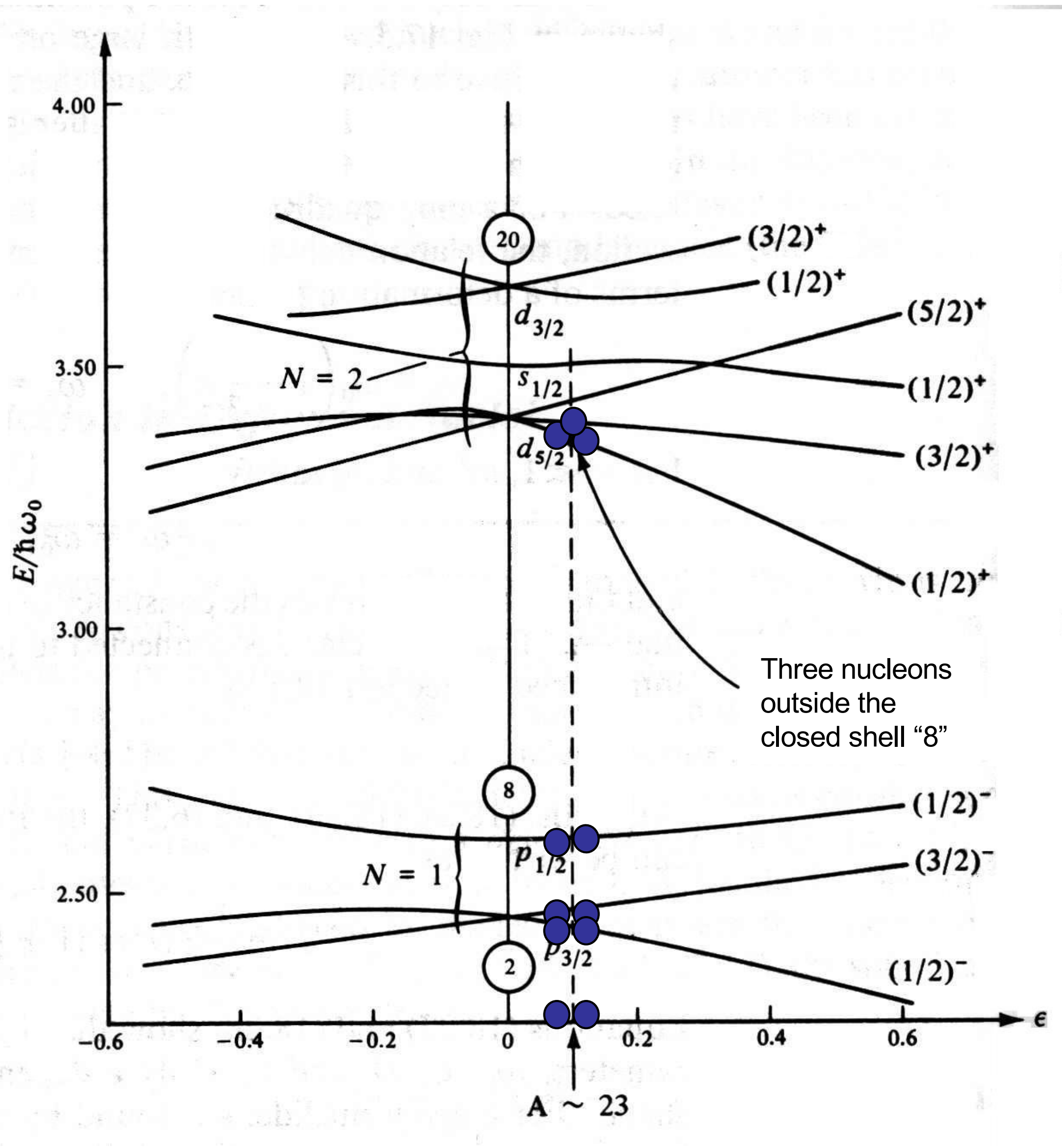


Deformed Nilsson potential

S. G. Nilsson *Mat. Fys. Medd. Dan. Vid. Selsk.* **29** no 16 (1955)

$$H = \frac{\mathbf{p}^2}{2m} + \frac{m[\omega_x^2(\mathbf{x}^2+\mathbf{y}^2)+\omega_z^2\mathbf{z}^2]}{2} + C\mathbf{l}\bullet\mathbf{s} + D\mathbf{l}^2$$





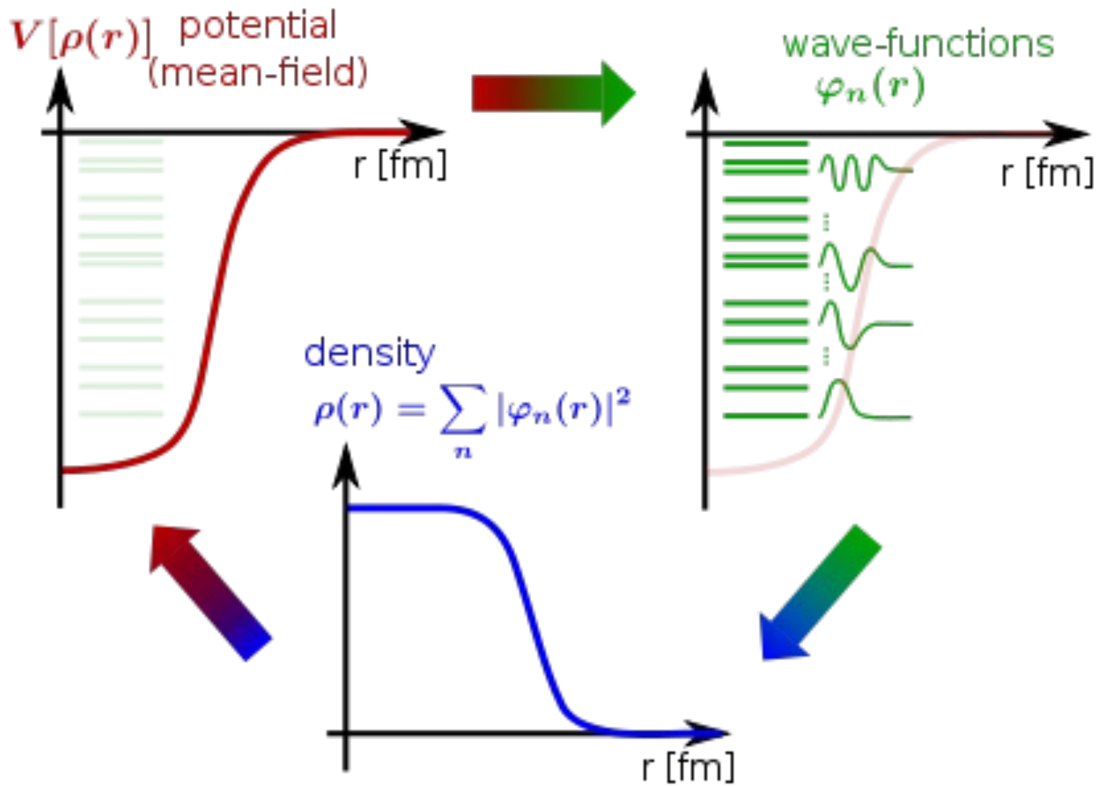
$^{21}Ne_{11}$ and $^{21}Na_{10}$

	g.s.	first E*
• spherical SM	$5/2^+$	$1/2^+$
• experiment	$3/2^+$	$5/2^+$

Sefl-consistent approaches

Goal: Deduce the nuclear potential from the N-N interaction

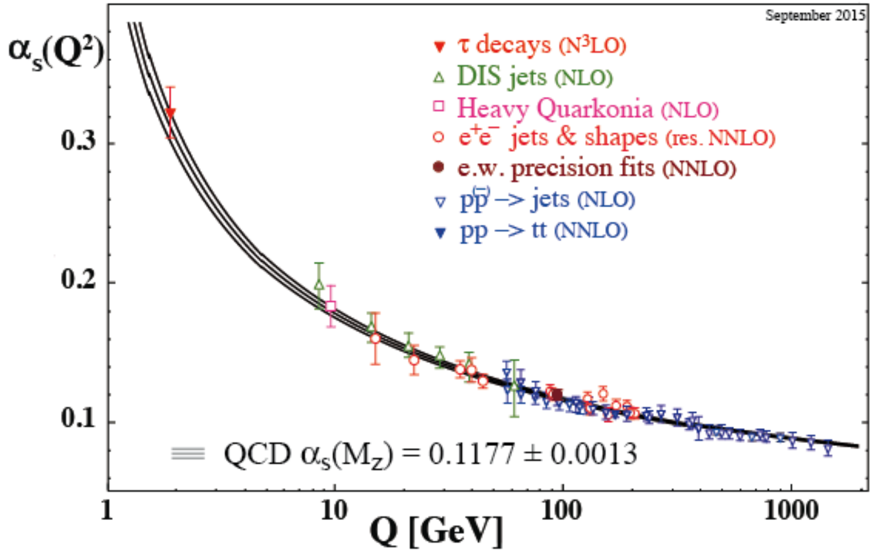
iterative procedure, because the potential resulting from all possible two-body interactions depends on the wave functions we are trying to determine



Self-consistent mean-field theory

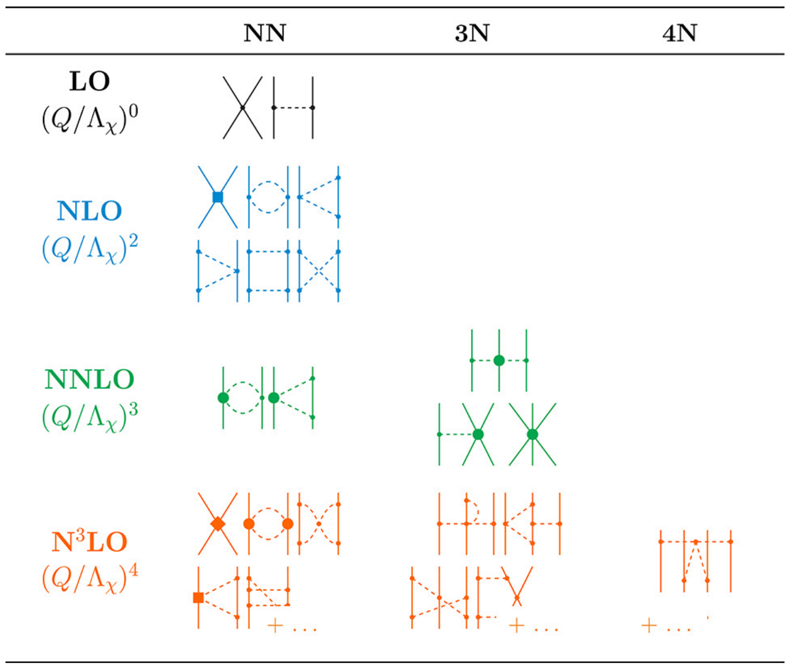
Exampled of N-N interaction:
- Skyrme (contact force)
- Gogny (finite range)

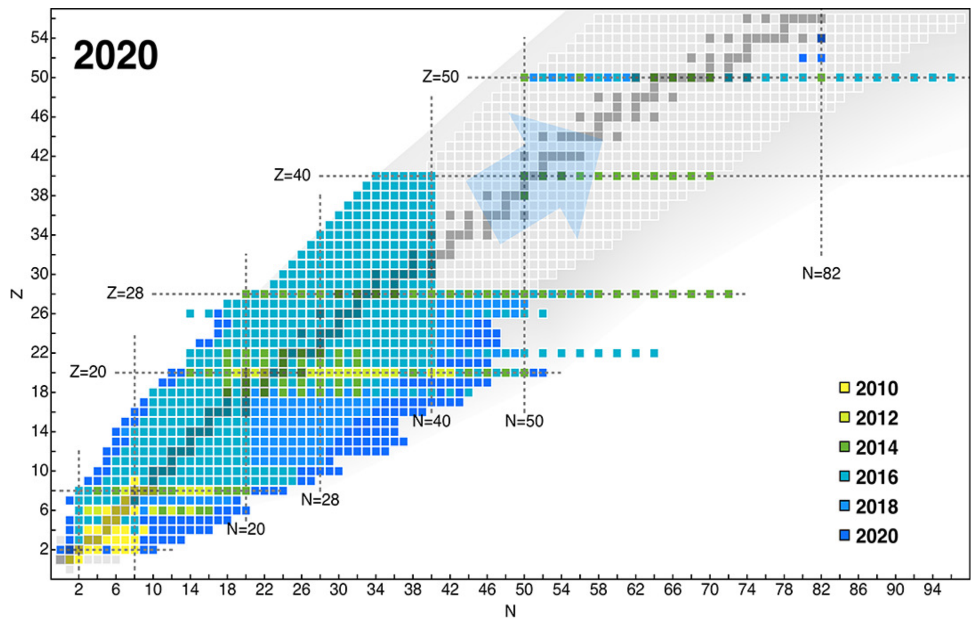
Theoretical advances



The strong interaction is so strong at the energies of nuclear physics that a perturbative approach to QCD is impossible for nuclei

For the past ~15 years: Construction of "ab initio" interactions consistent with QCD symmetries (chiral effective theories)
Degrees of freedom: nucleons & pions

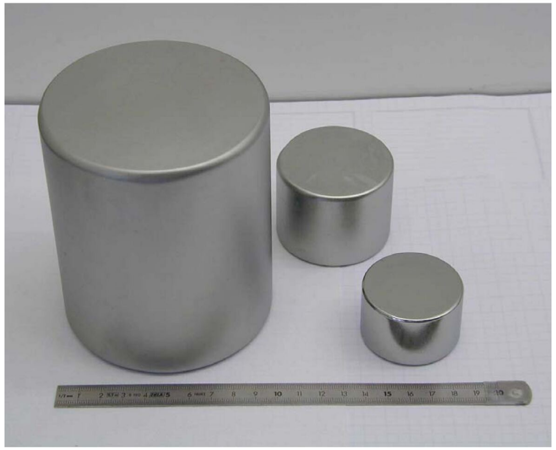




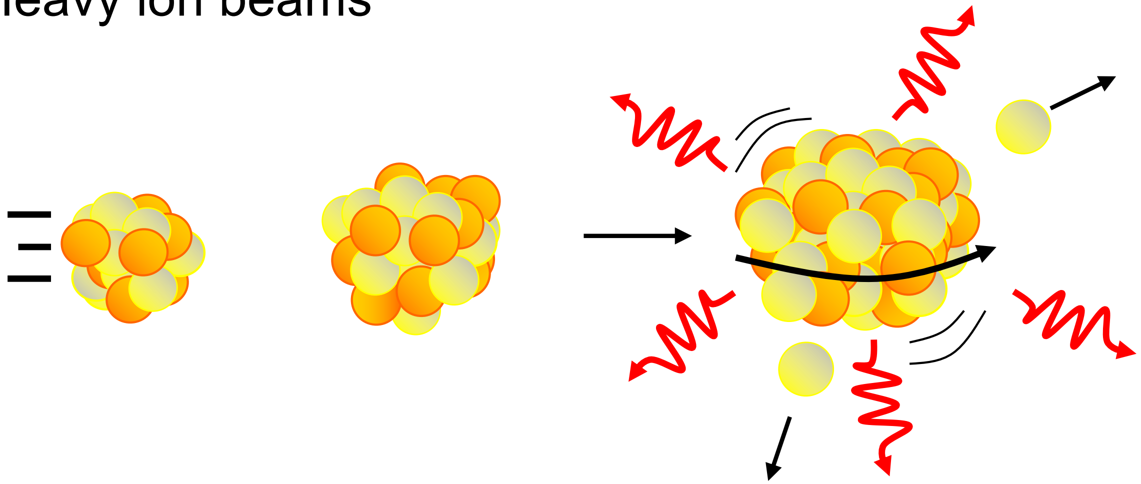
H. Hergert, Front. Phys., 07 October 2020

1950-1970: detection and accelerator developments

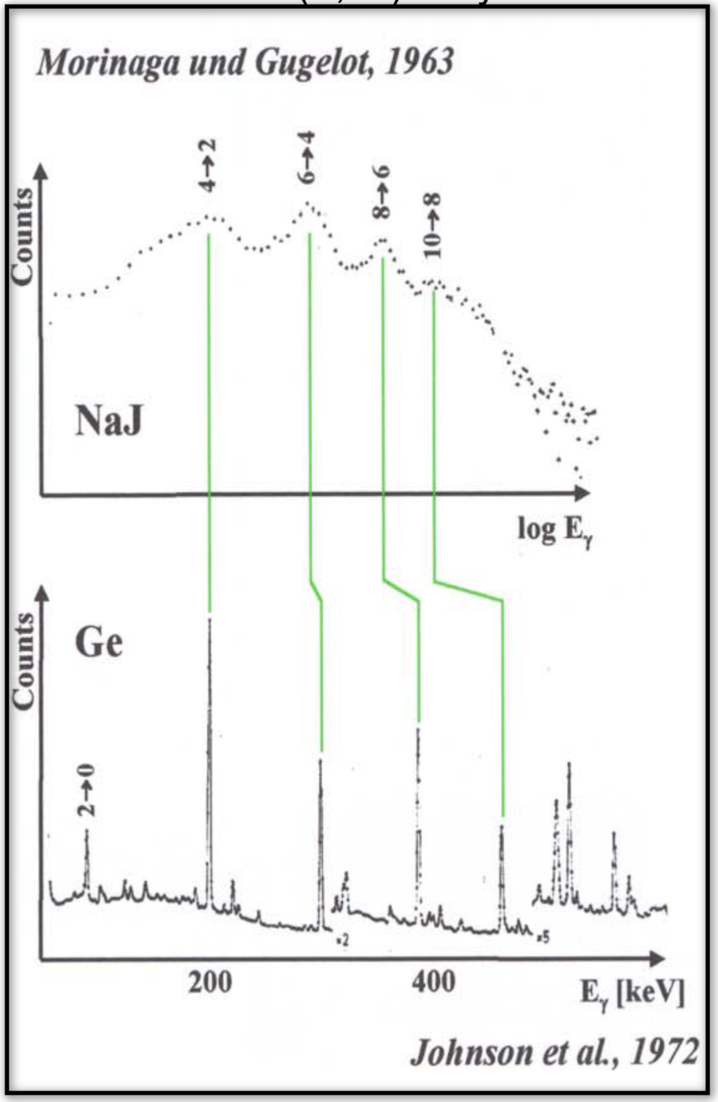
Scintillators & semi-conductors



Heavy ion beams

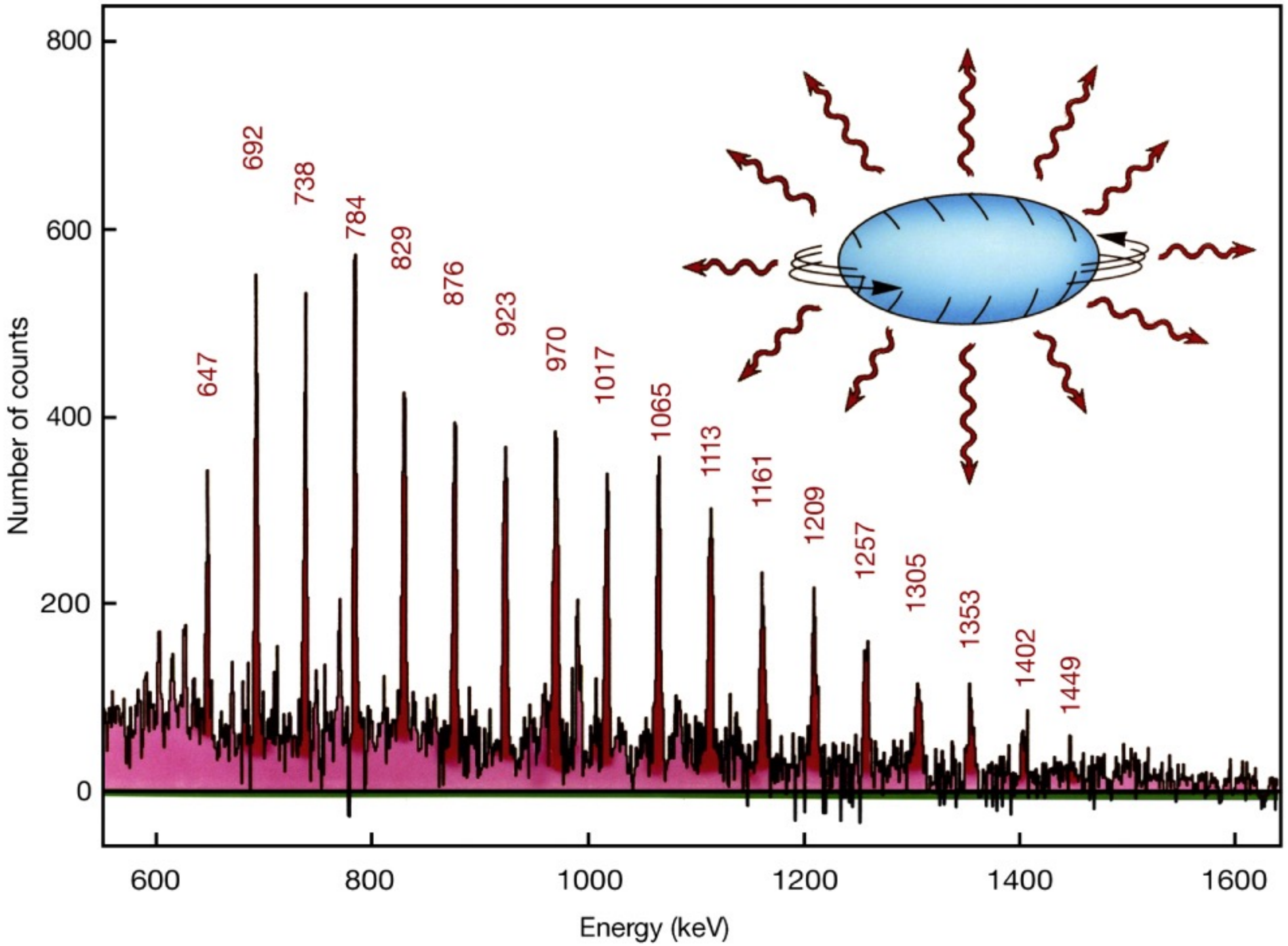


$^{160}Gd(\alpha,4n)^{160}Dy$



Extreme collectivity

P.J. Twin et al. Phys. Rev. Lett., 57:811, 1986

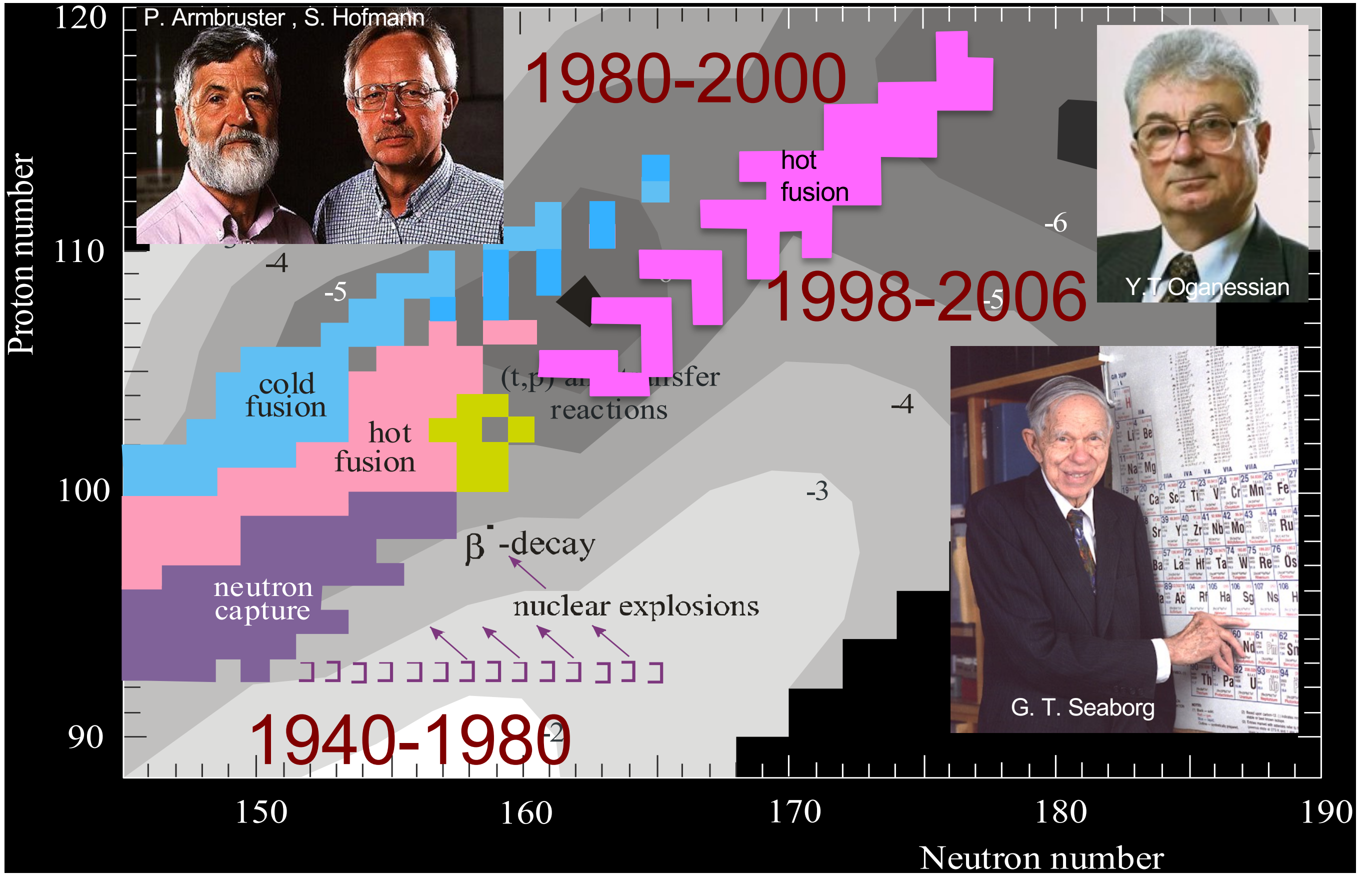


Superdeformation up to 68 $\hbar$!!

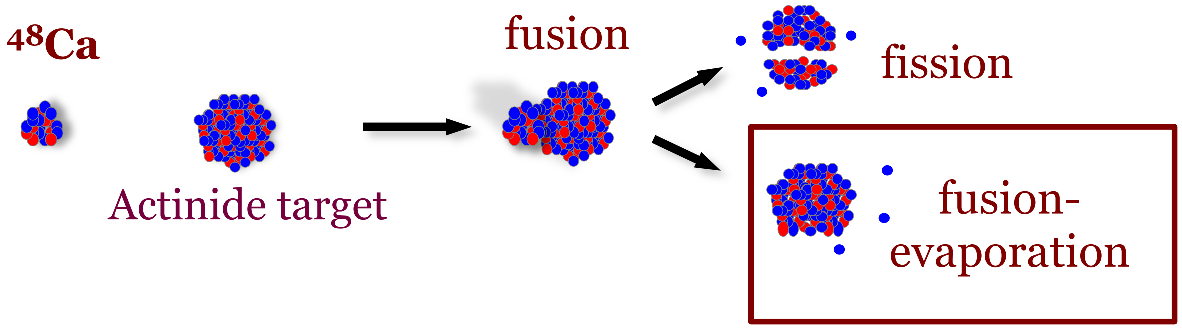
B(E2) ~ 2500 W.u !

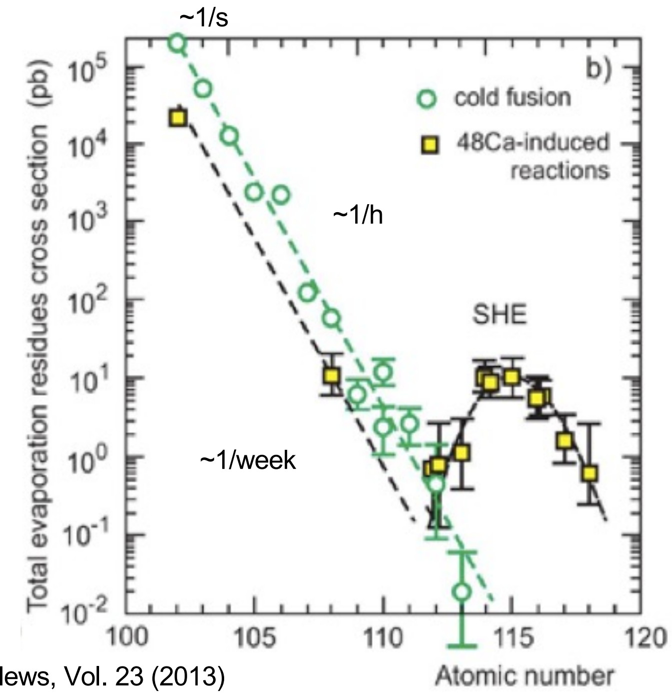
‘Top unexpected physics discoveries of the last five years’
(D. Kleppner, Physics Today, 1991)

Extreme elements



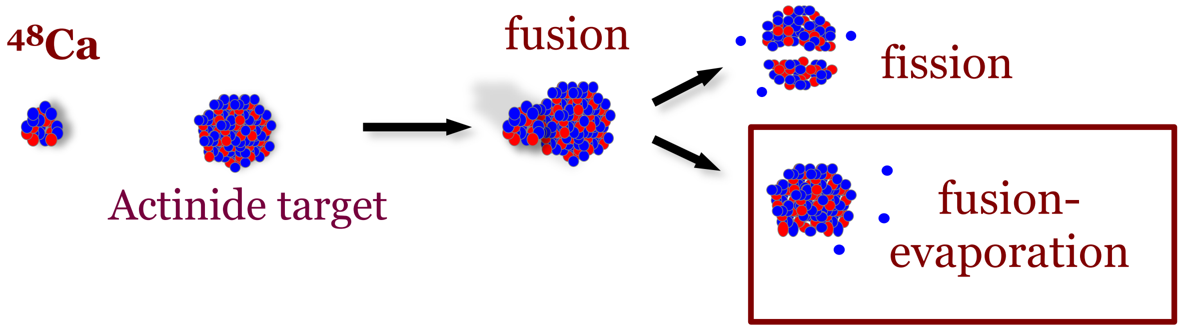
Synthesis of the heaviest elements in Dubna





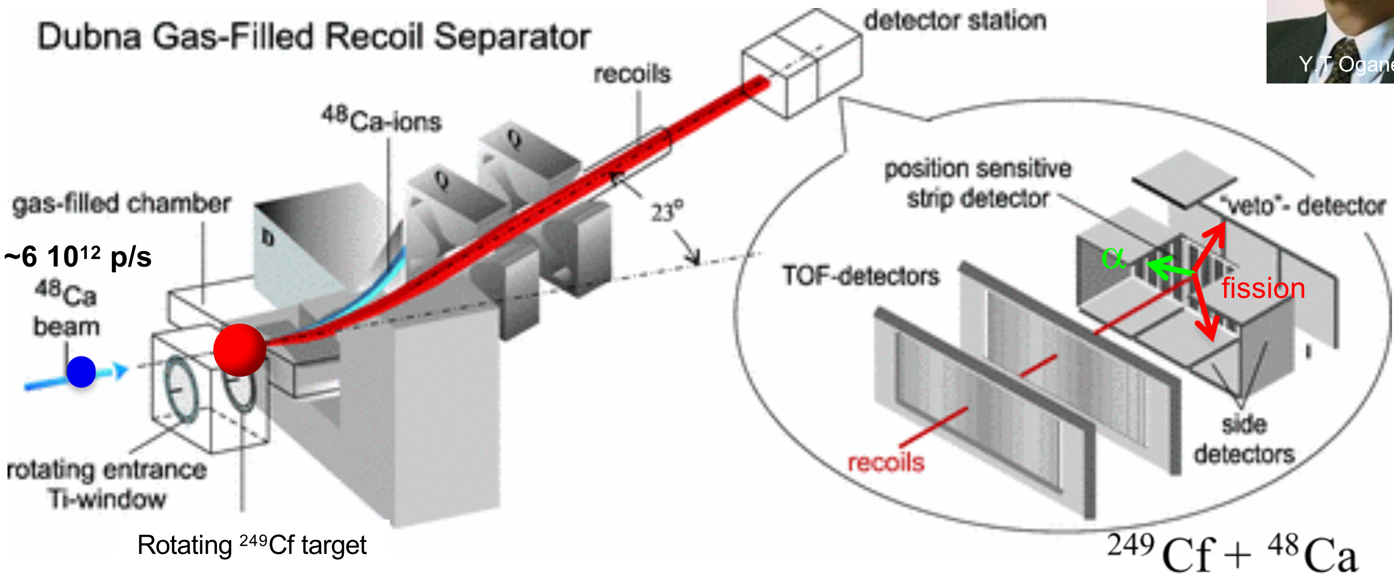
Y. Oganessian, Nuclear Physics News, Vol. 23 (2013)

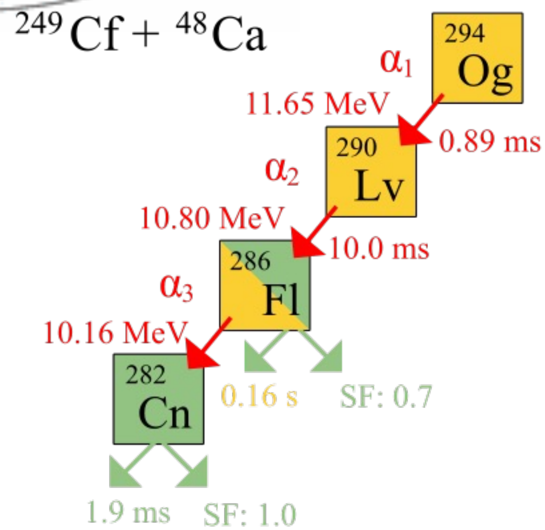
Synthesis of the heaviest elements in Dubna



22 mg of ^{249}Bk
250 days of irradiation in the Oak Ridge reactor
$T_{1/2}$ = 320 days

The needle in the haystack





Verification by cross bombardments:

$^{48}Ca + ^{245}Cm \rightarrow ^{290}Lv + 3n$

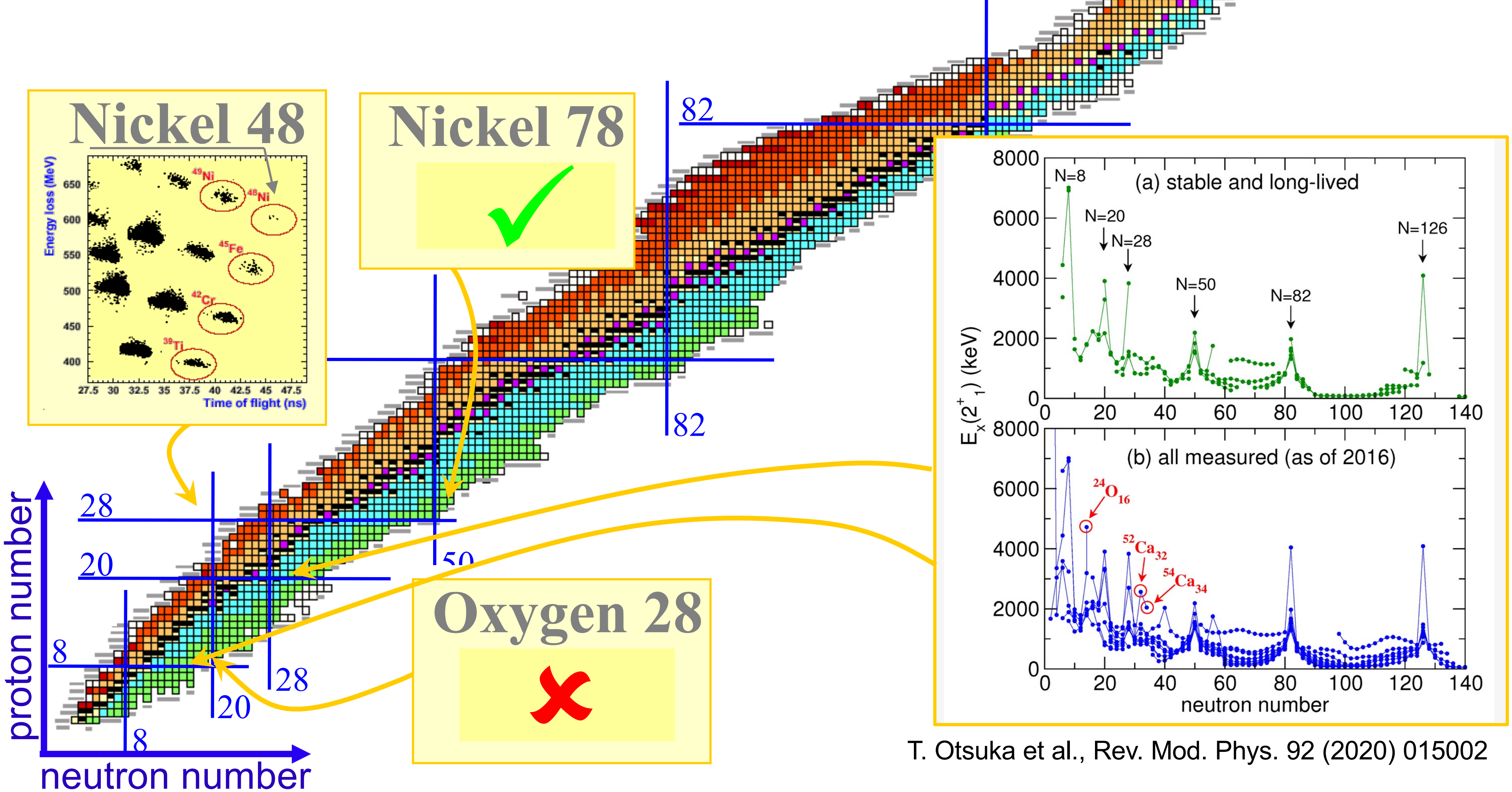
$^{48}Ca + ^{242}Pu \rightarrow ^{286}Fl + 4n$

$^{48}Ca + ^{238}U \rightarrow ^{282}Cn + 4n$

*however: firm identification in Z has not been performed

Are magic numbers universal ?

- Ni chain (Z=28): from A=48 (N=20) to A=78 (N=50) ✓
- ^{28}O (Z=8, N=20): not bound ✗

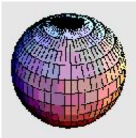


T. Otsuka et al., Rev. Mod. Phys. 92 (2020) 015002

Disappearance of the N=20 gap

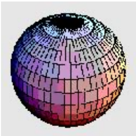
^{40}Ca → Doubly magic
- large 2+ energy
- small B(E2)

→ spherical



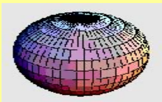
^{36}S - ^{34}Si → Simply magic
- large 2+ energy
- small B(E2)

→ spherical

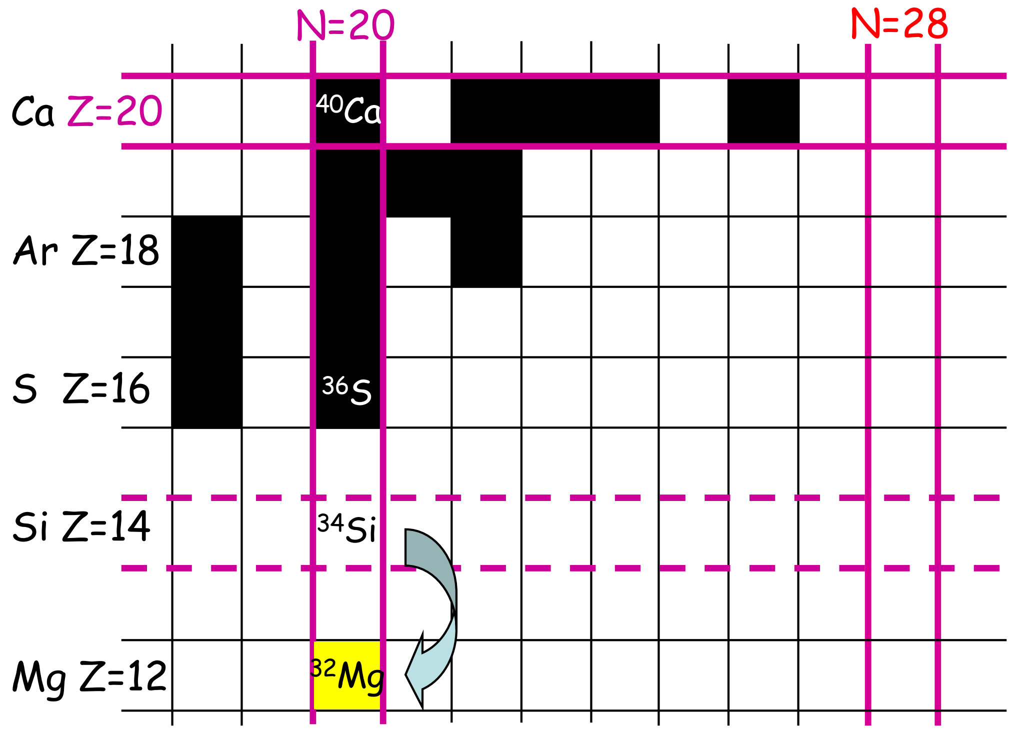


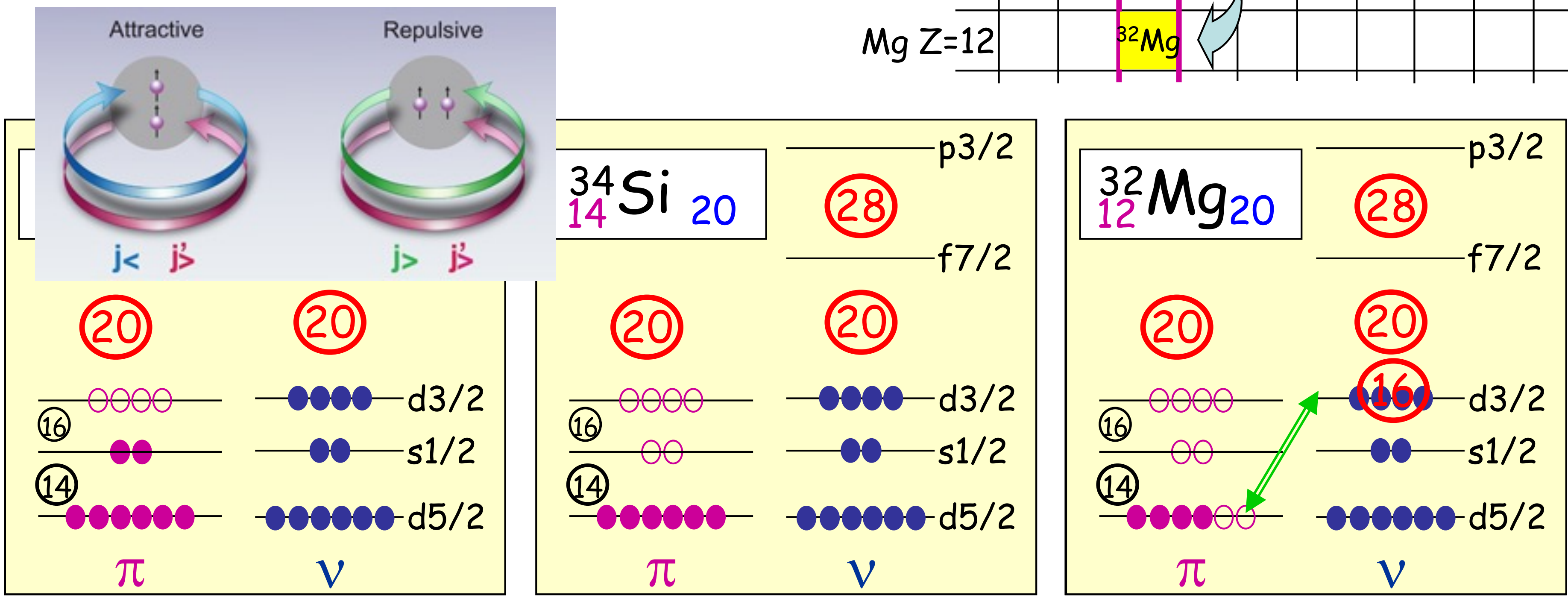
^{32}Mg → Simply magic
- low 2+ energy
- large B(E2)

→ déformed



T. Otsuka *et al.*, Phys. Rev. Lett. 95, 232502 (2005)

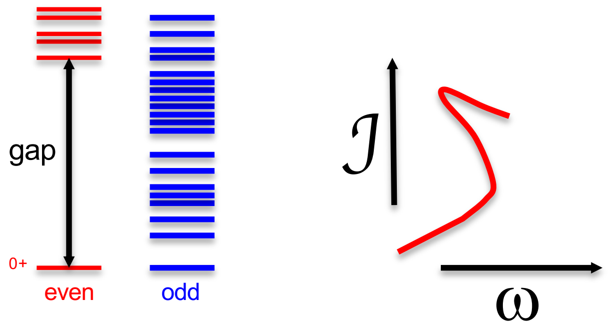




A large variety of phenomena

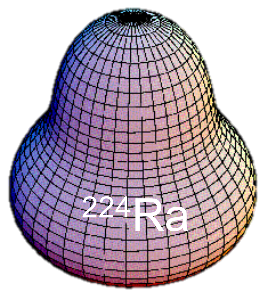
Nuclear superfluidity

A. Bohr et al., Phys. Rev. 110 (1958) 936
A. Johnson et al.,Nucl. Phys. A 179 (1972) 753



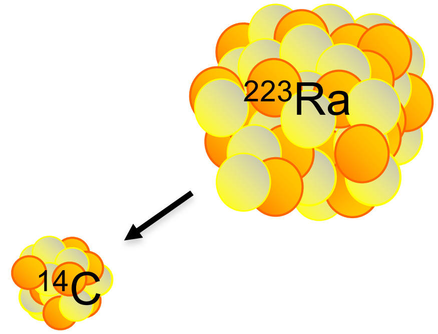
Exotic deformations

P. Butler et al.,
Phys. Rev. Lett. 124 (2020) 042503



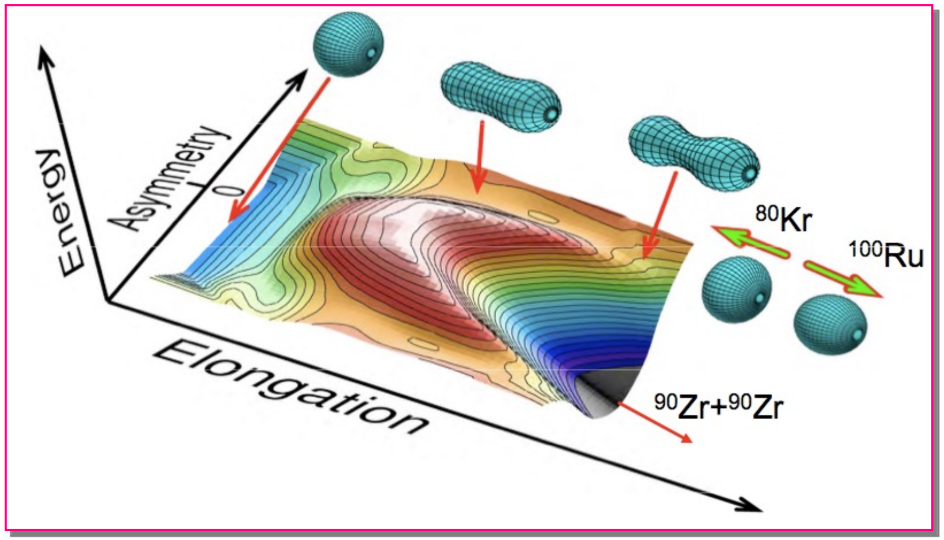
New radioactivities

H.J. Rose et al., Nature 307 (1984) 245

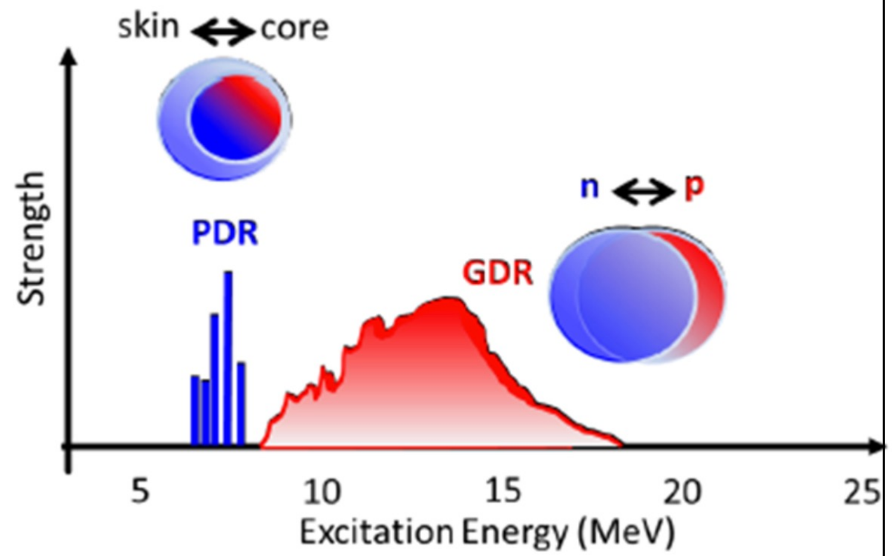


Unexpected fission modes

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



New collective vibration modes



At the dawn of the 21st century, the atomic nucleus continues to surprise us!