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# From the discovery of fission to the synthesis and decay of superheavy nuclei


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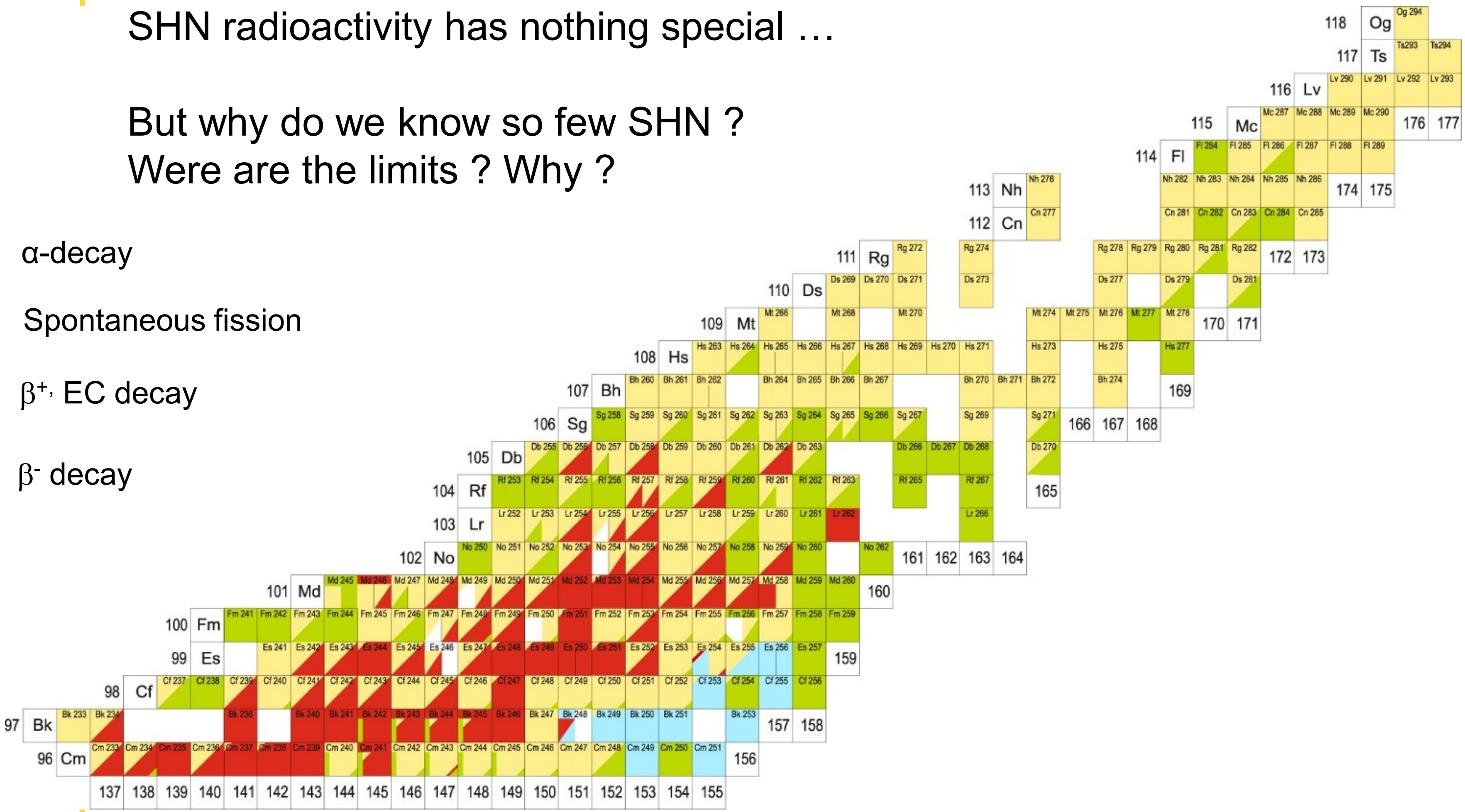
*DRF/IRFU/DPhN*

*Ecole Joliot-Curie 2017*

New view on the radioactivity ?

SHN radioactivity has nothing special …

But why do we know so few SHN ?
Were are the limits ? Why ?




α-decay

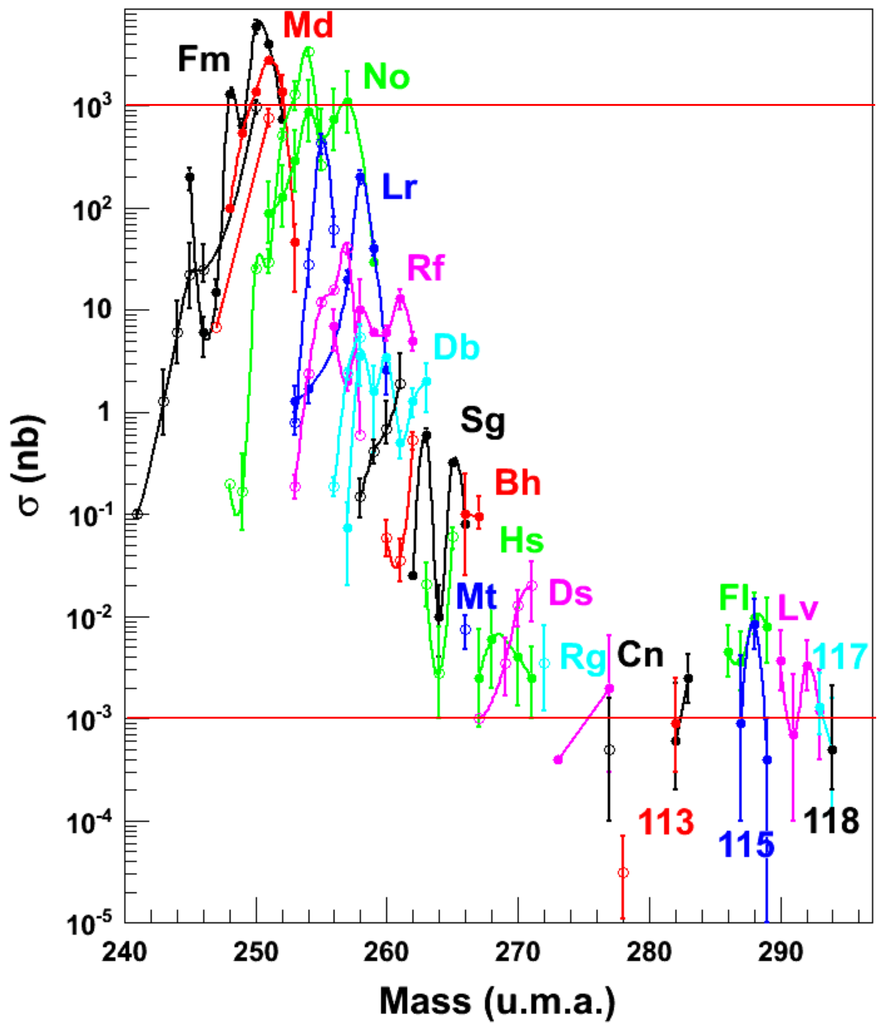
Spontaneous fission

β+, EC decay

β- decay

# Reaching the limits

Fusion-evaporation reactions

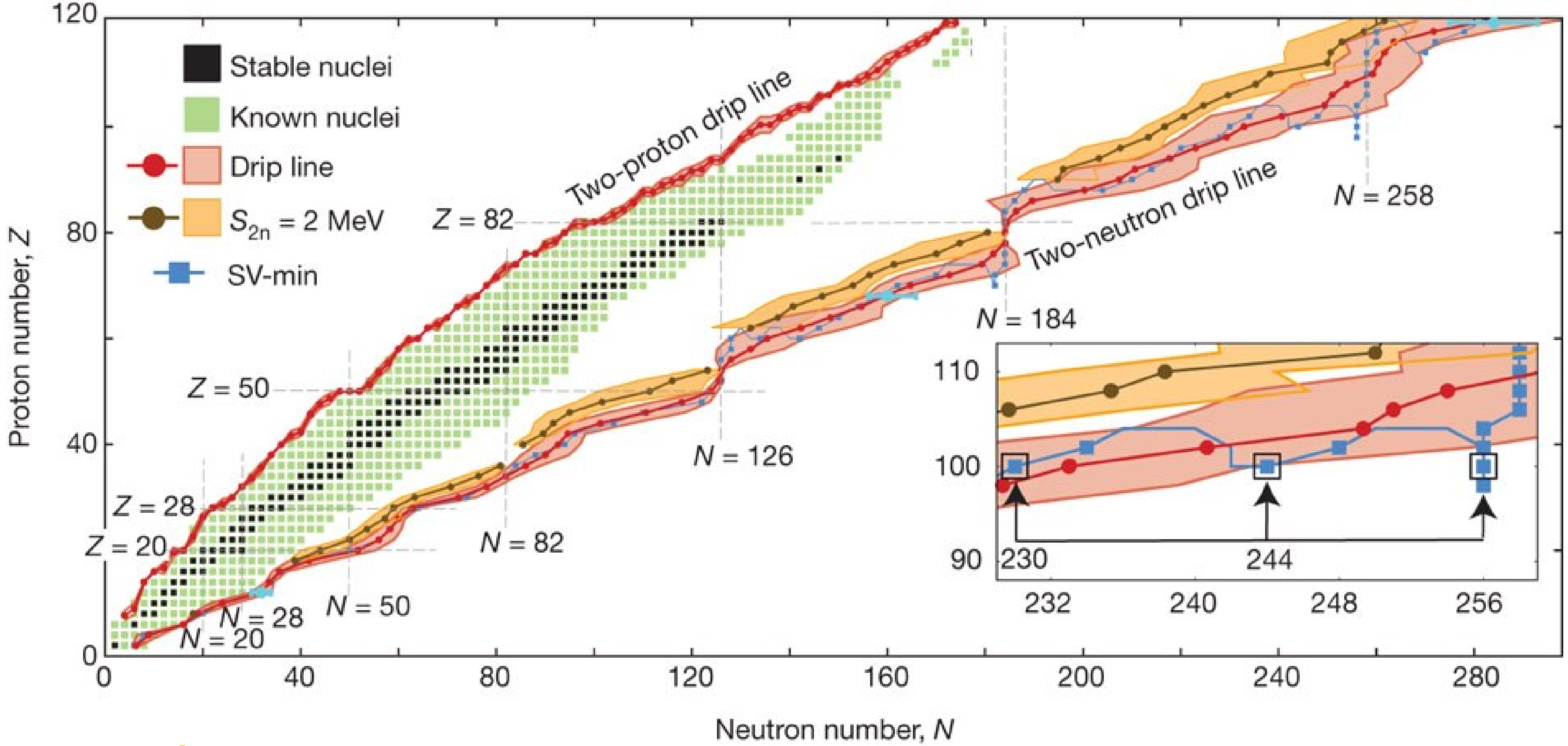



μb : production few/s/μA

pbarn : production ~ 20/month/μA

Challenge: sensitivity for the decay/de-excitation detection/study of nuclei lost in a huge majority of unwanted events → a new view is always needed.

# A lot of room for new isotopes !




J Erler et al. Nature 486 (2012) 509

# The discovery of the heaviest elements

1898
polonium (Z=84)
radium (Z=88)

1898 – First discoveries by Marie Skłodowska-Curie

1896
Discovery of radioactivity by A.H. Becquerel

1899
actinium (Z=89)

1908
radon (Z=86)

1917
protactinium (Z=91)

1934
Enrico Fermi proposes to irradiate Uranium with neutrons in order to synthesise even heavier elements

1938
Otto Hahn and Fritz Straßmann discover the neutron-induced nuclear fission

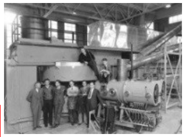
1939
francium (Z=87)

**Radioactivity period** (1896 – 1940)

1940
astatin (Z=85)
neptunium (Z=93)

1941
plutonium (Z=94)

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



1939
60-inch-cyclotron group:
Cooksey, Corson, Ernest O. Lawrence
Thornton, Backus, Salisbury,
Luis Alvarez und Edwin McMillan

1949
berkelium (Z=97)

1950
californium (Z=98)

**Neutron period** (1940 – 1952)

1952
einsteinium (Z=99)
fermium (Z=100)

1955
mendelevium (Z=101)

With Fermi's method and the 60"-cyclotron 7 transuranium (Z=93-98) could be synthesised. By irradiation of actinides with light ions the elements up Z=106 could be produced in Berkeley (CA, U.S.A.) and in Dubna (Russia).

1965
nobelium (Z=102)
lawrencium (Z=103)

1969
rutherfordium (Z=104)

1970
dubnium (Z=105)

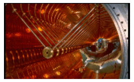
1974
seaborgium (Z=106)

**Synthesis of SHE via fusion of heavy target nuclei with light projectiles** (1952 – 1974)

1981
bohrium (Z=107)

1982
meitnerium (Z=109)

1984
hassium (Z=108)



The linear accelerator UNILAC and the velocity filter SHIP at GSI allowed for the synthesis of elements with Z=107-112.

1994
darmstadtium (Z=110)
roentgenium (Z=111)

1996
copernicium (Z=112)

**Synthesis of SHE via fusion "cold fusion" (Pb and Bi as target nuclei)** (1974 – 1999)

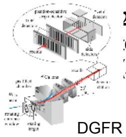
1999
flerovium (Z=114)

2000
livermorium (Z=116)

2002
oganesson (Z=118)

2004
moscovium (Z=115)

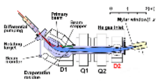
2004
nihonium (Z=113) - cold fusion


DGFRS

2009
tennessine (Z=117)

At the Dubna gas-filled separator the elements with Z=114-118 were synthesized. This series of hot fusion reactions was only interrupted by the synthesis of element 113 in a cold fusion experiment at GARIS/RIKEN.

RIKEN GARIS



**Synthesis of SHE via fusion "hot fusion" ($^{48}Ca$ projectiles on actinide targets)** (1999 – 2016)

# Outline :

- Historical notes : Studies using U decay, reactions with alpha and neutrons
- Fermi neutrons irradiations and evidences for transuranium elements
- The discovery of fission, the liquid drop model
- First transuranium elements
- What is a superheavy nucleus: macroscopic and microscopic views…
- From the chemistry to identification using nuclear properties
- Genetic correlations, separators
- Spectroscopy after alpha decay, interplay with atomic properties
- X-ray identification
- High-K isomers
- Ground states properties : mass measurement and laser spectroscopy
- New facilities
- Naming of the elements

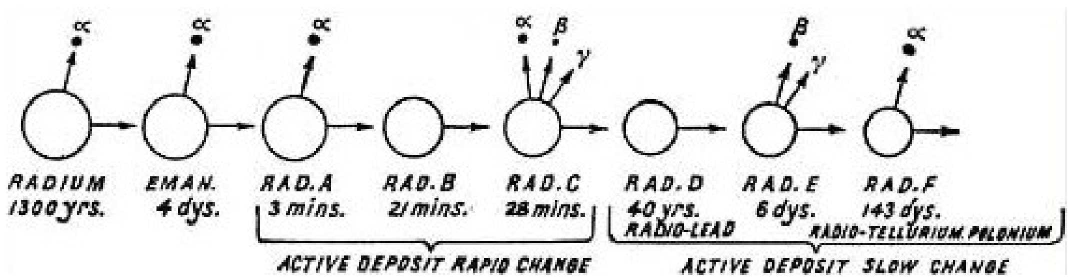
# Subjects not covered in this lecture

- Prompt spectroscopy (including particle spectroscopy after transfer, coulex, …)
- Reaction mechanism
- Fission barrier measurement
- Shape isomers
- Search for SHE/SHN in nature
- Chemistry
- “Exotic” predictions and phenomena (cluster radioactivity, superdeformed gs, exotic shapes …)
- “Exotic” techniques (crystal blocking, lifetime using X-ray fluorescence, …)
- Not so much theory
- …

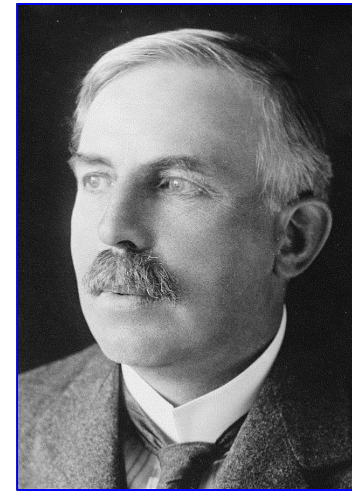
# Historical notes

1899 Rutherford isolates α and β radioactivities from uranium

1902 Rutherford and Soddy.
Emission of α → transmutation



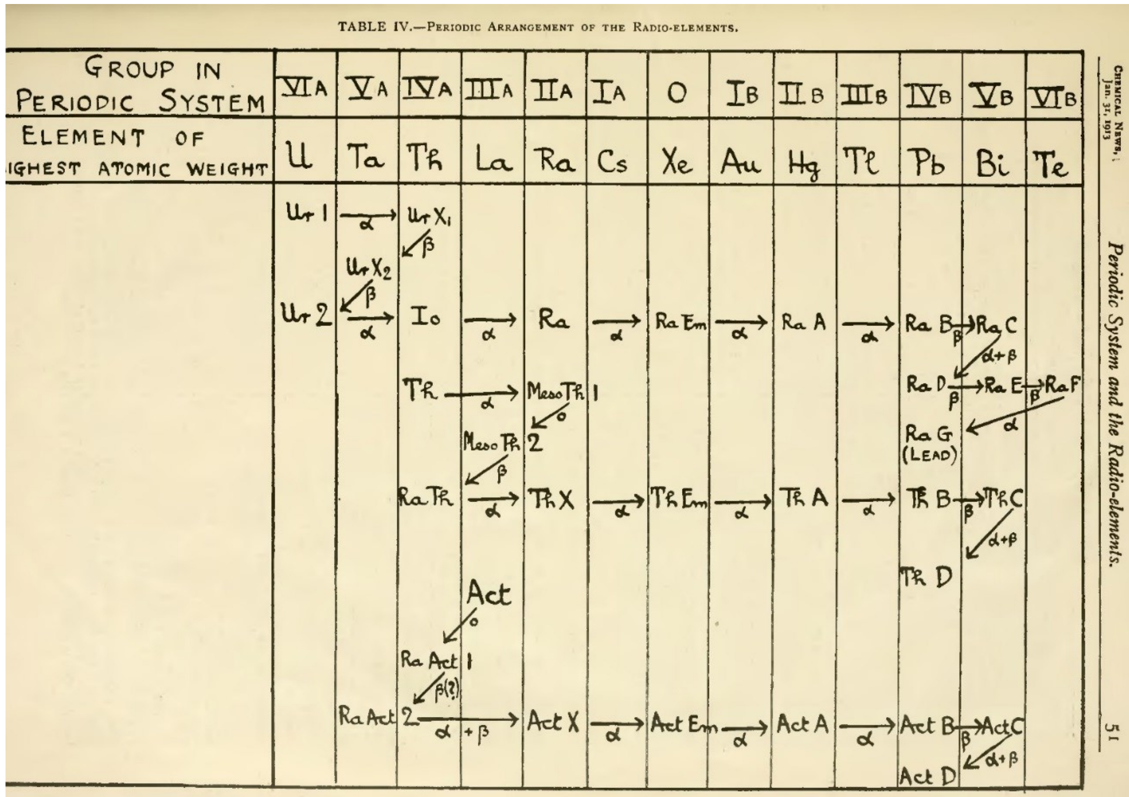

1908 Rutherford and Geiger : α = Helium (from thorium emanations)



Ernest Rutherford

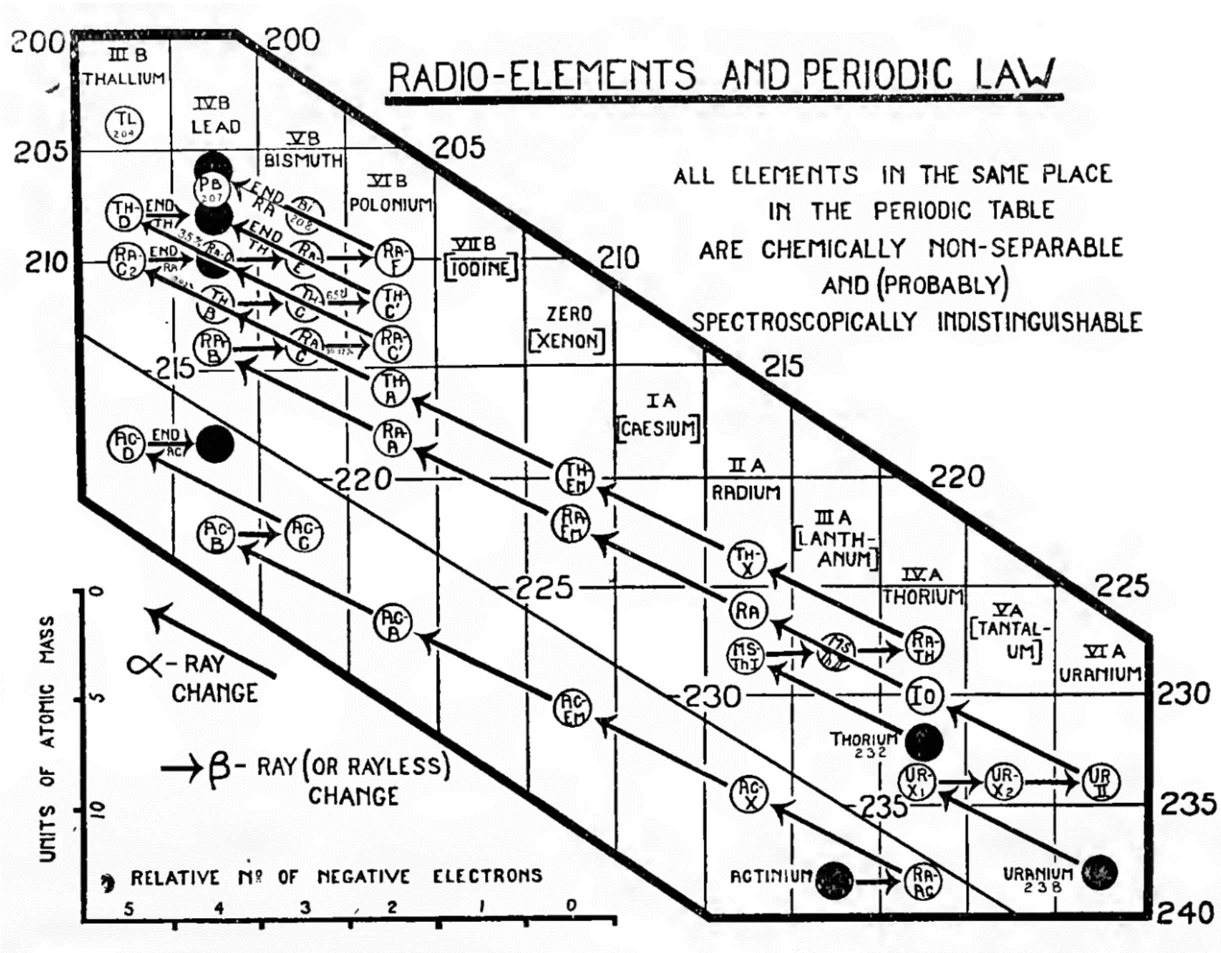
Frederick Soddy

# 1911 Soddy, Russel : Relation between isotopes after alpha and beta decay




Placement of elements in columns. Chemical similarities with known elements. Rules to change column after alpha and beta decay.

A.S. Russell, The Chemical news CVII (1913) 49.




F. Soddy. Rep. Brit. Ass. Adv. Sci, 83 (1913) 445

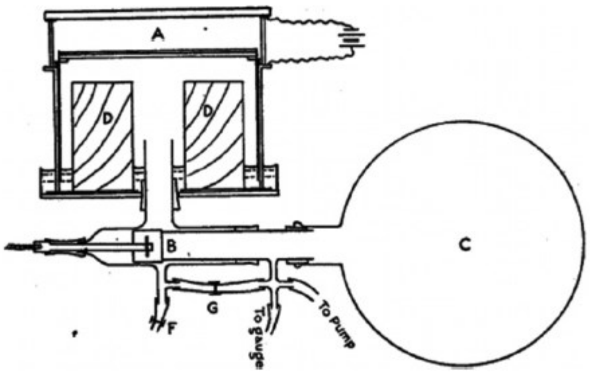
1919 Rutherford Transmutation using α « beam ». α + Nitrogen.

First nuclear reaction ! Interpreted as α + Nitrogen → p + something

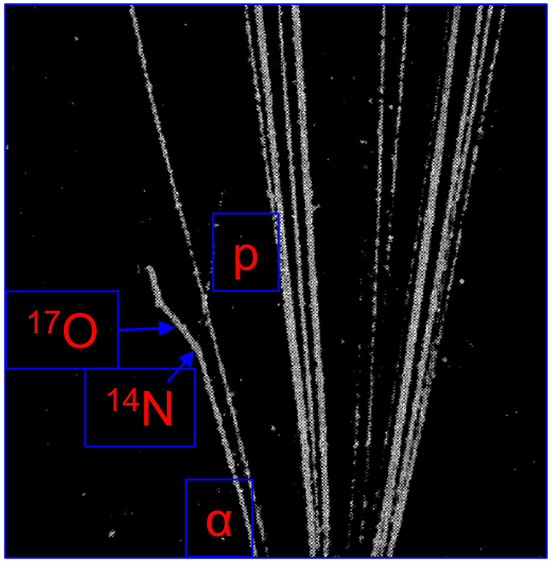
Phil. Mag. 37 (1919) 537, 562, 571, 581

1924 Blackett. Visualization of the reaction using a cloud chamber

P.M.S. Blackett, Proc. Roy. Soc. A **107**, 349 (1925)




C.T.R. Wilson, Proc. Roy. Soc. A **87**, 277 (1912)



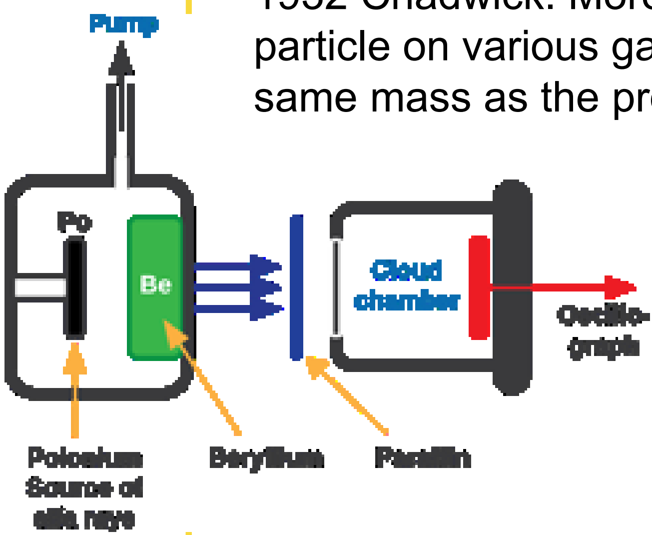

→ Use of α « beam » to induce nuclear reactions.

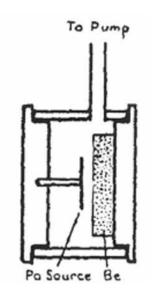
# The neutron discovery

1930. Walther Bothe. Unknown radiations from α + $^{9}$Be interpreted as
$\alpha + {}^{9}Be \rightarrow {}^{13}C^{*} \rightarrow {}^{13}C + \gamma$

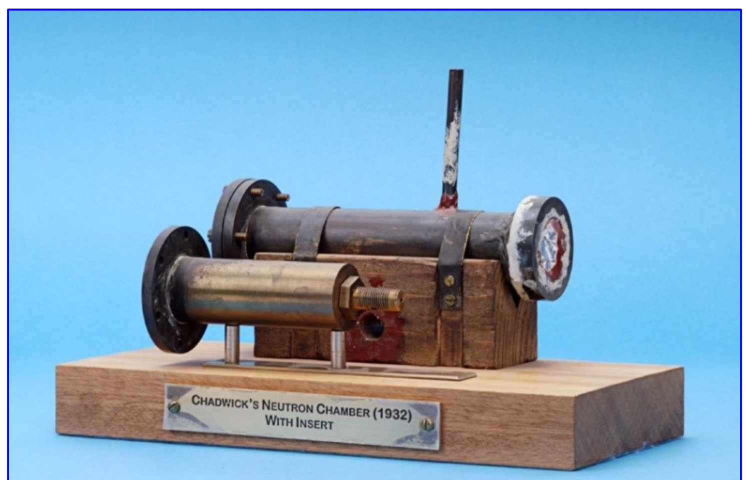
1931 F. Joliot and I. Curie. Interpretation as high-energy protons by Compton effect but inconsistent according to Majorana and Rutherford

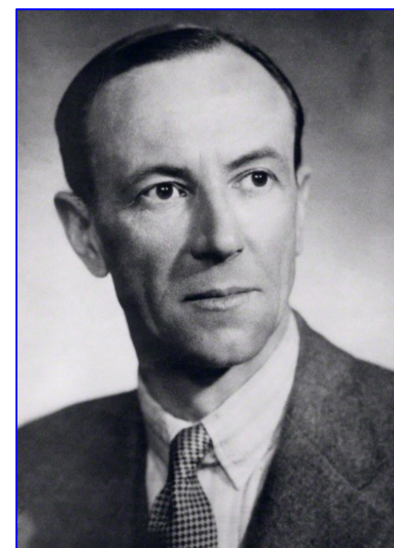
1932 Chadwick. More sensitive device. Range of protons and impact of the unknown particle on various gases. → Existence of a neutral particle « neutron » having the same mass as the proton




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



James Chadwick

# Artificial radioactivity

Irène and Fréderic Joliot-Curie, 1934

$\alpha\ (^{210}Po\ \text{source}) + {}^{27}Al \rightarrow {}^{30}P + n \xrightarrow{\beta^+} {}^{30}Si$ Stable

New isotope, radioactive

Then with $^{10}B$, $^{24}Mg$, …

→ reactions with α

→ application of radioisotopes

→ Speculate production of new radioelements using p, d, n

C.R. Acad. Sci. 198 (1934) 254

… Drawback of using of α « beam » to induce nuclear reactions: limited to Z~15 due to coulomb repulsion… Not possible to go beyond. Also rather low yield.

# Fermi : neutron induced reactions

- Work initiated by Orso Mario Corbino
- Neutron produced using Rn alpha source (800 mC) + Be. Rather low neutron production (1000 n/s/mC) but compensated by high cross-section of neutron-induced reaction
- Systematic investigation in Roma of neutron-induced reaction along the periodic table for H to U.

Methodology

- Irradiation ${}^{A}_{Z}X + n \rightarrow {}^{A+1}_{Z}X \xrightarrow{\beta\ decay} {}^{A+1}_{Z+1}Y$
- (chemical separation)
- Detection of radioactivity (β-)

Using a Geiger-Müller counter

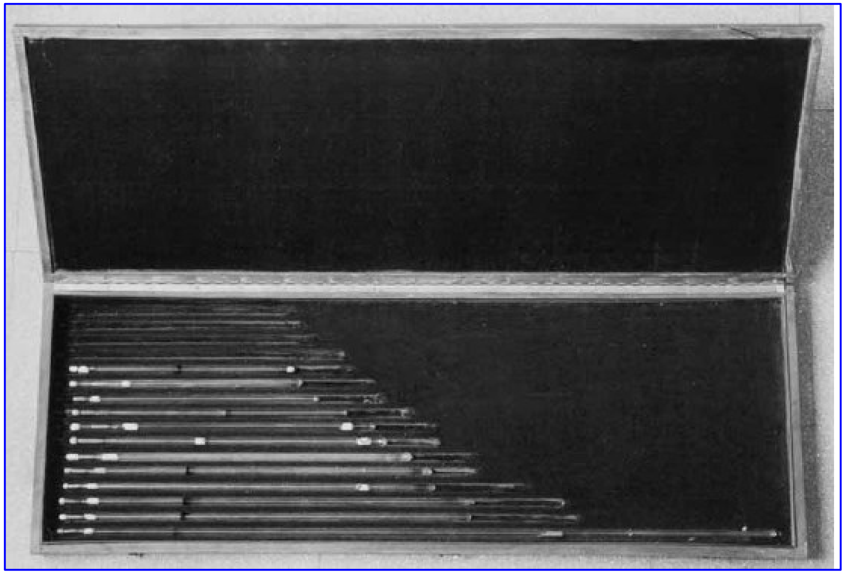
- → lifetime and eventually β-

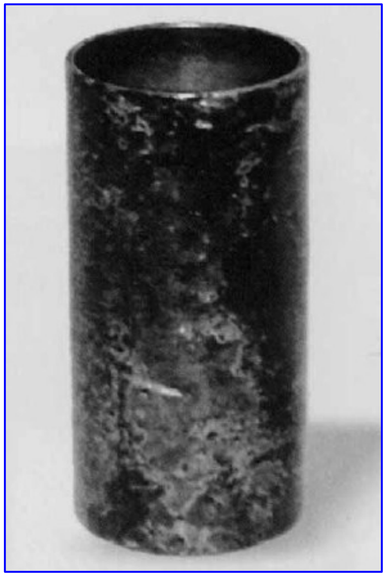
energy using absorbers

Neutron source inside

About 30 new isotopes discovered !

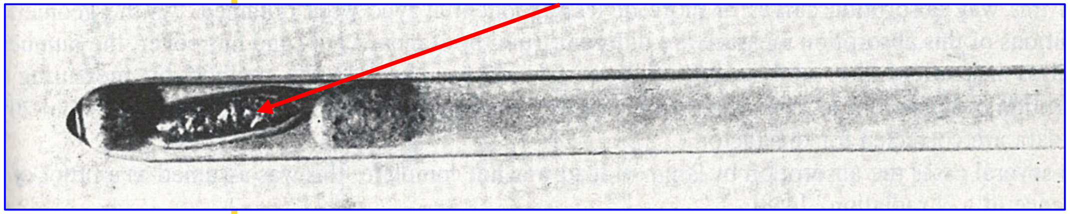
# Fermi's tools

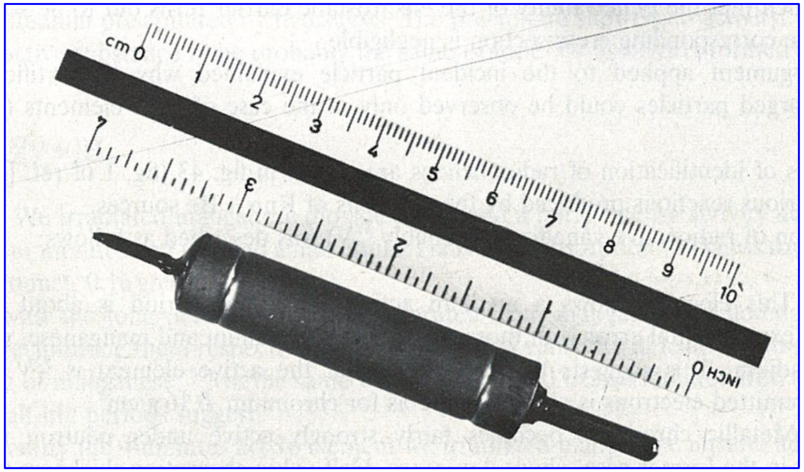




Glass tubes with Rn+Be

Cylinder irradiated





Geiger-Müller counter

# I Ragazzi di via Panisperna

Oscar D'Agostino, Emilio Segrè, Edoardo Amaldi, Franco Rasetti, Enrico Fermi
(picture taken by Bruno Pontecorvo ?)

# Ausonium and Hesperium

Possible Production of Elements of Atomic Number Higher than 92

By Prof. E. Fermi, Royal University of Rome

Nature 133 (1934) 898

In this way it appears that we have excluded the possibility that the 13 min.-activity is due to isotopes of uranium (92), palladium (91), thorium (90), actinium (89), radium (88), bismuth (83), lead (82). Its behaviour excludes also ekacæsium (87) and emanation (86).

This negative evidence about the identity of the 13 min.-activity from a large number of heavy elements suggests the possibility that the atomic number of the element may be greater than 92. If it were an element 93, it would be chemically homologous with manganese and rhenium. This hypothesis is supported to some extent also by the observed fact that the 13 min.-activity is carried down by a precipitate of rhenium sulphide insoluble in hydrochloric acid. However, as several elements are easily precipitated in this form, this evidence cannot be considered as very strong.

(Tc was not yet discovered)

$$^{238}U + n \rightarrow {}^{239}U \xrightarrow{\beta^-} {}^{239}93 \xrightarrow{\beta^-} {}^{239}94$$

Elements named Ausonium and Hesperium by Franco Rasetti

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Several decay products found with 10s, 40s, 13 and 90 min lifetime.

Attempts to prove due to Z=93 using chemical separation.

| I A | II A | III B | IV B | V B | VI B | VII B | VIII | | | I B | II B | III A | IV A | V A | VI A | VII A | O |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 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 | 57-71 Ln | 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) | (94) | (95) | (96) | (97) | (98) | (99) | | | | | |
| | | 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 | |

Periodic table in the 1920s-1930s following Moseley's work (identification of new elements using X-ray spectroscopy)

# Bohemium Z=93

Claim for discovery of element 93 by Odolen Koblic, a Czech engineer.

Found in pitchblende ores. Chemical solution acidified with nitric acid then thallium nitrate added

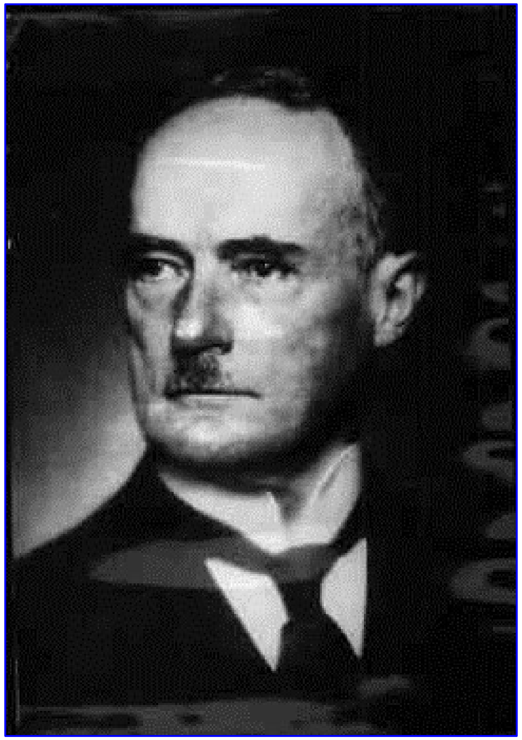
«Just as expected a vermillion coloured crystalline sediment appeared ».

Chemical analysis using hydrogen sulphide.

Bohemium (Bo) in honour to fatherland.

Chemiker-Zeitung 28 (1934) 581

Retracted the same year (Koblic, O. Chem. Obzor. 9 (1934) 146)



Odolen Koblic

# 1938 : Fermi Nobel lecture

December 10, 1938

- "We concluded that the carriers were one or more elements of atomic number larger than 92 ; we, in Rome, use to call the elements 93 and 94 Ausenium and Hesperium respectively."

- After the Nobel lecture, Fermi leaves to the US.

- The Roma group was already dispersed → no continuation of the transuranium neutron-induced studies from 1935
  - Rasetti 1935 → US → Canada
  - Pontecorvo 1936 → France then Canada then UK then URSS
  - Segre 1938 → US
  - Amaldi 1939 → US

Footenote in Fermi's lecture :
"The discovery by Hahn and Strassmann of barium among the disintegration products of bombarded uranium, as a consequence of a process in which uranium splits into two approximately equal parts, makes it necessary to reexamine all the problems of the transuranic elements, as many of them might be found to be products of a splitting of uranium."

# Element 93 confirmed at Berlin… and much more !

1935 : neutron induced reaction repeated by chemists Hahn, Meitner and Strassmann at Kaiser Wilhelm-Institut far Chemie, Berlin (and in other places)

Compared to Fermi group, improved chemical separation, more lifetime component identified and better lifetime measurement.

$$1.\quad U + n \longrightarrow {}^{10''}_{92}\mathrm{U} \xrightarrow{\beta} {}^{2,2'}_{93}\mathrm{Eka\ Re} \xrightarrow{\beta} {}^{59'}_{94}\mathrm{Eka\ Os} \xrightarrow{\beta} {}^{66\,h}_{95}\mathrm{Eka\ Ir} \xrightarrow{\beta} {}^{2,5\,h}_{96}\mathrm{Eka\ Pt} \xrightarrow{\beta} {}_{97}\mathrm{Eka\ Au}\,?$$

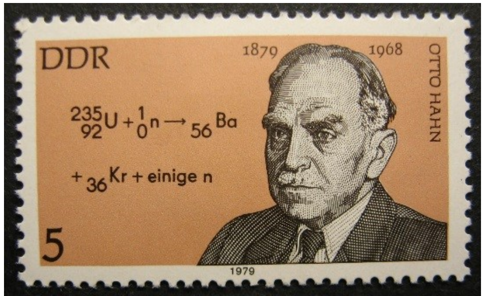
$$2.\quad U + n \longrightarrow {}^{40''}_{92}\mathrm{U} \xrightarrow{\beta} {}^{16'}_{93}\mathrm{Eka\ Re} \xrightarrow{\beta} {}^{5,7\,h}_{94}\mathrm{Eka\ Os} \xrightarrow{\beta} {}_{95}\mathrm{Eka\ Ir}\,?$$

$$3.\quad U + n \longrightarrow {}^{23'}_{92}\mathrm{U} \xrightarrow{\beta} {}_{93}\mathrm{Eka\ Re}\,?$$

Meitner, Hahn, Strassmann. ZP 106 (1937) 249

Otto Hahn, Lise Meitner

P. Abelson using the Berkeley Cyclotron as a neutron source (large flux) → no conclusive results, no alpha decay found.



1938 Irène Curie and Pavel Savitch. New approach: first counting without separation → a new β- 3.5 h activity, but chemistry uncertain (looks like La)

C.R; Acad. Sci. 206 (1938) 906, 1643

Fritz Strassmann

Hahn and Strassmann, activity follows a Ba carrier

→ isotope of Ra (in the same column) ?

Meitner leaves Germany, still close contact With Hahn. Some doubts on the Ra result (need two α emissions).

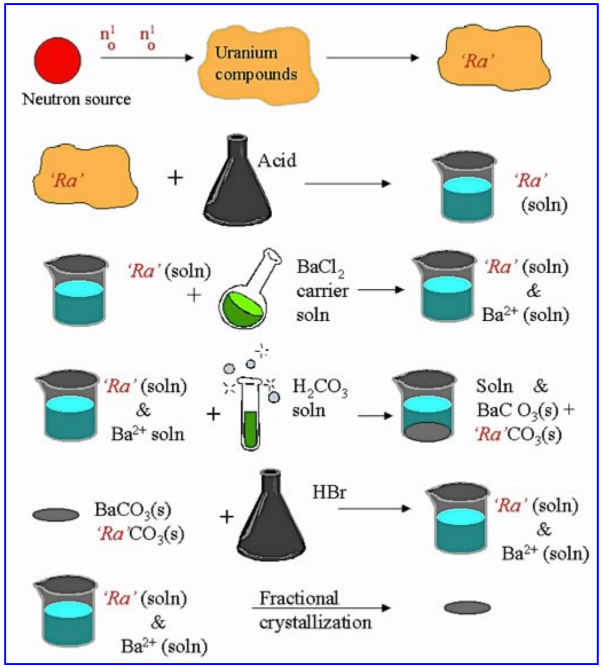
Hahn and Strassmann. Fractional crystallization (M. Curie method)

→ No Ra

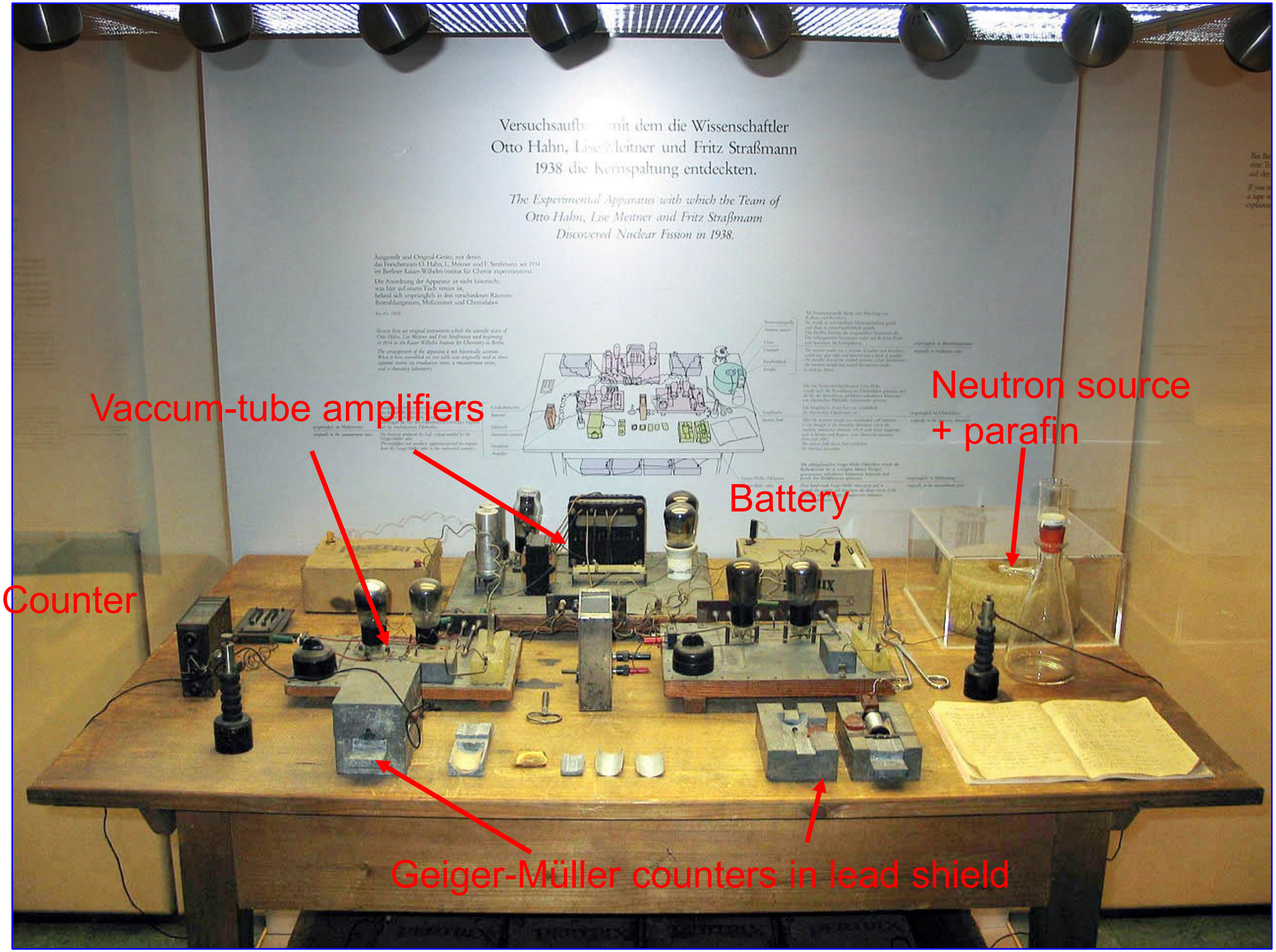
→ product is Ba

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

A result that "contradicts all the experiences of nuclear physics to date"



# Hahn-Meitner-Strassmann device at Deutsches Museum, Munich

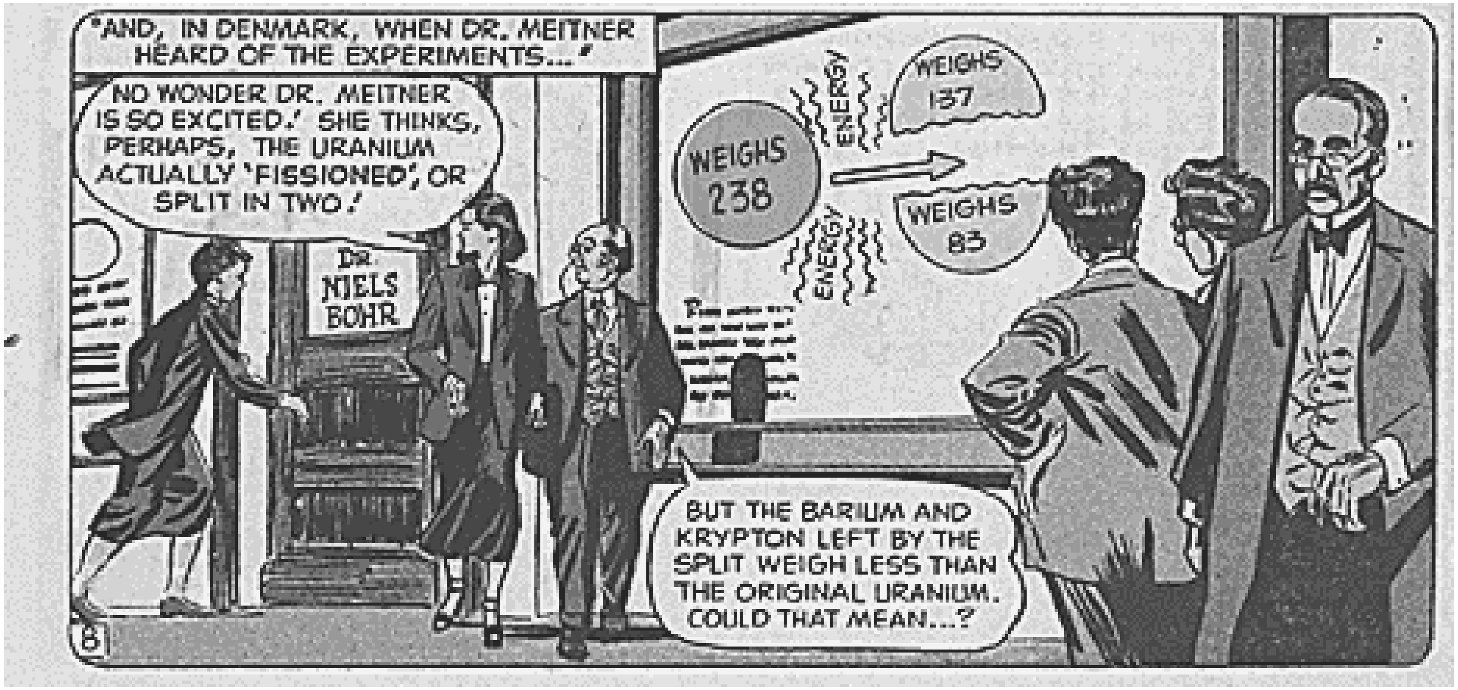


# Fission …

Christmas 1938 : Lise Meitner meets his nephew Otto Frisch in Sweeden. During a hike outdoor, they discuss recent results by Hahn and Strassmann, and conceive the fission process.

Estimate energy released by fission ~ 200 MeV using the liquid drop model.

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



# Fission, interpretation

Jan 1939 :

- Frisch discusses with Bohr in Copenhagen *"Oh, what idiots we all have been ! Oh but this is wonderful ! That is just as is must be !"**

Frisch reminiscences « What little I remember », 1979

- Frisch first detects the fission fragments from uranium using an ionization chamber → Nature 143 (1939) 276
- Fission also detected by Herbert Anderson et al, US. PR 55 (1939) 511
- Evidences that huge energy production is possible
- Frédéric Joliot detects fission fragment C.R. Acad. Sci 208 (1939) 341 (1939); J. phys. et radium 10 (1939) 159

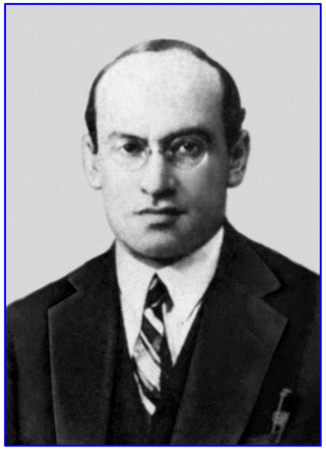
…

Spring 1939 : Theory of fission by Bohr and Wheeler

(PR 56 (1939) 426), Frenkel (PR 55 (1939) 987)

using the liquid drop model

Dec. 1939 : about 100 papers on fission published !



Yakov Frenkel

# Slow neutrons

- 1934, Pontecorvo, Amaldi. Ag irradiation by neutron : more efficient on a wood table compared to rock or metal
- Paraffin more efficient
- Water in garden fountain

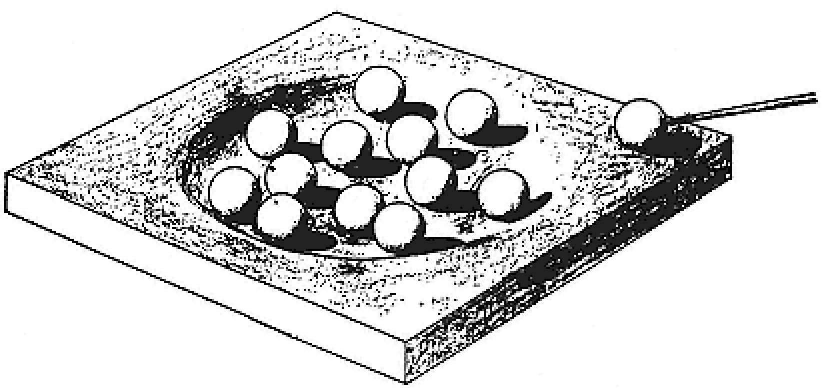
even more efficient !

→ neutrons slow-down by H

→ neutrons spent more time

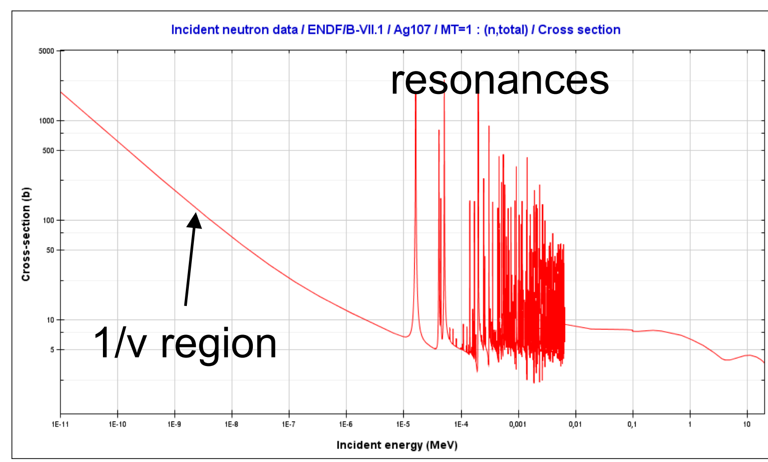
in the nucleus → higher cross-section

E. Fermi et al *La Ricerca Scientifica* 5 (1934), 282



Bohr's picture of neutron capture

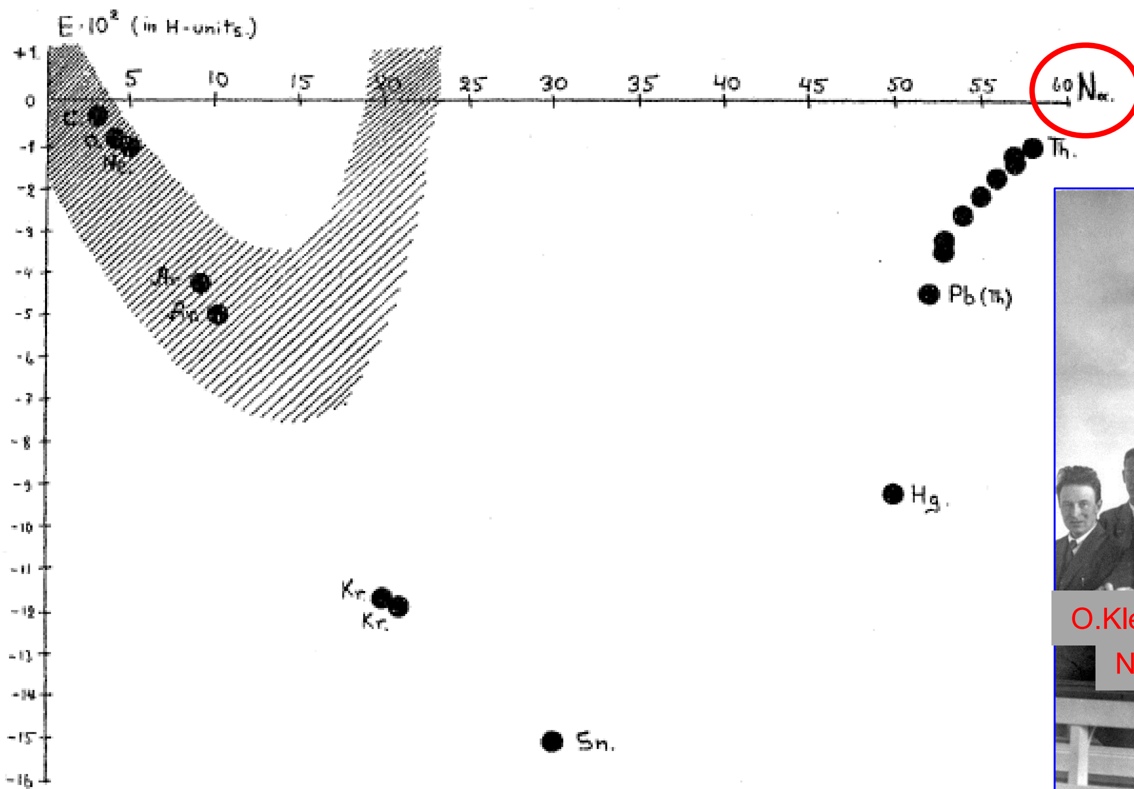
Science, 86 (1937) 161



# The liquid drop model



Early versions by G. Gamow (1929), W. Heisenberg (1933) to account for the mass-defect of the nuclei (Aston curve)



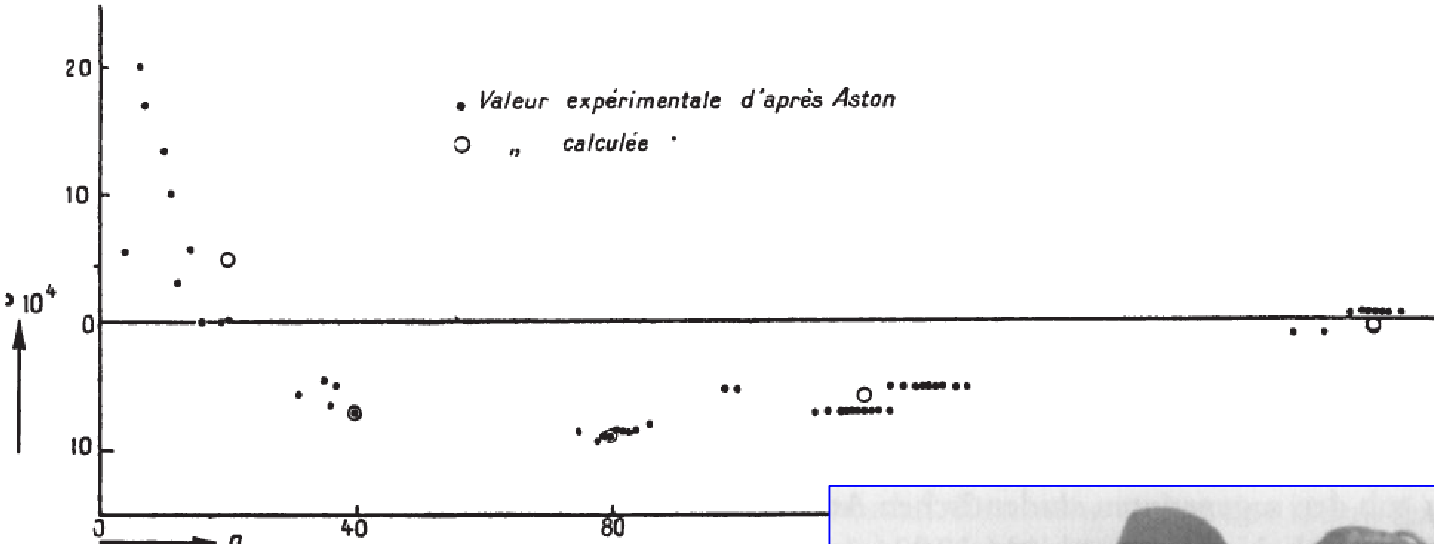


G. Gamow. Proc. Roy. Soc. A 126 (1930) 632

Water drop of α particles with surface tension

# The liquid drop model

Heisenberg using Majorana's exchange term




W. Heisenberg, *Considérations théoriques sur la structure du noyau* (in French !), congrès Solvay 1933

Continuation by Carl Friedrich von Weizsäcker (Heisenberg's student).

W. Heizenberg, C.F. von Weizäcker 1935

# The liquid drop model

## The Bethe - Weizsäcker mass formula

$BE(A,Z) = a_v A$ Volume → attractive
→ short interaction range
→ binding energy ~ constant = saturation

$- a_c Z^2/A^{1/3}$ Coulomb → repulsive

$-a_s A^{2/3}$ Surface : less neighbours → repulsive
(re)introduced by von Weizsäcker (1935)
Z. Phys. 96 (1935) 431

$-a_a (N-Z)^2/A$ Asymmetry

$+ \delta(A,Z)$ Pairing introduced by Bethe and Bacher (1936)
Rev. Mod. Phys. 8 (1936) 82 "the bible"

Warning : liquid drop is not a phenomenological model, it is based on first principles although in practice parameters are fitted on known masses

1939 Bohr and Wheeler, Frankel
Stability = balance between coulomb and surface terms

# Deformed liquid drop and fission barrier

Energy of a deformed liquid drop :

$$E_C(a) = E_C(0)\left(1 - \frac{1}{5}a^2 - \frac{4}{105}a^3 + \ldots\right),$$

$$E_S(a) = E_S(0)\left(1 + \frac{1}{5}a^2 - \frac{4}{105}a^3 + \ldots\right).$$

$$a = \sqrt{\frac{5}{4\pi}}\beta_2.$$

Change of energy as a function of deformation :

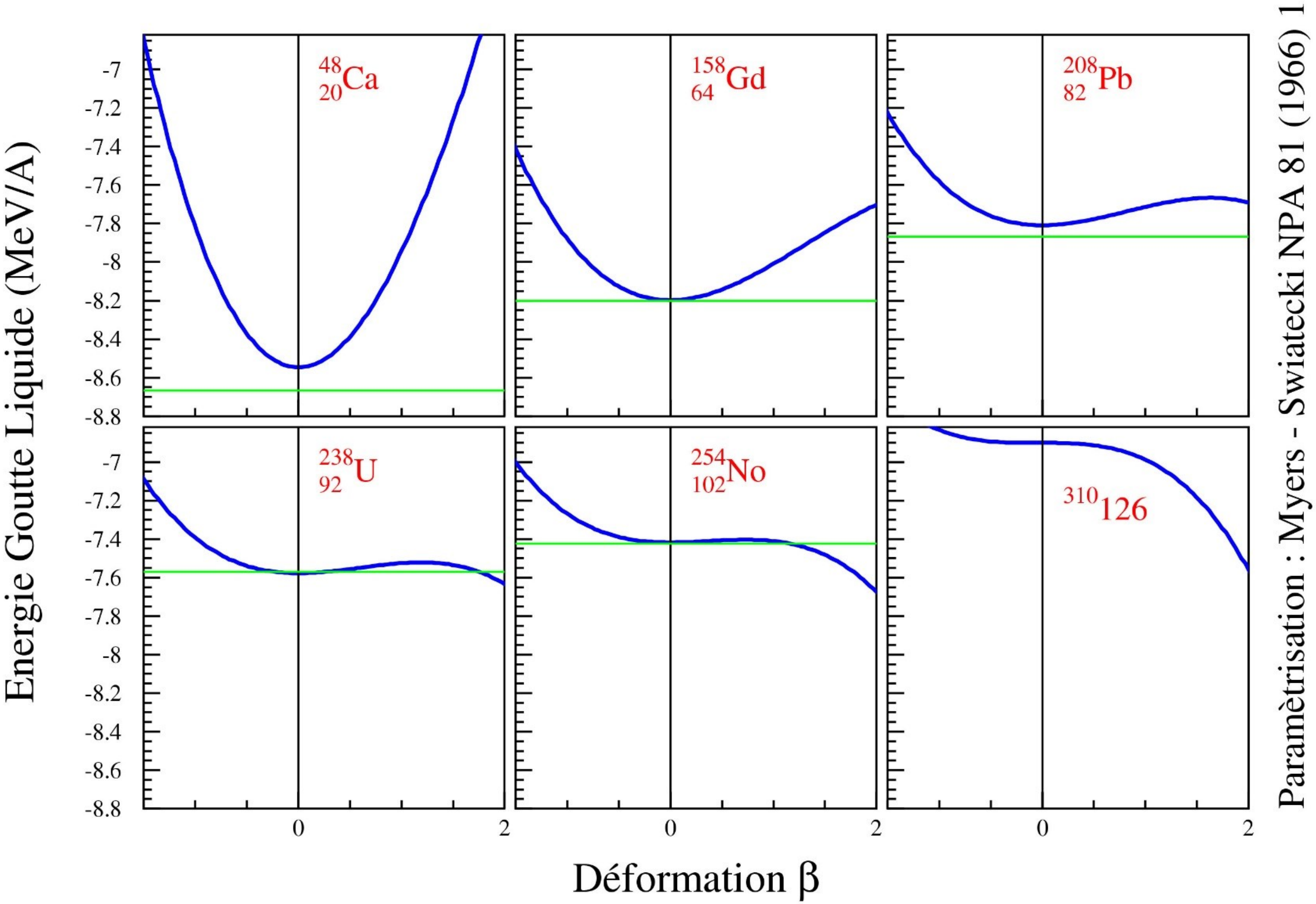
$$\Delta E = E_S(a) + E_C(a) - E_S(0) - E_C(0)$$
$$= E_S(0)\left[\frac{2}{5}\boxed{(1 - x)}a^2 - \frac{4}{105}(1 + 2x)a^3 + \ldots\right].$$

$$x = \frac{1}{2}\frac{a_C\, Z^2/A^{1/3}}{a_S\, A^{2/3}} = \frac{a_C}{2\, a_S}\frac{Z^2}{A}.$$

Liquid drop instable if x>1 → $Z^2/A \gtrsim 48$
x = fissility parameter

$^{238}U$ + n → $^{239}U$ + excitation energy → fission although x = 0,77

# Deformed liquid drop and fission barrier



# Liquid-drop fission barrier and lifetime

$$B_f = \frac{98}{15}\frac{(1-x)^3}{(1+2x)^2}Es(0).$$

Penetration through the barrier : Wentzel–Kramers–Brillouin–Jeffreys semi-classical approximation →

$$T_{1/2}(s) = \ln 2\ 10^{-21} \exp(2\pi B_f / \hbar\omega_f)$$

$\hbar\omega_f$ : barrier curvature ~ 0,5 meV

| Nucleus | x | $B_f$ LDM | $T_{1/2}$ (s) LDM |
|---|---|---|---|
| $^{238}$U | 0.77 | 7.76 | 1.6 $10^{21}$ |
| $^{240}$Pu | 0.79 | 5.8 | 3.6 $10^{10}$ |
| $^{255}$Fm | 0.84 | 2.45 | 1.5 $10^{-8}$ |
| $^{254}$No | 0.86 | 1.45 | 6 $10^{-14}$ |
| $^{256}$Rf | 0.89 | 0.85 | 3 $10^{-17}$ |
| $^{290}$Fl | 0.96 | 0.04 | 1.1 $10^{-21}$ |

Warning : nuclei assumed spherical in their ground-state.
Deformation systematics came later (eg Townes 1949)

# Spontaneous fission ?

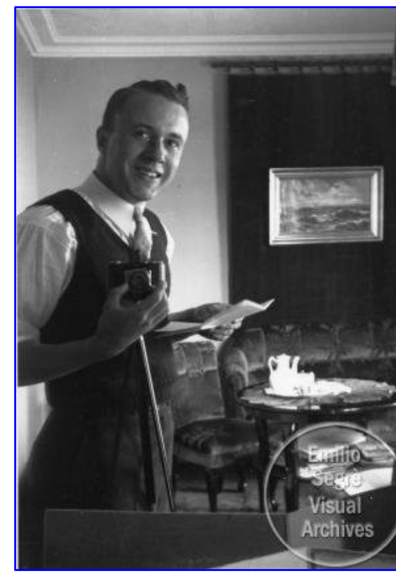
Predicted by Bohr & Wheeler in their seminal paper

> Although nuclei for which the quantity $Z^2/A$ is slightly less than the limiting value (11) are stable with respect to small arbitrary deformations, a larger deformation will give the long range repulsions more advantage over the short range attractions responsible for the surface tension, and it will therefore be possible for the nucleus, when suitably deformed, to divide spontaneously. Particularly important will be

Predicted lifetime ~ $10^{30}$ s ~$10^{22}$ years for $^{239}$U
Physical Review 56 (1939) 426

Search for spontaneous fission by chemist W.F. Libby, 1939 (Berkeley)
Detection of neutrons
→ Uranium, thorium T1/2 > $10^{14}$ year
Phys. Rev. 55 (1939) 1269

Niels Bohr




John Archibald Wheeler (selfie !)

# Consequences of the liquid drop

1 : heavy nuclei can fission spontaneously

2 : fission releases energy

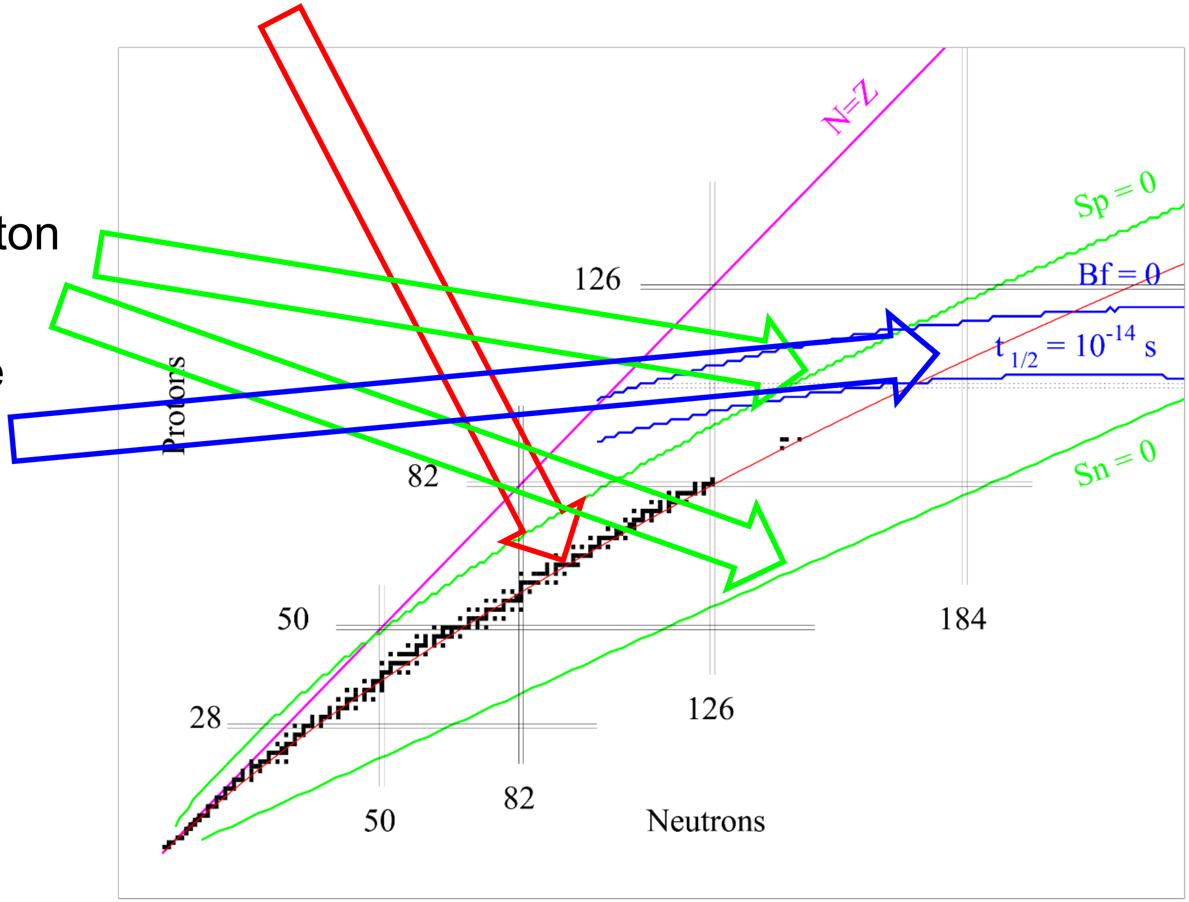
3 : one can estimate the $Q_{\beta-}$, $Q_{\beta+}$, Qα decay energies

4 : most stable nuclei = Beta line of stability « Green approximation »

$$Z \approx \frac{A}{2}\left(\frac{1}{1+\frac{a_C}{4\,a_A}A^{2/3}}\right)$$

5 : neutron and proton drip lines

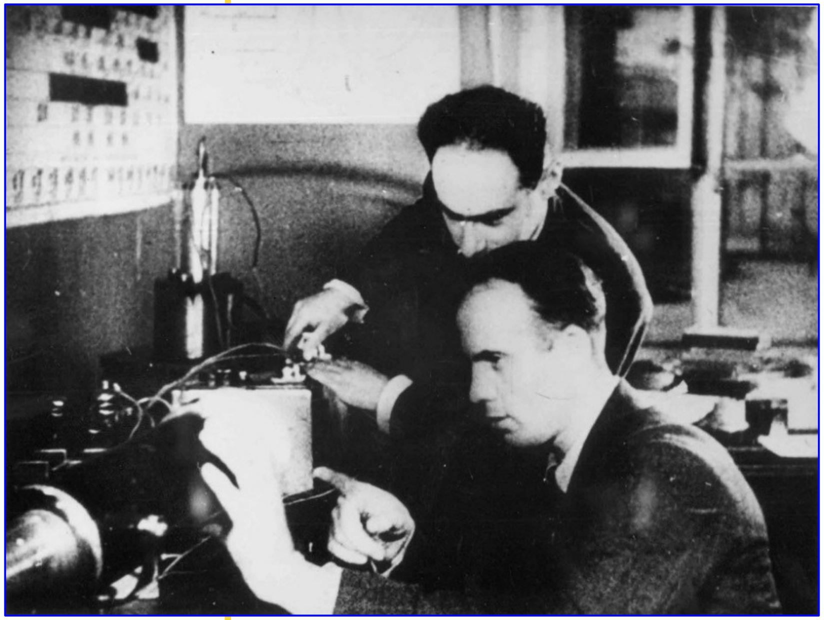
6 : upper end of the nuclear chart



# Spontaneous fission by Flerov & Petrzhak

Context = possible use of nuclear energy

- Can be produced using $^{235}$U, but problem = isotopic separation (only 0,7 % $^{235}$U in natural U).
- Work investigated by I. Kurchatov : search for alternate solutions ($^{238}$U in particular) using different neutron energies
- Work performed by two young collaborators : Flerov & Petrzhak

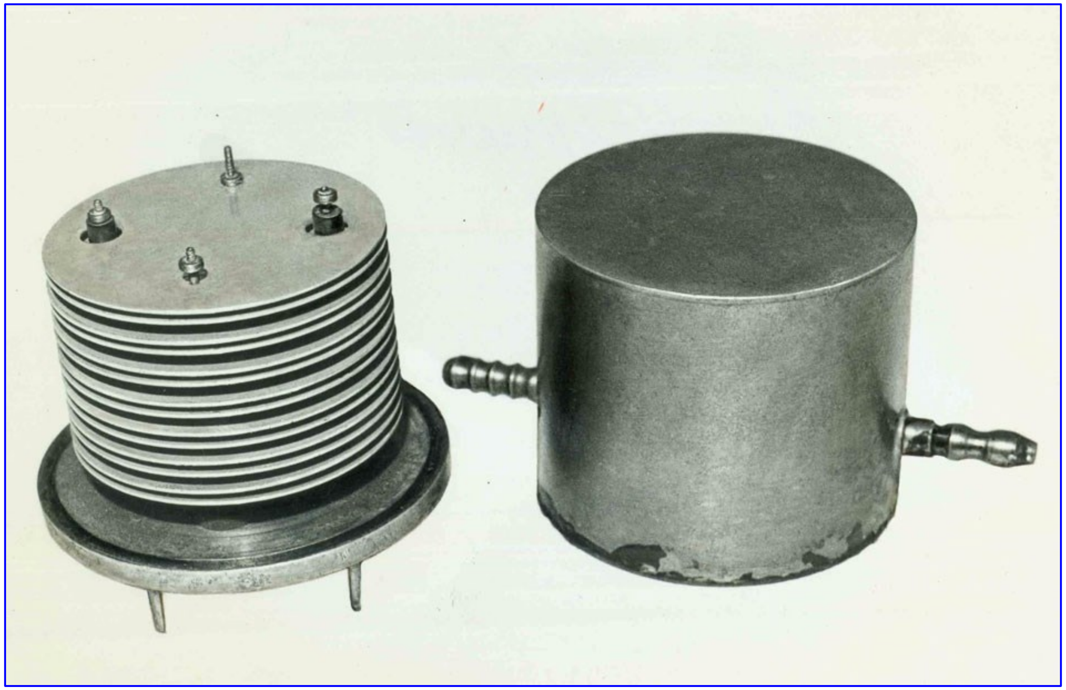


G.N Flerov and Konstantin Petrzhak, 1940

Georgy Nikolayevich Flerov, 1940

Igor Kurchatov, 1933

# Multilayer ionization chamber



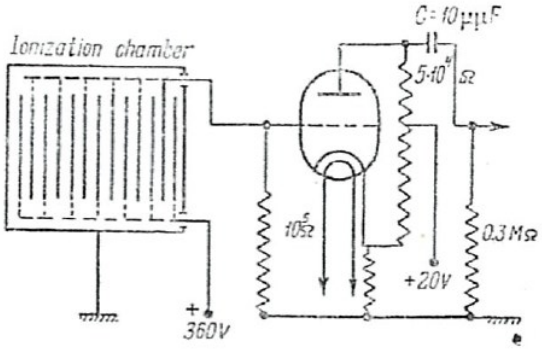


Fig. 1

Multilayer fission ionization chamber: 15 plates area = 1000, 6000 cm2, uranium oxide $\rho \approx 10–20$ mg/cm$^2$

Signal without neutron beam : ~ 6 counts / hour
Several cross-checks : vibrations, electronics noise, alpha pilup, gas discharge, several chambers, effect related to U quantity, measurement of the signal, amplitude (about 160 MeV).

Fission induced by cosmic rays ?

→ test in a Moscow subway station (Dinamo) 50 m underground

**Spontaneous Fission of Uranium**

With 15 plates ionization chambers adjusted for detection of uranium fission products we observed 6 pulses per hour which we ascribe to spontaneous fission of uranium. A series of control experiments seem to exclude other possible explanations. Energy of pulses and absorption properties coincide with fission products of uranium bombarded by neutrons. No pulses were found with UX and Th. Mean lifetime of uranium follows ten to sixteen or seventeen years.

FLEROV
PETRJAK

Physico Technical Institute (F),
Radium Institute (P),
Leningrad, U. S. S. R.,
June 14, 1940 (by cable).

PR 58 (1940) 89

- Shortest nuclear physics paper ever ?
- Kurchatov not signing the paper
- Which U isotope ? (later identified as $^{238}$U).
- Lifetime = ?
- More detail in Russian journals

Reminiscences in Petrzhak & Flerov : Soviet. Phys. Uspekhi 4 (1961) 305

- No reaction from the west countries….

# Idiots ?

Alternative interpretation of Fermi experiments by I.Noddack
Angewandte Chemie 37 (1934) 653 (in german)

Ida Noddack

"It is conceivable, that when heavy nuclei are bombarded by neutrons, these nuclei break up into several larger fragments, which would of course be isotopes of known elements but not neighbours of the irradiated elements."

But comment ignored. Noddack's reputation was not that good in particular since she claimed discovery of Z=43 which could not be verified.

# Fission was already postulated in 1930 !

Henry A. Barton. Phys. Rev. 15 (1930) 408
« A new regularity in the list of existing nuclei »
A paper in a series trying to explain regularities in (e-,p) plots (it was still belived that nuclei we built from electron and protons only). This kind of work lead to evidences for the shell model.

and electrons as the center of the symmetrical cluster. Such a nucleus has not been found to exist in the earth's crust and may hypothetically be regarded as unstable. Suppose there to be a tendency on the part of this nuclear type to break into just two nearly (but not precisely) equal parts. The products of any one such event would be $(80+X, 45+Y)$ and, since the second part is postulated to contain the rest of the nuclear matter, $(80-X, 45-Y)$. Obviously there would thus come into existence always two nuclei symmetrically located $X, Y$ and $-X, -Y$ units respectively from the symmetry center (80, 45). The possible values $X, Y$ would presumably be governed by nuclear forces of cohesion. That is, like a crystal, the nucleus might have particular surfaces of division more probable than others.

Actually Barton postulated fission !!
… and asymmetric fission modes !
(speculation not based on anything, and which does not explain the regularities)

# What was observed by Fermi, Hahn & Strassmann, Curie and Savitch

$$1.\quad U + n \longrightarrow {}^{10''}_{92}U \xrightarrow{\beta} {}^{2,2'}_{93}\text{Eka Re} \xrightarrow{\beta} {}^{59'}_{94}\text{Eka Os} \xrightarrow{\beta}$$

$$\quad {}^{66\,h}_{95}\text{Eka Ir} \xrightarrow{\beta} {}^{2,5\,h}_{96}\text{Eka Pt} \xrightarrow{\beta} {}_{97}\text{Eka Au ?}$$

$$2.\quad U + n \longrightarrow {}^{40''}_{92}U \xrightarrow{\beta} {}^{16'}_{93}\text{Eka Re} \xrightarrow{\beta} {}^{5,7\,h}_{94}\text{Eka Os} \xrightarrow{\beta} {}_{95}\text{Eka Ir ?}$$

$$3.\quad U + n \longrightarrow {}^{23'}_{92}U \xrightarrow{\beta} {}_{93}\text{Eka Re ?}$$

Correct !

$$ {}_{0}n + {}_{92}U \nearrow {}_{56}Ba \rightarrow {}_{57}La \rightarrow {}_{58}Ce \rightarrow {}_{59}Pr \rightarrow {}_{60}Nd \rightarrow \ldots$$

$$ {}_{0}n + {}_{92}U \searrow {}_{36}Kr \rightarrow {}_{37}Rb \rightarrow {}_{38}Sr \rightarrow {}_{39}Y \rightarrow {}_{40}Zr \rightarrow {}_{41}Nb \rightarrow \ldots$$

Experiment repeated 1971 : H. Menke, G. Herrmann. Rad. Acta 16 (1971) 119

At least 22 fission products

66h : $^{99}$Mo (67h) + $^{132}$Te (78hr)

2.5h : $^{132}$I (2,26h)

Other complicated mixtures e.g.

16min = $^{101}$Tc+$^{101}$Mo+$^{131}$Sb+$^{131}$Te+$^{130}$Sb (18min)

3.5 h Curie & Savitch activity : mixture of Y and La isotopes

Herrmann, radioch. Acta 3 (1964) 164.

# Sequanium Z=93

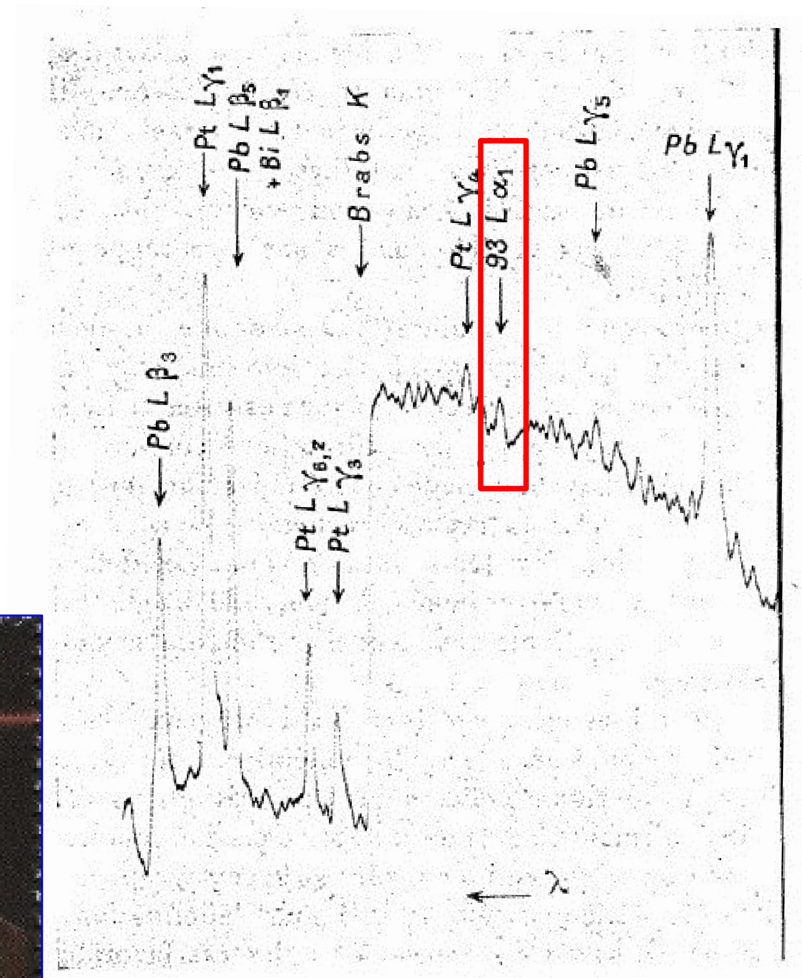


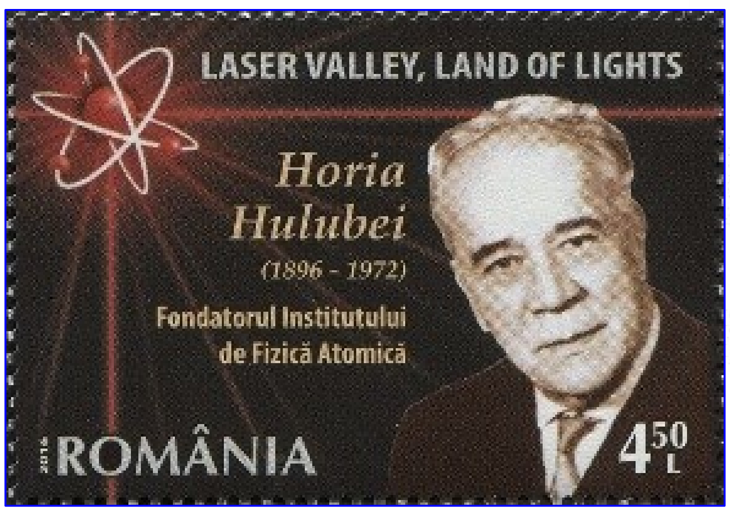
Horia Hulubei and Yvette Cauchois.

Search for element 93 in natural samples.

Analysis of minerals betafite from Madagascar, tantalite from France. Chemical analysis + X-ray spectroscopy.

C.R. Acad. Sci 209 (1939) 476



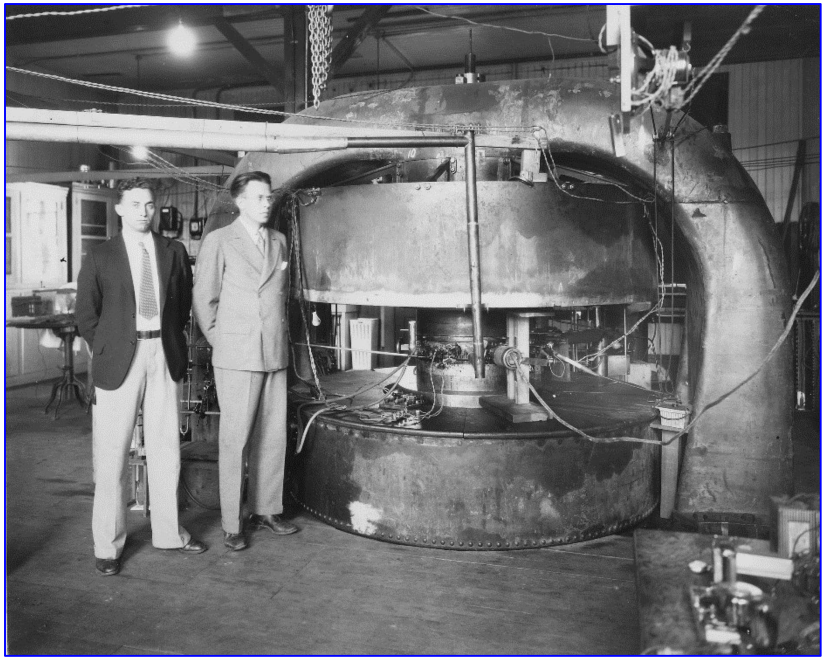



# Discovery of elements 93, 94

1930's : first electrostatic accelerator by John Douglas Cockroft and Ernest Walton, cyclotron by Ernest Lawrence

Very fast development of cyclotrons in the US then in other countries: Russia (1934), UK (1935); France(1937), Japan (1937), Denmark (1938); Sweeden (1938), …

1933 production of neutrons using a 27 inch cyclotron at Berkeley : M. S. Livingston, M. C. Henderson, and . E.O. Lawrence. d (1.3 MeV, $10^{-8}$ A) + $^{9}$Be → $^{10}$Be+n ~ 500 000 n/s.
PR 44 (1933) 782



Livingston and Lawrence, 27'' cyclotron

# Neptunium

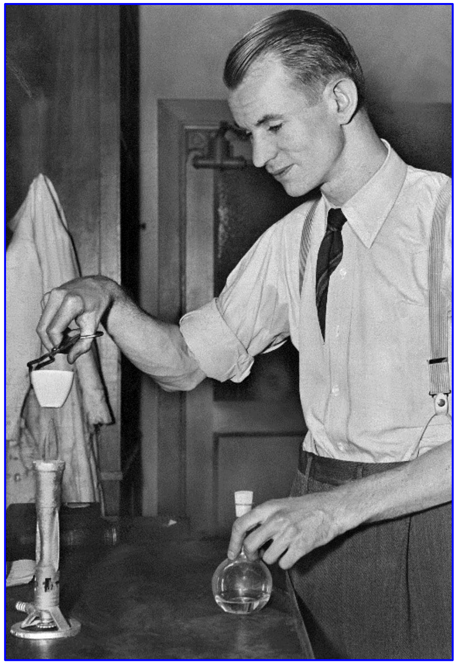
1939 : Edwin Mc Millan and Emilio Segré. Berkeley Cyclotron. Neutron from d(8MeV) + $^{8}$Be reaction.

23-min activity from $^{239}$U isotope.

Observe a 2.3-day activity. Daughter of $^{239}$U ? Chemistry → rare-earth.

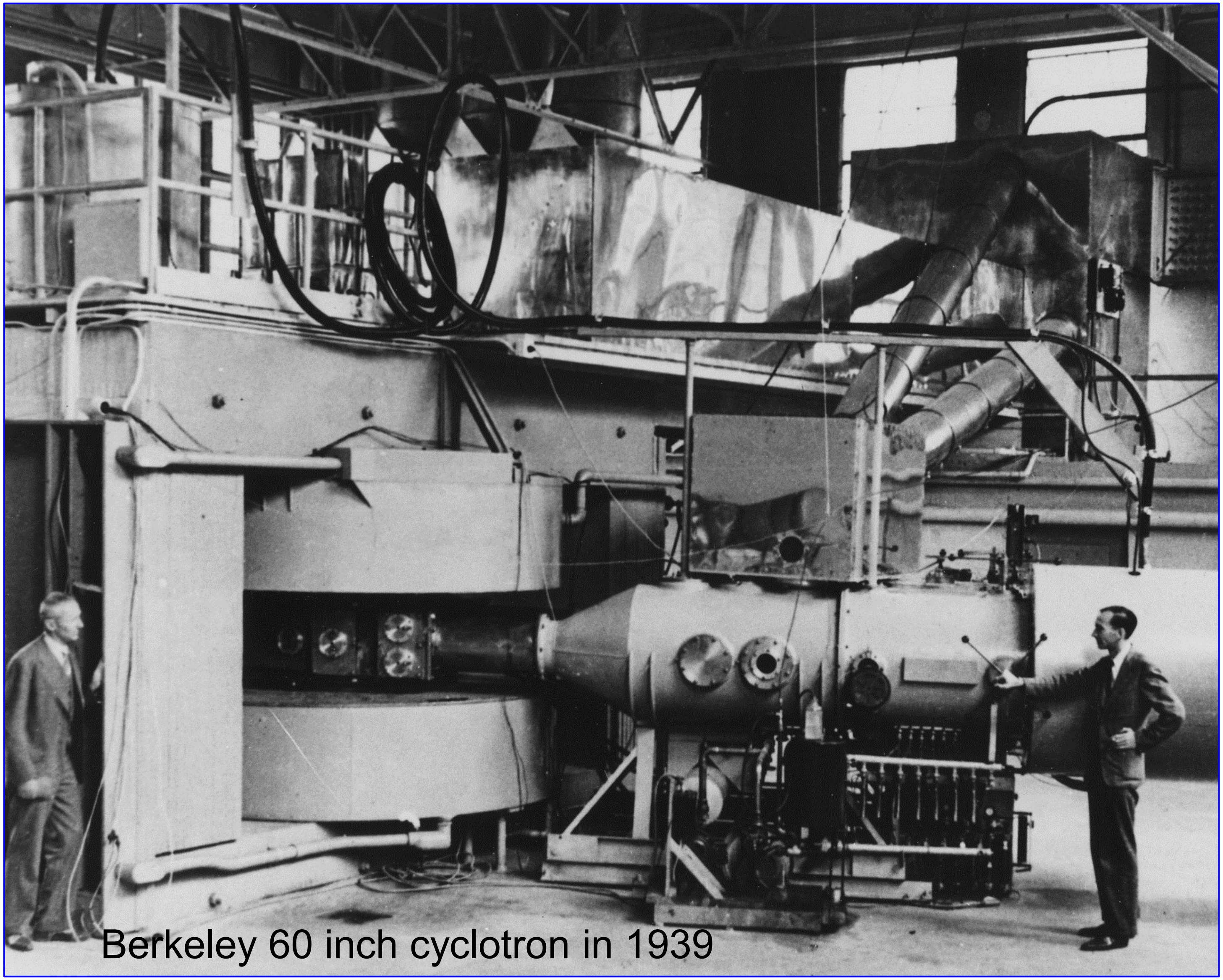
PR 55 (1939) 510, 1104

1940 : McMillan and Alberson. Experiments in Berkeley and Washington.
2.3 day activity is not a rare-earth, not homolog to Re.
properties similar to U !
Second « rare-earth » group starting from U ?
2.3-day activity is the daughter of the 23-min U activity
→ proof 2.3-day activity corresponds to $^{239}93$; low energy beta particles
→ Unsuccessful search for $^{239}94$
PR 57 (1940) 1185



Edwin McMillan 1940

# Neptunium



# Plutonium

Search for element 94 starting from 1940.

McMillan : d(16 MeV)+$^{238}$U, continuation by Seaborg, Kennedy, Wahl. New activity 2 ~ days ($^{238,\ 236\ or\ 235}$93).

Observation of daughter α activity (proportional counter) with lifetime ~ 50 years → $^{238}$94 (modern value = 87,7 years).

Not a formal proof however but letter sent to PR on January 28th, 1941.

Continuation to identify chemically the alpha emitter

→ product has chemical properties similar to U, but different to Os

Letter sent to PR in March 7th 1941

In parallel continuation of the Mc Millan and Segré work using neutrons

Alpha activity (ionization chamber) of the $^{239}$93 daughter → 30000 years (modern value = 24110 years)

Letter sent to PR May 29th, 1941

Voluntary restrictions on publications of papers on fission and transuranium elements: potential application for energy production.

(explains why nobody reacted to the discovery of spontaneous fission)

# Plutonium

Physical Review 69 (1946) 366

**Radioactive Element 94 from Deuterons on Uranium**

G. T. Seaborg, E. M. McMillan, J. W. Kennedy, and A. C. Wahl
*Department of Chemistry, Radiation Laboratory, Department of Physics, University of California, Berkeley, California*

January 28, 1941*

WE are writing to report some results obtained in the bombardment of uranium with deuterons in the 60-inch cyclotron.

* This letter was received for publication on the date indicated but was voluntarily withheld from publication until the end of the war.

Physical Review 69 (1946) 367

**Radioactive Element 94 from Deuterons on Uranium**

G. T. Seaborg, A. C. Wahl, and J. W. Kennedy
*Department of Chemistry, Radiation Laboratory, Department of Physics University of California, Berkeley, California*

March 7, 1941*

WE should like to report a few more results which we have found regarding the element 94 alpha-radioactivity formed in the 16-Mev deuteron bombardment of uranium. We sent a first report[1] of this work in a

* This letter was received for publication on the date indicated but was voluntarily withheld from publication until the end of the war.
[1] G. T. Seaborg, E. M. McMillan, J. W. Kennedy and A. C. Wahl, Phys. Rev. **69**, 366 (1946).

PHYSICAL REVIEW VOLUME 70, NUMBERS 7 AND 8 OCTOBER 1 AND 15, 1946

**Properties of 94(239)**

J. W. Kennedy, G. T. Seaborg, E. Segrè, and A. C. Wahl
*Radiation Laboratory and Department of Chemistry, University of California, Berkeley, California*

(Received May 29, 1941)*

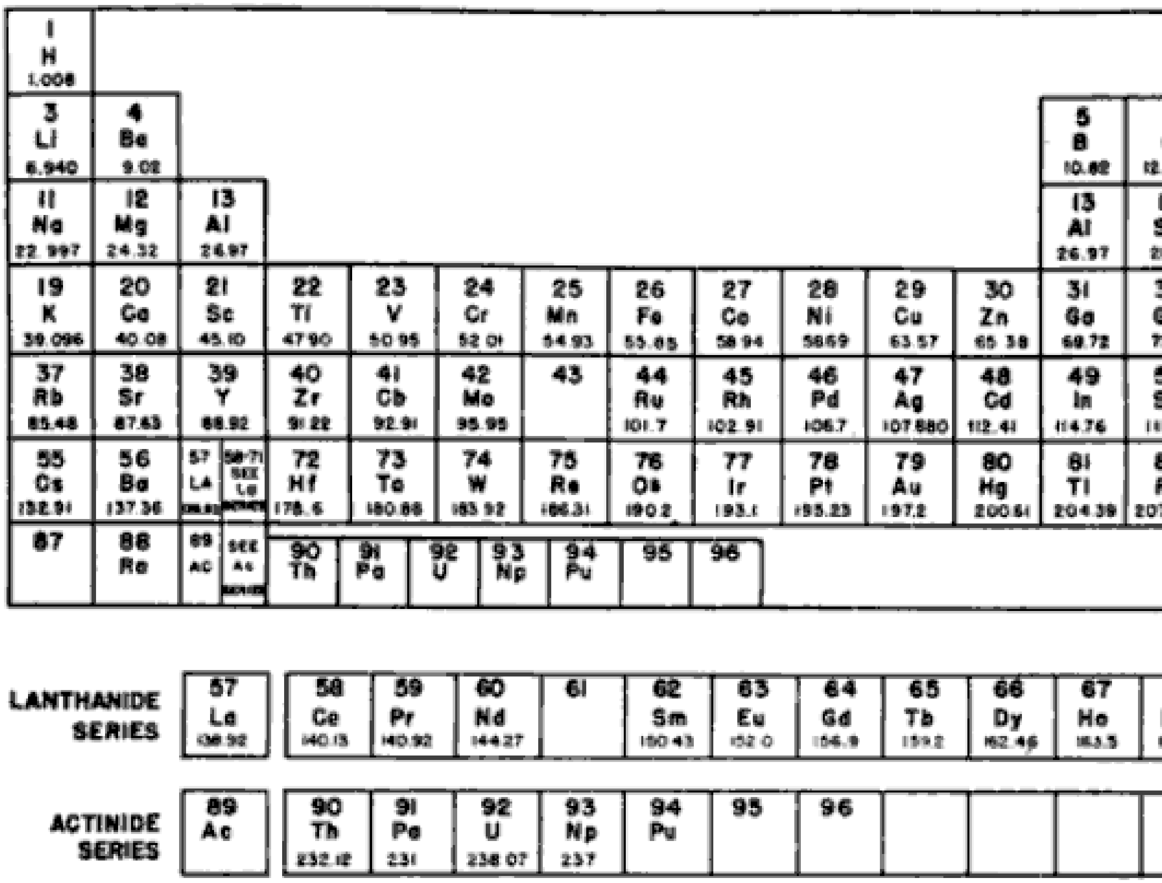
* This letter was received for publication on the date indicated but was voluntarily withheld from publication until the end of the war. The original text has been somewhat changed, by omissions, in order to conform to present declassification standards.

# Chemical identification : what was wrong ?

| IA | IIA | IIIB | IVB | VB | VIB | VIIB | VIII | | | IB | IIB | IIIA | IVA | VA | VIA | VIIA | O |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 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 | 57-71 Ln | 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) | (94) | (95) | (96) | (97) | (98) | (99) | | | | | |
| | | 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 | |

Periodic table ~1930 : Z=93 same column as Mn, Tc, Re

# The actinide serie




Glen Seaborg

Actinide concept : Glen Seaborg ~ 1944

Table from G. Seaborg, Science 104 (1946) 379

V · T · E **Periodic table** (extended form)

Superheavy elements may not exist, and may not follow the order of this table even if they do exist

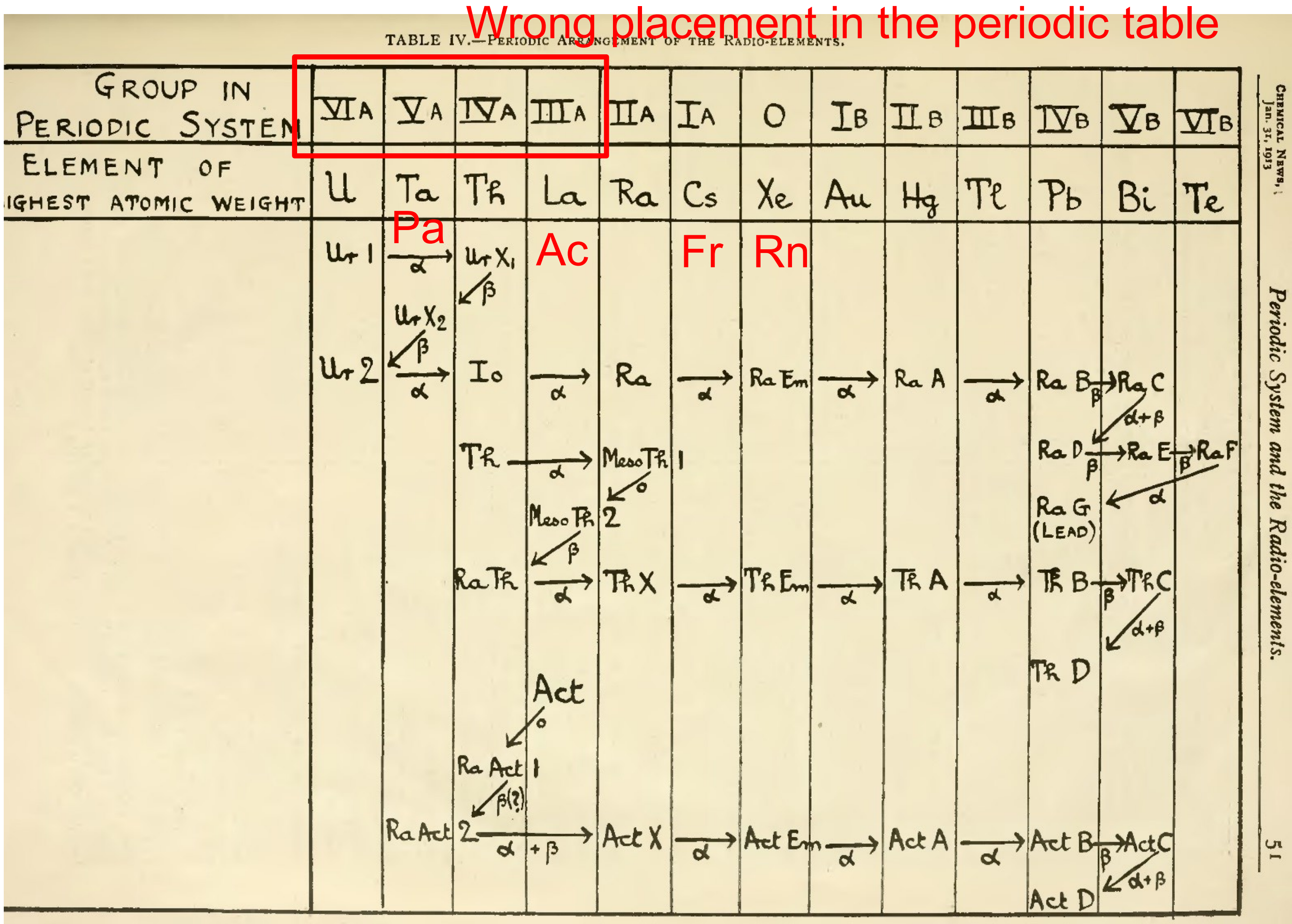
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 H | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 2 He |
| 2 | 3 Li | 4 Be | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 5 B | 6 C | 7 N | 8 O | 9 F | 10 Ne |
| 3 | 11 Na | 12 Mg | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 13 Al | 14 Si | 15 P | 16 S | 17 Cl | 18 Ar |
| 4 | 19 K | 20 Ca | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 21 Sc | 22 Ti | 23 V | 24 Cr | 25 Mn | 26 Fe | 27 Co | 28 Ni | 29 Cu | 30 Zn | 31 Ga | 32 Ge | 33 As | 34 Se | 35 Br | 36 Kr |
| 5 | 37 Rb | 38 Sr | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 39 Y | 40 Zr | 41 Nb | 42 Mo | 43 Tc | 44 Ru | 45 Rh | 46 Pd | 47 Ag | 48 Cd | 49 In | 50 Sn | 51 Sb | 52 Te | 53 I | 54 Xe |
| 6 | 55 Cs | 56 Ba | | | | | | | | | | | | | | | | | | 57 La | 58 Ce | 59 Pr | 60 Nd | 61 Pm | 62 Sm | 63 Eu | 64 Gd | 65 Tb | 66 Dy | 67 Ho | 68 Er | 69 Tm | 70 Yb | 71 Lu | 72 Hf | 73 Ta | 74 W | 75 Re | 76 Os | 77 Ir | 78 Pt | 79 Au | 80 Hg | 81 Tl | 82 Pb | 83 Bi | 84 Po | 85 At | 86 Rn |
| 7 | 87 Fr | 88 Ra | | | | | | | | | | | | | | | | | | 89 Ac | 90 Th | 91 Pa | 92 U | 93 Np | 94 Pu | 95 Am | 96 Cm | 97 Bk | 98 Cf | 99 Es | 100 Fm | 101 Md | 102 No | 103 Lr | 104 Rf | 105 Db | 106 Sg | 107 Bh | 108 Hs | 109 Mt | 110 Ds | 111 Rg | 112 Cn | 113 Uut | 114 Fl | 115 Uup | 116 Lv | 117 Uus | 118 Uuo |
| 8 | 119 Uue | 120 Ubn | 121 Ubu | 122 Ubb | 123 Ubt | 124 Ubq | 125 Ubp | 126 Ubh | 127 Ubs | 128 Ubo | 129 Ube | 130 Utn | 131 Utu | 132 Utb | 133 Utt | 134 Utq | 135 Utp | 136 Uth | 137 Uts | 138 Uto | 139 Ute | 140 Uqn | 141 Uqu | 142 Uqb | 143 Uqt | 144 Uqq | 145 Uqp | 146 Uqh | 147 Uqs | 148 Uqo | 149 Uqe | 150 Upn | 151 Upu | 152 Upb | 153 Upt | 154 Upq | 155 Upp | 156 Uph | 157 Ups | 158 Upo | 159 Upe | 160 Uhn | 161 Uhu | 162 Uhb | 163 Uht | 164 Uhq | 165 Uhp | 166 Uhh | 167 Uhs | 168 Uho |
| 9 | 169 Uhe | 170 Usn | 171 Usu | 172 Usb | 173 Ust | 174 Usq | 175 Usp | 176 Ush | 177 Uss | 178 Uso | 179 Use | 180 Uon | 181 Uou | 182 Uob | 183 Uot | 184 Uoq | 185 Uop | 186 Uoh | 187 Uos | 188 Uoo | 189 Uoe | 190 Uen | 191 Ueu | 192 Ueb | 193 Uet | 194 Ueq | 195 Uep | 196 Ueh | 197 Ues | 198 Ueo | 199 Uee | 200 Bnn | 201 Bnu | 202 Bnb | 203 Bnt | 204 Bnq | 205 Bnp | 206 Bnh | 207 Bns | 208 Bno | 209 Bne | 210 Bun | 211 Buu | 212 Bub | 213 But | 214 Buq | 215 Bup | 216 Buh | 217 Bus | 218 Buo |

**Blocks of the periodic table** V · T · E

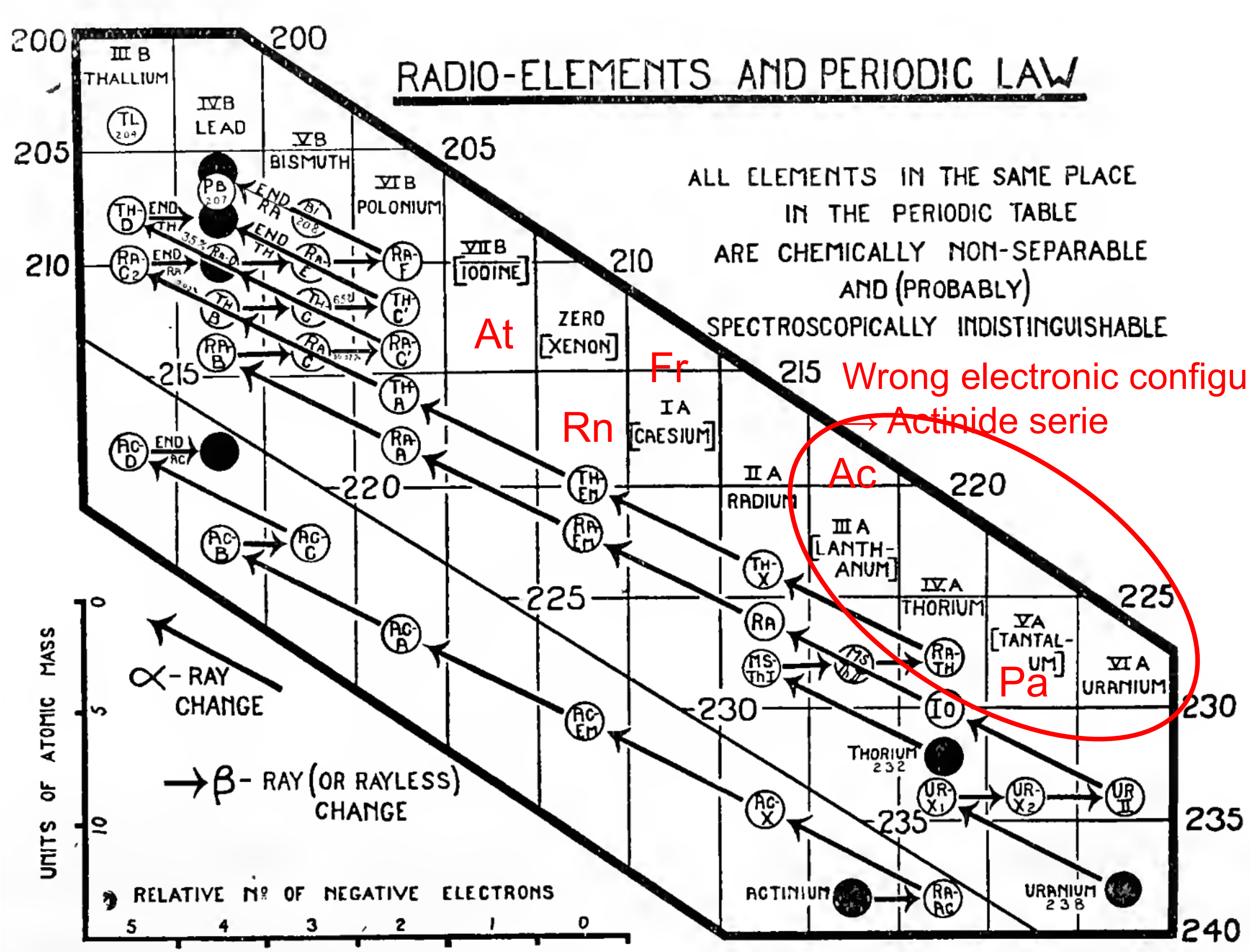
s-block p-block d-block f-block

Predicted elements are coloured in a lighter shade:

s-block p-block d-block f-block g-block




A.S. Russell, The Chemical news CVII (1913) 49.




F. Soddy – Rep. Brit. Ass. Adv. Sci, 83 (1913) 445

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# Element discoveries and errors

Discovery of new elements : an history full of errors (and fakes)

**458. Gerhard Krüss und L. F. Nilson: Studien über die Componenten der Absorptionsspectra erzeugenden seltenen Erden.**

(Vorgetragen in der Sitzung vom 25. April von Hrn. Gerhard Krüss.)

**I.**

Im Anschluss an eine Untersuchung über das Aequivalent und Atomgewicht des Thoriums [1]) untersuchten wir auch die anderen neben der Thorerde in den Thoriten von Brevig und Arendal vorkommenden seltenen Erden. Die Nitrate derselben lieferten sehr schöne Absorptionsspectren, welche mehrere, den Didym-, Samarium, Erbin-, Thulium-Verbindungen, sowie jenen der Soret'schen Erde X oder den Holmiumverbindungen eigene Linien aufwiesen.

Eine genauere Messung der Absorptionsspectren der Thoriterden führte nun zu der auffälligen Beobachtung, dass in diesem Falle nur ein Theil einiger den seltenen Erden eigenen Absorptionsstreifen sicht-

Berichte der Deutschen Chelischen Gesellschaft zu Berlin 20 (1887) 2134

Claim for the discovery of 23 lanthanide elements, all wrong

| Date | Element | Discoverer | Reference | Page |
|---|---|---|---|---|
| 1919 | Asteroid elements Crustaterrium, Primordial matter Terrium Chondrium, Pallasium Siderium Cosmium | P. N. Chirvinsky | Chirvinskii, P. N. *Bull. Inst. Polytechn. Don* **1919**, *7*(Sect. 2), 94. | 411 |
| 1919 | "Helium system" "Hydrogen" system | W. D. Harkins | Harkins,W. D. *Science* **1919**, *50*, 577. | 445 |
| 1921 | Emilium | P. Loisel | Loisel, P. *Compt. Rend. Chim.* **1921**, *173*, 1098. | 284 |
| 1922 | Hibernium | J. Joly | Joly, J. *Proc. Roy Soc. A* **1922**, *102*, 682. | 270 |
| 1923 | Oceanium | A. Scott | Scott, A. *J. Chem. Soc.* **1923**, *38*, 311. | 116 |
| 1925 | Neutronium Neuton Neutronon | A. von Antropoff | von Antropoff, A., *Z. angew. Chem.***1925**, *38*, 971. | 444 |
| 1933 | Element Z = zero | W. D. Harkins | Harkins, W. D. *Nature* **1933**, *131*, 23. | 445 |
| 1925 | Masurium | W. Noddack; I. Tacke; O. Berg | Zingales, R. "From masurium to trinacrium: The troubled story of element 43," *J. Chem. Educ.* **2005**, *82*, 221–27. | 310 |
| 1925 | Pragium | G. Druce | Karpenko,V. *Ambix* **1980**, *27*, 77; Ref. 44a. | 250 |
| 1925 | Dvi-manganese | Dolejšek, J.; Heyrovský, J. | Dolejšek, J.; Heyrovský, J. *Nature* **1925**, *116*, 782. | 250 |
| 1926 | Illinium | B S. Hopkins, *et al.* | Hopkins, B S. *Nature* **1926**, *117*, 792 | 296 |
| 1927 | Florentium | L. Rolla, *et al.* | Rolla, L. *Nature*, **1927**, *119*, 637 | 296 |
| 1928 | Hypon | W. S. Andrews | Andrews, W. S. *The Scientific Monthly* **1928**, *27*(6), 535. | 416 |
| 1930 | Alkalinium | F. H. Loring | Loring F. H. *Chem. News J. Ind. Sci.* **1930**, *140*, 178. | 253 |
| 1931 | Virginium (verium) | F. Allison | Allison, F.; Murphy, E. J.; Bishop, E. R.; Sommer, A. L. *Phys. Rev.*, **1931**, *37*, 1178. | 323 |
| 1931 | Element 108 | R. Swinne | Swinne, R. *Wiss. Veroffentlich. Siemens-Konzern* **1931**, *10*(No. 4), 137. | 326 |
| 1932 | Adyarium Meta-Elements | Jinarajadasa, C.; C. W. Leadbeater | Jinarajadasa, C.; Leadbeater, C. W. *Theosophist* **1932**, *XII*, 361. | 439 |

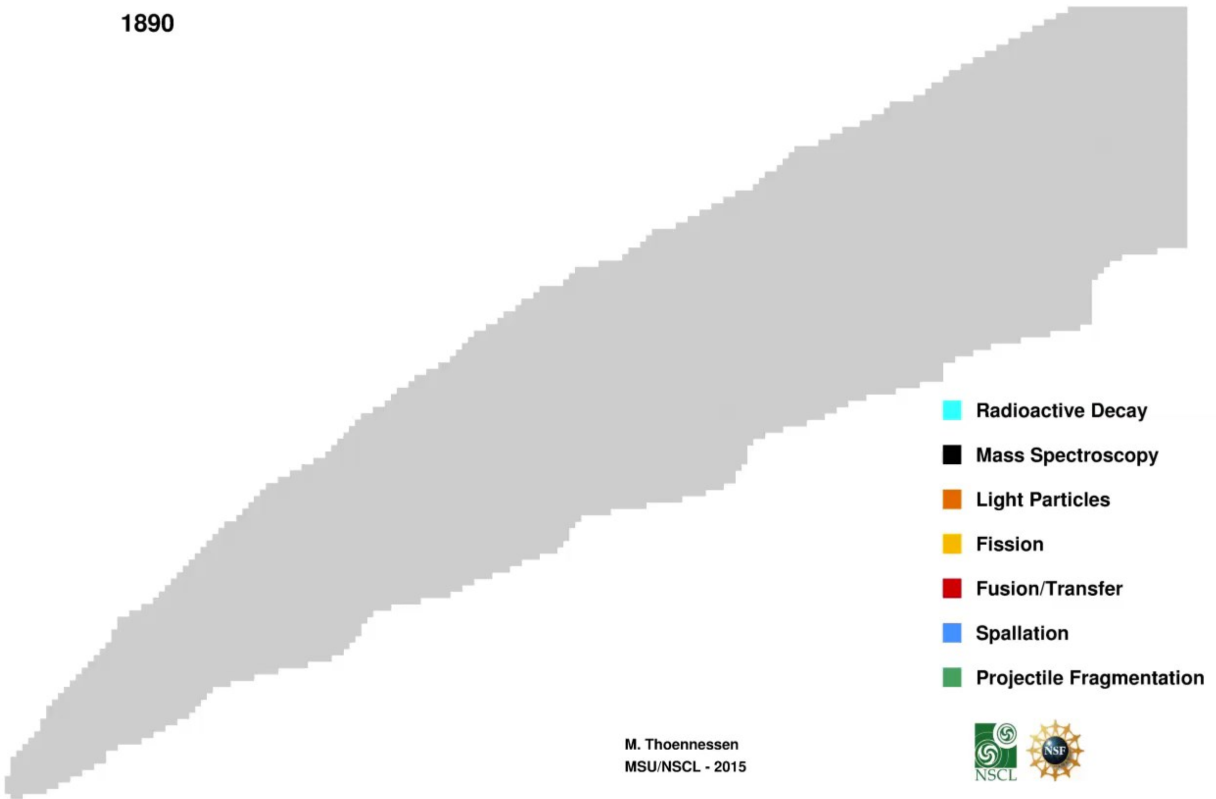
| Date | Element | Discoverer | Reference | Page |
|---|---|---|---|---|
| 1932 | Alabamine (alabamium, eline) | F. Allison | Allison, F. *et al. J. Am. Chem. Soc.* **1932**, *54*, 613. | 328 |
| 1933 | Néo-actinium Néo-radium Néo-elements | A. Debierne | Debierne, A. *Compt. Rend. Chim.* **1933**, *196*, 770. | 151 |
| 1934 | Ausonium Hesperium | E. Fermi and co-workers | Fermi, E.; Rasetti, F.; D'Agostino, O. *Ricerca Scientifica* **1934**, 6(1), 9. | 316 |
| 1934 | Bohemium | O. Koblic | Koblic, O. *Chem. Obzor* **1934**, *9*, 129. | 327 |
| 1937 | Eka-iodine Th-F; Gourium Dakin (Dacinum), Dekhine | R. De | De, R. *Separate* (Bani Press, Dacca) **1937**, 18. | 338 |
| 1937 | Moldavium | H. Hulubei | Hulubei, H. *Compt. Rend. Chim.* **1937**, *205*, 854. | 323 |
| 1938 | Sequanium | H. Hulubei; Y. Cauchois | Hulubei, H.; Cauchois, Y. *Compt. Rend. Chim.* **1938**, *207*, 333. | 320 |
| 1939 | Dor | H. Hulubei; Y. Cauchois | Hulubei, H. *Bull. Soc. Roum. Phys.* **1944**, *45*, no. 82, 3; Hulubei, H. *Bull. Acad. Roum.* **1945**, *27*, no. 3, 124. | 331 |
| 1940 | Helvetium | W. Minder | Minder, W. *Helv. Phys. Acta* **1940**, *13*, 144. | 340 |
| 1942 | Anglo-helvetium | W. Minder, A. Leigh-Smith | Minder, W.; Leigh-Smith, A. *Nature* **1942**, *150*, 767. | 342 |
| 1963 | Sulfénium | M. Duchaine | Duchaine, M. P. J. *French Demande* (May 4, 1973) 4 pp., CODEN: FRXXBL FR 2149300. | 88 |
| 1972 | T. W. Kow | Zunzenium | Kow, T. W., *J. Chem. Educ.* **1972**, *49*, 59. | 392 |
| 1997 | Quebecium | P. Demers | Demers, P. *Le Nouveau Système des Elements: Le Système du Quebecium*; Presses universitaires: Montreal, Canada, 1997. | 225 |
| 2004 | Hawkingium | Anastasovski, P. K. | Anastasovski, P. K. *AIP Conference Proceedings* **2004**, 699 (Space Technology and Applications International Forum—STAIF 2004), 1230. | 393 |

…

- V. Karpenko. «The discovery of supposed new elements: two centuries of errors». Ambix 27 (1980) 77
- Fontani, Costa and Orna «The Lost Elements: The Periodic Table's Shadow Side» Oxford University Press, 2014

Hundreds of wrong or fake discoveries listed !

# Discovery of isotopes




https://people.nscl.msu.edu/~thoennes/isotopes/yearchart-2015.mp4

# Z=96-98

## Z=96 Cm : Seaborg 1944 (60'' cyclotron)

$^{239}Pu(\alpha,n)^{242}Cm \xrightarrow[150d]{\alpha} {}^{238}Pu$

AECD-2182 report, Chem. Eng. News 23 (1945) 2190

## Z=95 Am : Seaborg 1944 (60'' cyclotron)

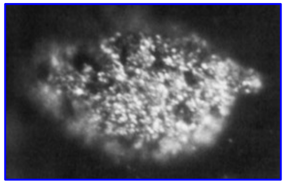
$^{238}U(\alpha,n)^{241}Pu \xrightarrow[\sim 10\ y]{\beta^-} {}^{241}Am$

AECD-2185 report, Chem. Eng. News 23 (1945) 2190

## Z=97 Bk : Thompson 1949 (60'' cyclotron)

$^{241}Am(\alpha,2n)^{243}Bk \xrightarrow[4.8h]{EC} {}^{234}Cm$

UCRL-669 report, PR 77 (1950) 838

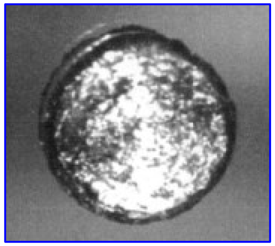


## Z=98 Cf: Thompson 1950 (60'' cyclotron)

$^{242}Cm(\alpha,n)^{245}Cf \xrightarrow[44m]{\alpha} {}^{241}Cm$

UCRL-790 report PR 87 (1950) 298, 102 (1956) 747

(mass assignment was wrong in the 1950 paper)



# Einsteinium (Z=99) and Fermium (Z=100)

First thermonuclear explosion
« Mike » November 1rst 1952,
Eniwetok Atoll
~10 Mtons

Explosion debris
collected by a plane transferred
to Los Alamos.

Results obviously classified.

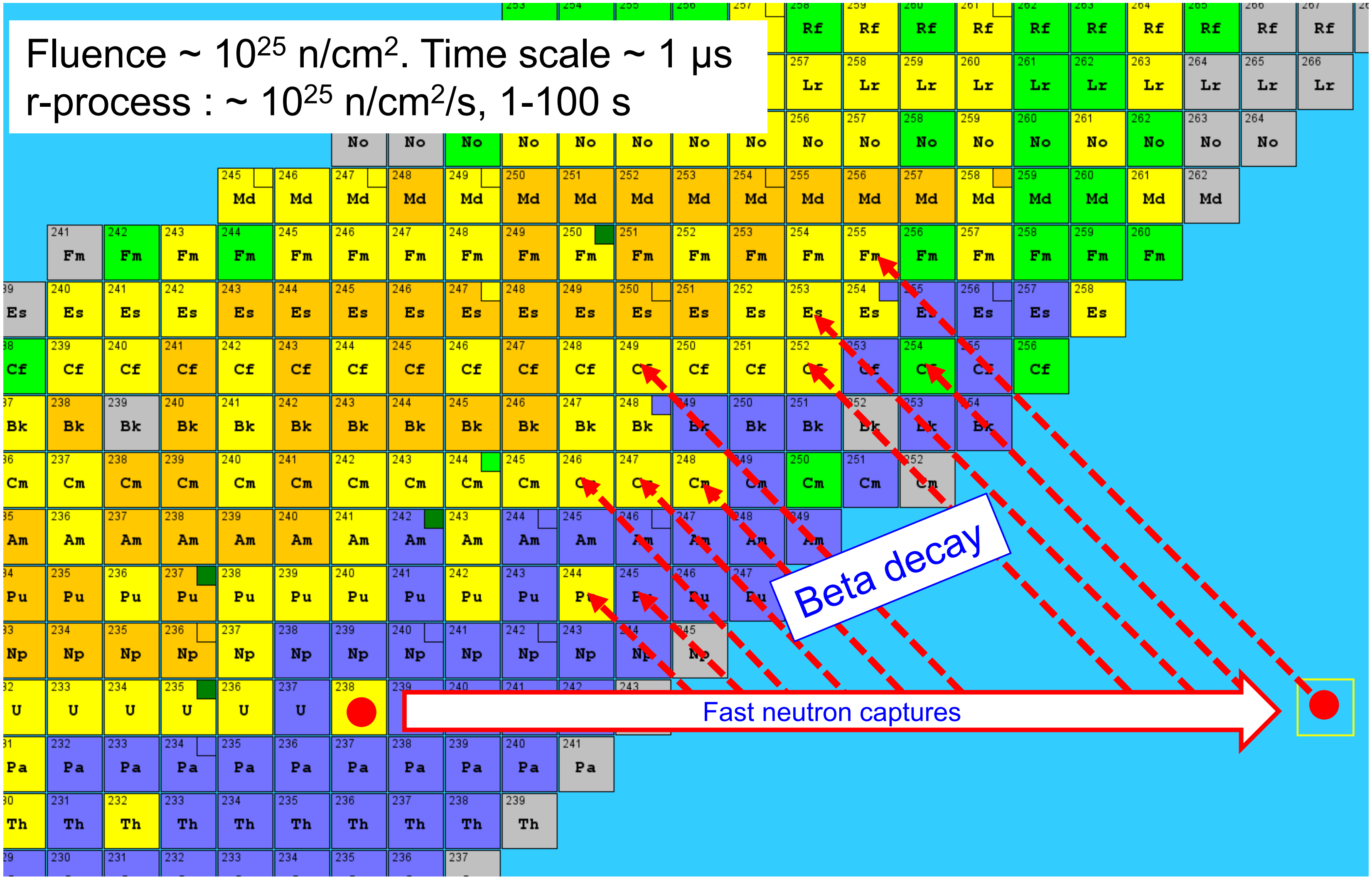
Some new alpha-rays.

Albert Ghiorso, Berkekey obtains some samples.
→ Discovery $^{253}$Es and $^{255}$Fm

In total 15 new isotopes discovered : $^{244,245,246}$Pu, $^{246}$Am, $^{246,247,248}$Cm, $^{249}$Bk, $^{249,252,253,254}$Cf, $^{253,255}$Es, $^{255}$Fm

Fluence ~ $10^{25}$ n/cm$^2$. Time scale ~ 1 µs

r-process : ~ $10^{25}$ n/cm$^2$/s, 1-100 s



Mike results classified

→ no publication of Es, Fm discovery possible

→ « soft » synthesis using $^{238}U(^{14}N,6n)^{246}Es$

→ $^{239}Pu$ $^{252}Cf$ neutron captures in a material testing reactor

Thompson et al PR 93 (1954) 908, Harvey, et al PR 93 (1954) 1129

**Reactions of $U^{238}$ with Cyclotron-Produced Nitrogen Ions***

ALBERT GHIORSO, G. BERNARD ROSSI, BERNARD G. HARVEY, AND STANLEY G. THOMPSON
*Radiation Laboratory and Department of Chemistry, University of California, Berkeley, California*

(Received November 25, 1953)

THE acceleration of $N^{14}(+6)$ ions with the Berkeley Crocker Laboratory 60-inch cyclotron[1] has made it possible to study nuclear reactions of these ions with $U^{238}$.

The following transmutation products have been observed: $99^{247(?)}$, $99^{246}$, $Cf^{244}$, $Cf^{246}$, $Cf^{247(?)}$, $Cf^{248}$, $Bk^{243}$, and other berkelium isotopes not yet identified. The identification of the elements

[4] There is unpublished information relevant to element 99 at the University of California, Argonne National Laboratory, and Los Alamos Scientific Laboratory. Until this information is published the question of the first preparation should not be prejudged on the basis of this paper.

Ghiroso et al, PR 93 (1954) 257

**New Elements Einsteinium and Fermium, Atomic Numbers 99 and 100**

A. GHIORSO, S. G. THOMPSON, G. H. HIGGINS, AND G. T. SEABORG, *Radiation Laboratory and Department of Chemistry, University of California, Berkeley, California*

M. H. STUDIER, P. R. FIELDS, S. M. FRIED, H. DIAMOND, J. F. MECH, G. L. PYLE, J. R. HUIZENGA, A. HIRSCH, AND W. M. MANNING, *Argonne National Laboratory, Lemont, Illinois*

AND

C. I. BROWNE, H. L. SMITH, AND R. W. SPENCE, *Los Alamos Scientific Laboratory, Los Alamos, New Mexico*

(Received June 20, 1955)

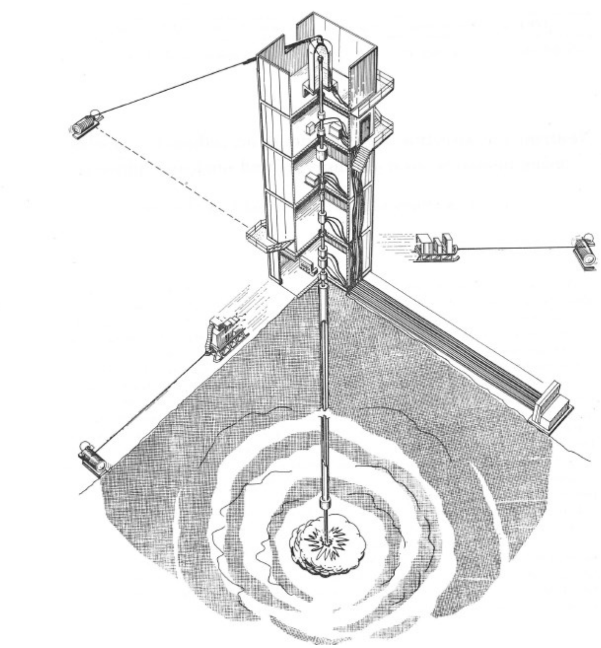
THIS communication is a description of the results of experiments performed in December, 1952 and the following months at the University of California Radiation Laboratory (UCRL), Argonne National Laboratory (ANL), and Los Alamos Scientific Laboratory (LASL), which represent the discovery of the elements with the atomic numbers 99 and 100.

The source of the material which was used for the first chemical identification of these elements was the Los Alamos Scientific Laboratory which provided uranium which had been subjected to a very high instantaneous neutron flux in the "Mike" thermonuclear explosion (November, 1952). Initial investigations at

Ghiroso et al, PR 99 (1955) 1048

Plowshare program in the US on peaceful uses of nuclear explosion (1958-1975)

- 1961-1973 : 27 tests
- Mainly excavation techniques, and neutron flux studies (including ~10 tests for heavy element production).
- e.g. Hutch event June 1969 neutron flux 4,5 $10^{25}$ neutron/$cm^2$/s
- Heaviest nucleus observed = $^{257}$Fm



# Heavy elements and the r-process

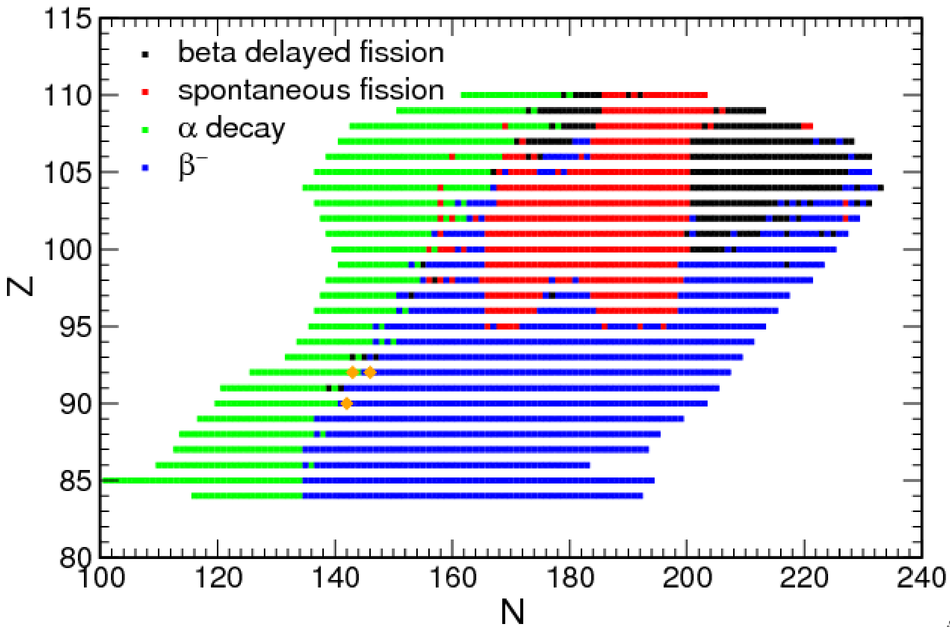
Related questions

- Production of super-heavy in nature; r-process : Supernovae explosion
- Why nothing heavier than $^{257}$Fm in thermonuclear

Explosions ?

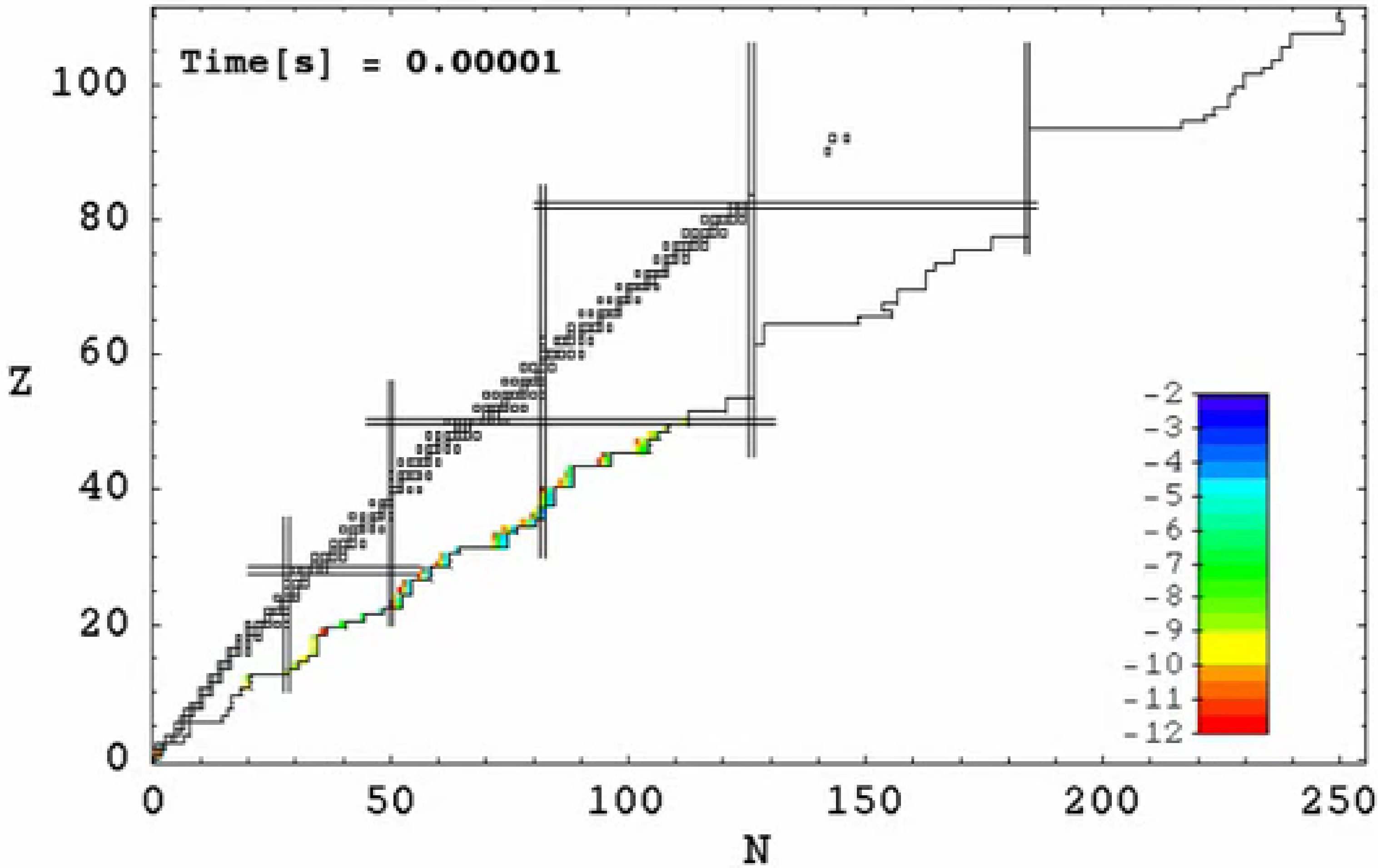
Need very neutron rich Fm nuclei to reach Beta-decaying nuclei (because Z=100 deformed magic shell gap). But $^{256-258}$Fm predicted too short lived.

Petermann et al
« Have superheavy elements been produced in nature? »
EPJA 48 (2012) 122



# Heavy elements and the r-process

Production of super-heavy in nature; r-process : Supernovae explosion

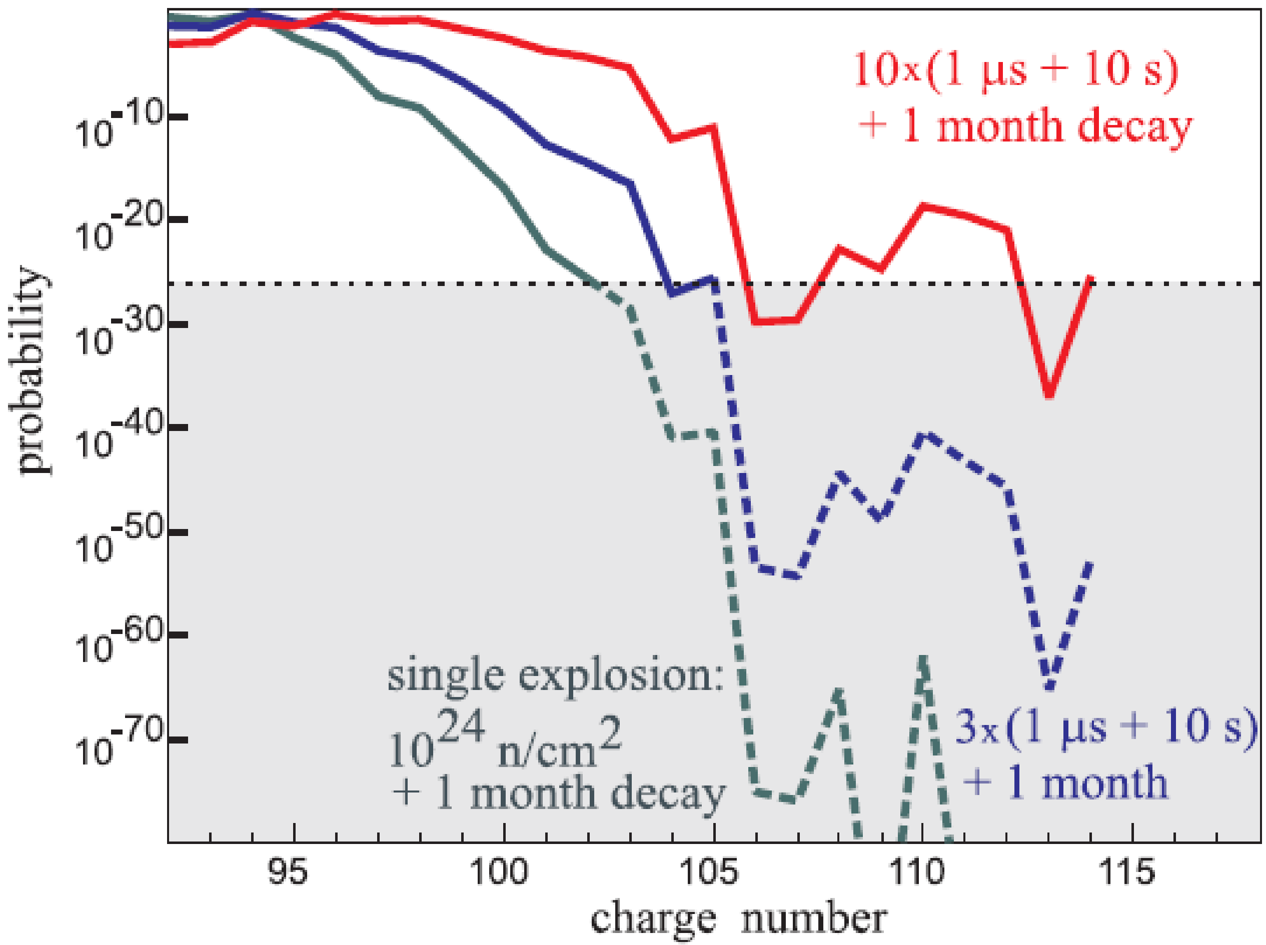



Stephane Goriely, Andreas Bauswein, Hans-Thomas Janka

https://www.youtube.com/watch?v=zouvhsFvKiM

See also S.Goriely, G.Martínez-Pinedo NPA 944 (2015) 158

# By-passing the Fm gap…




Soft *(sic)* mike-like thermonuclear explosions
V.I. Zagrebaev et al. EPJ Web of conferences 17 (2011) 12003

# Search for SHE in nature

A vast program with great hopes (and great fakes)

See e.g.

Ter-Akopian and Dimitriev NPA 944 (2015) 177

Korschineka and Kutschera NPA 944 (2015) 190

And references therein

# The limits of the periodic table

Oveview in « Superheavy elements and the upper limit of the periodic table: early speculations ». H. Kragh. EPJH 38 (2013) 411

- 19th century chemistry → no limitation
- Bohr-Sommerfeld atomic physics ca 1920. Electron orbits ~ nuclear size → $Z \leq 137$.
- Swinne 1926, atomic physics. Possible existence of « transuranic » long lived elements Z=98-102 then Z=108-110.
- Minimum-time hypothesis « chronon ». Minimum period of revolution. Flind and Richardson 1928 → $Z < 97$
- Cosmic speculations. Long-lived elements descendants of early radioactive state of the universe (Rutherford 1923, Kolhöster 1924, Nernst 1928) → idea that one can find transuranium elements on earth
- Jean 1926 Stellar matter. Center of the stars : elements Z~95.
- Lemaitre 1931. Early universe = giant atom of ~ $10^{54}$g
- G. Fournier. Geometric lattice model of the nucleus. Maximum size of the nucleus. Z=136, A=360. C.R. Acad. Sci. 203 (1936) 1495

# Limit of stability : positron emission

Nuclei for Z larger than 173 become unstable against positron emission.

This is because the most deeply bound electrons from the $1s_{1/2}$ shell reach an energy of -511 keV

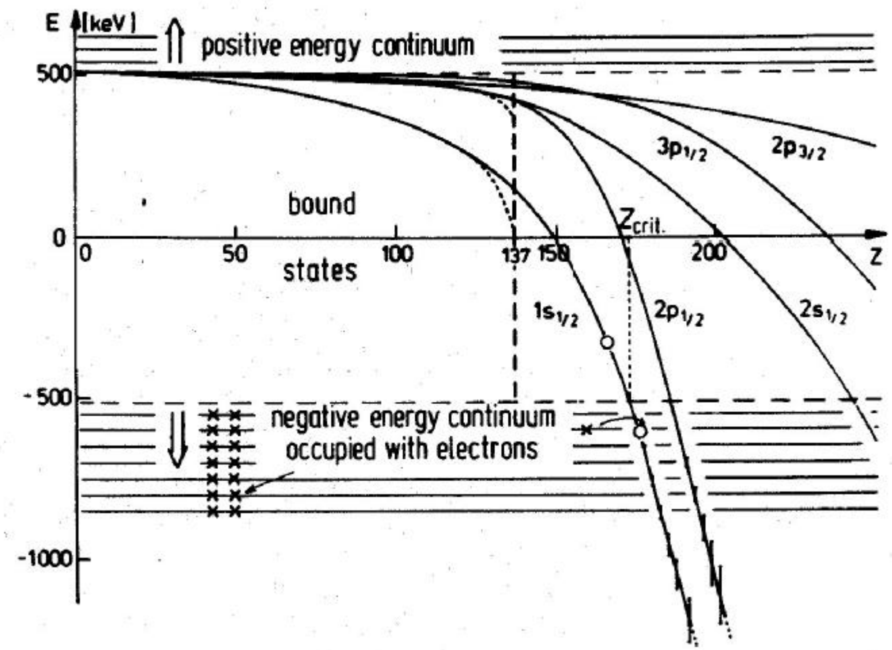



Fig. 2. Binding energies of electronic states in atoms as function of nuclear charge Z. At $Z_c$ = 173 the 1s-state dives into the negative energy continuum.

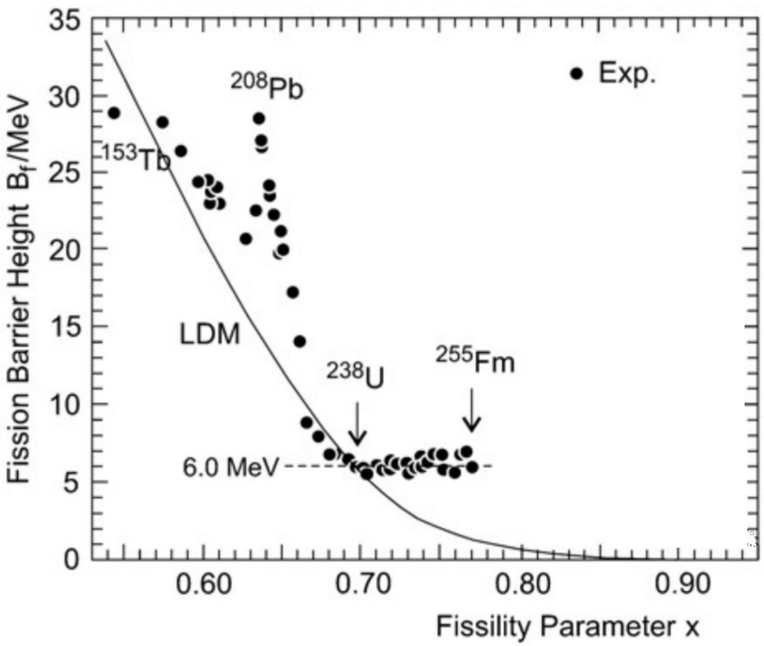
See eg W. Pieper, W. Greiner Z. Phys. A 218 (1968) 327
J. Reinhardt et al, Z. Phys. A 303 (1981) 173

# Fission vs liquid drop model

| Nucleus | x | $B_f$ LDM | $T_{1/2}$ (s) LDM | $T_{1/2}$ (s) exp |
|---|---|---|---|---|
| $^{238}$U | 0.77 | 7.76 | 1.6 $10^{21}$ | 0.6 $10^{23}$ |
| $^{240}$Pu | 0.79 | 5.8 | 3.6 $10^{10}$ | 3.6 $10^{18}$ |
| $^{255}$Fm | 0.84 | 2.45 | 1.5 $10^{-8}$ | 3.2 $10^{11}$ |
| $^{254}$No | 0.86 | 1.45 | 6 $10^{-14}$ | 2.9 $10^{4}$ |
| $^{256}$Rf | 0.89 | 0.85 | 3 $10^{-17}$ | 6.2 $10^{-3}$ |
| $^{290}$Fl | 0.96 | 0.04 | 1.1 $10^{-21}$ | |

Swiatecki 1955 : correcting the liquid drop-model for shell structure may improve the description of spontaneous fission half-lives

PR 100 (1955) 937

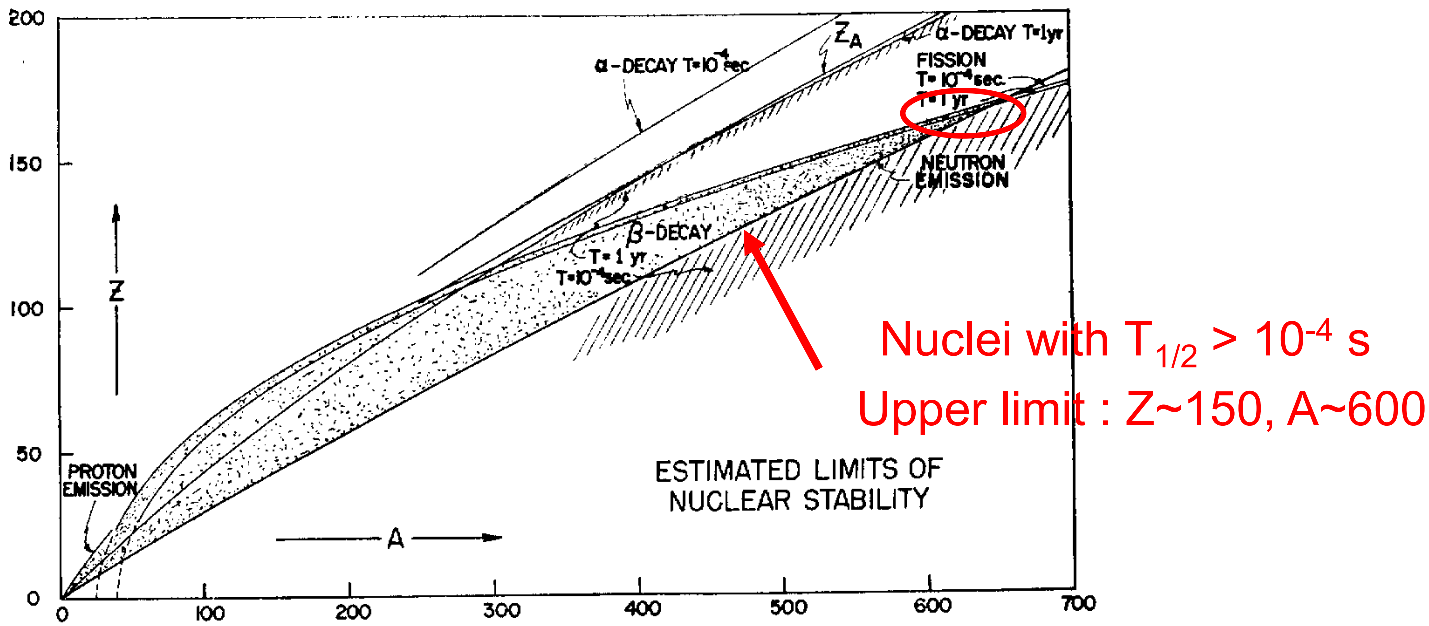



Oganessian J. Phys. G 34 (2007) R165

# Wheeler phenomenological approach.
# « Superheavy » nuclei

After the discovery of the first transuranium elements (up to Fm), the limits of nuclear matter were not at the heart of discussion.

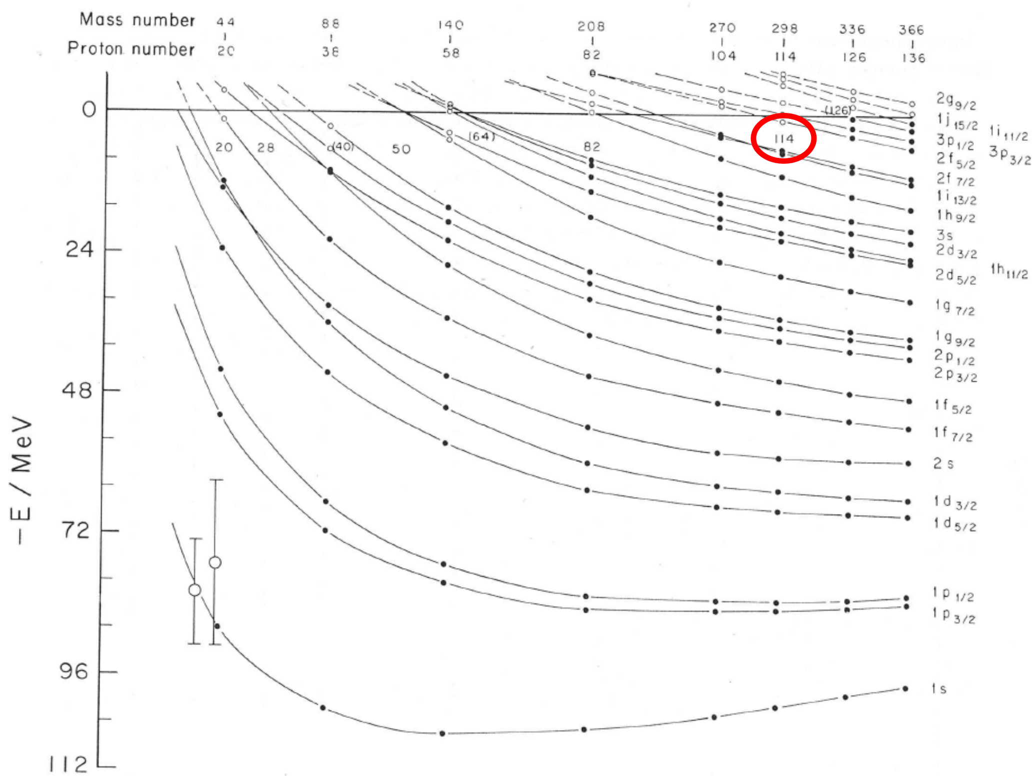
In 1955, John Wheeler coined the term « superheavy » during the (famous) Geneva International conference on the peaceful uses of atomic energy




Estimates based mostly on the liquid drop model. No shell effects included, although the Nilsson Model was known and used to discuss fission barriers (by John Wheeler itself). Calculations using both macroscopic and microsocopic ingredients was not yet possible. Therefore fission lifetime scaled empirically using Known actinides (Th-Fm).

# Stability and shell structure (spherical)

- 1949 : The spherical shell model (Mayer, Haxel, Jensen and Suess).
- 1957 : G. Scharff-Goldhaber "There may be, for instance, another region of relative stability at the doubly magic nucleus $_{126}X^{310}$"
- 1966 : Lysekil symposium "Why and how should we investigate nuclei far from the stability line?"




H. Meldner, Ark. Fiz. 36 (1966) 593, shell model
→ Z=114, N=184

Confirmed by
C.Y. Wong PL 21 (1966) 688 (shell model)
A. Sobiczewski et al. PL 22 (1966) 500 (Woods-Saxon)
…
= calculations using phenomenological potentials

# Effective forces

HFB calculations with Skyrme forces : Vautherin 1970

+ Davies 1971, Köhler 1971, Bassichis 1972, Rouben 1972 and 1977, Saunier 1972, Beiner 1974, Brack 1974, Cusson 1976, Vallières 1977, Kolb 1977, Tondeur 1978 and 1980

Spherical calculation for few nuclei, some simplifications

RMF calculations Gambhir 1990, Boersma 1993

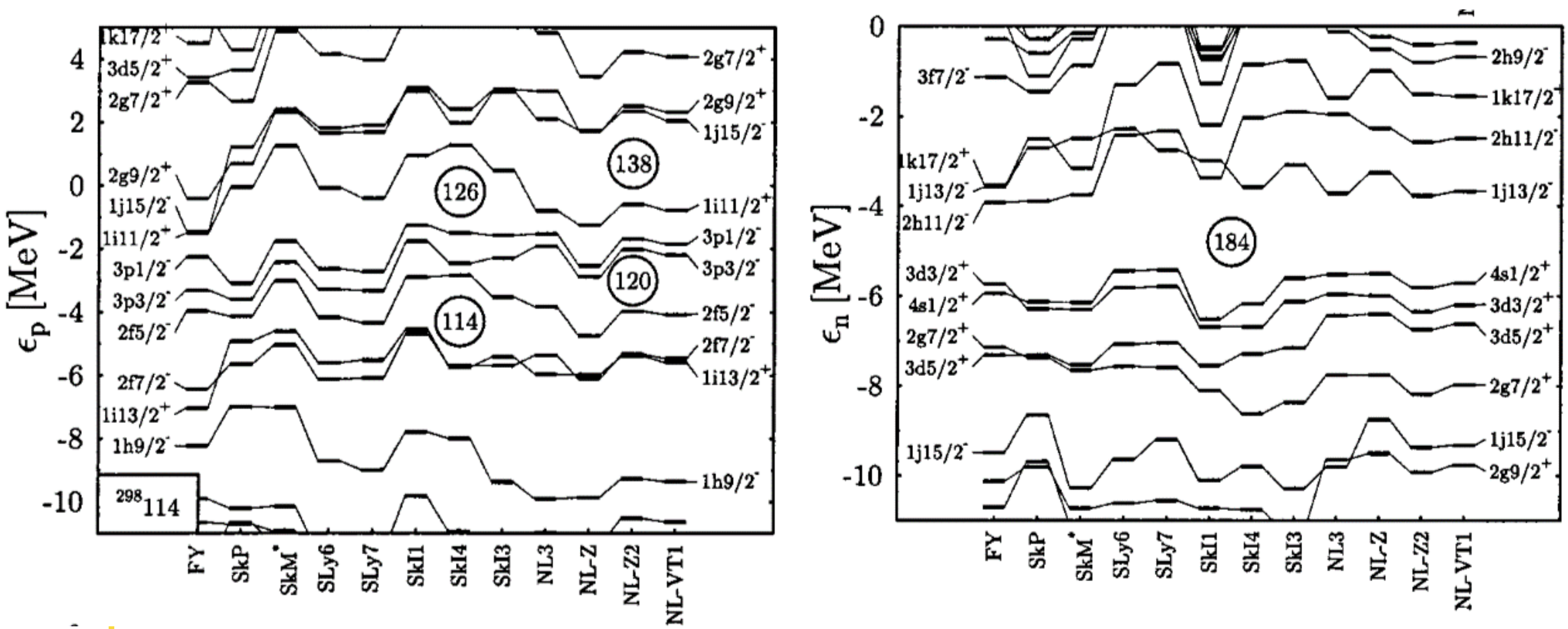
→ Z= 114 not refuted, although Z = 120, 126 or 138 also suggested

HFB calculations with Gogny force, Berger 1996 : Z=114 not magic !

systematic calculations using self-consistent models (spherical nuclei)

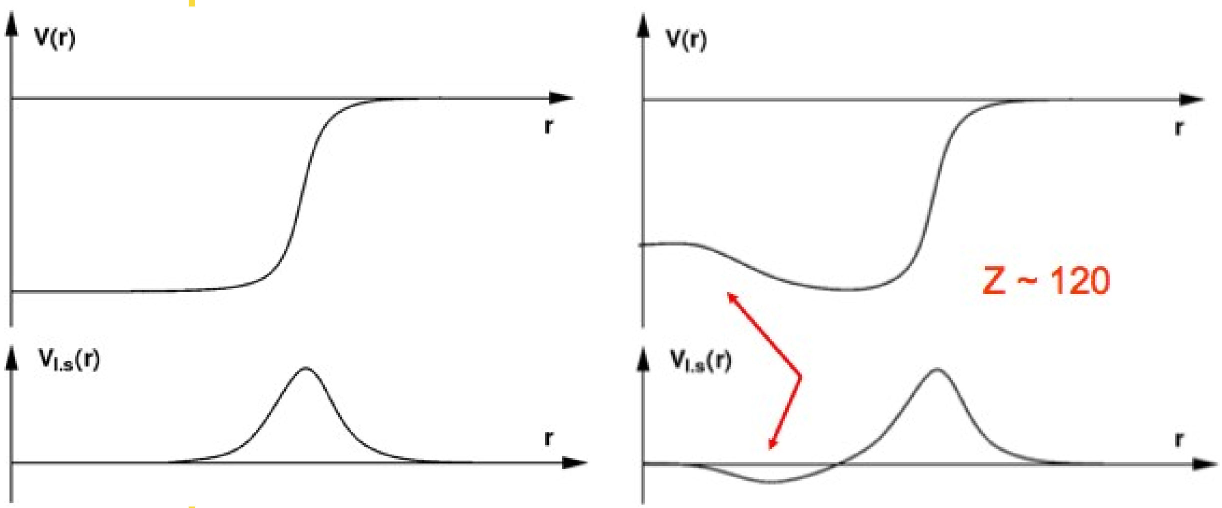
Skyrme forces by Ćwiok, Dobaczewski, Heenen, Magierski and Nazarewicz. NPA 611 (1996) 211

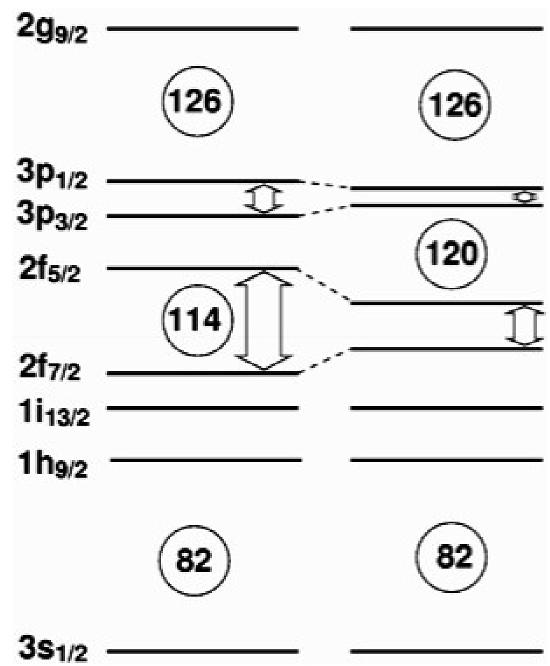
Skyrme and RMF : Rutz, Bender, Bürvenich, Schilling, Reinhard, Maruhn and Greiner, Skyrme and RMF forces. PRC 56 (1997) 238, Bender, Rutz, Reinhard, Maruhn and Greiner PRC 60 (1990) 034304



# Spin-orbit splitting

$$V_{l.s}(r) = -\frac{1}{r}\frac{\partial V(r)}{\partial r}$$



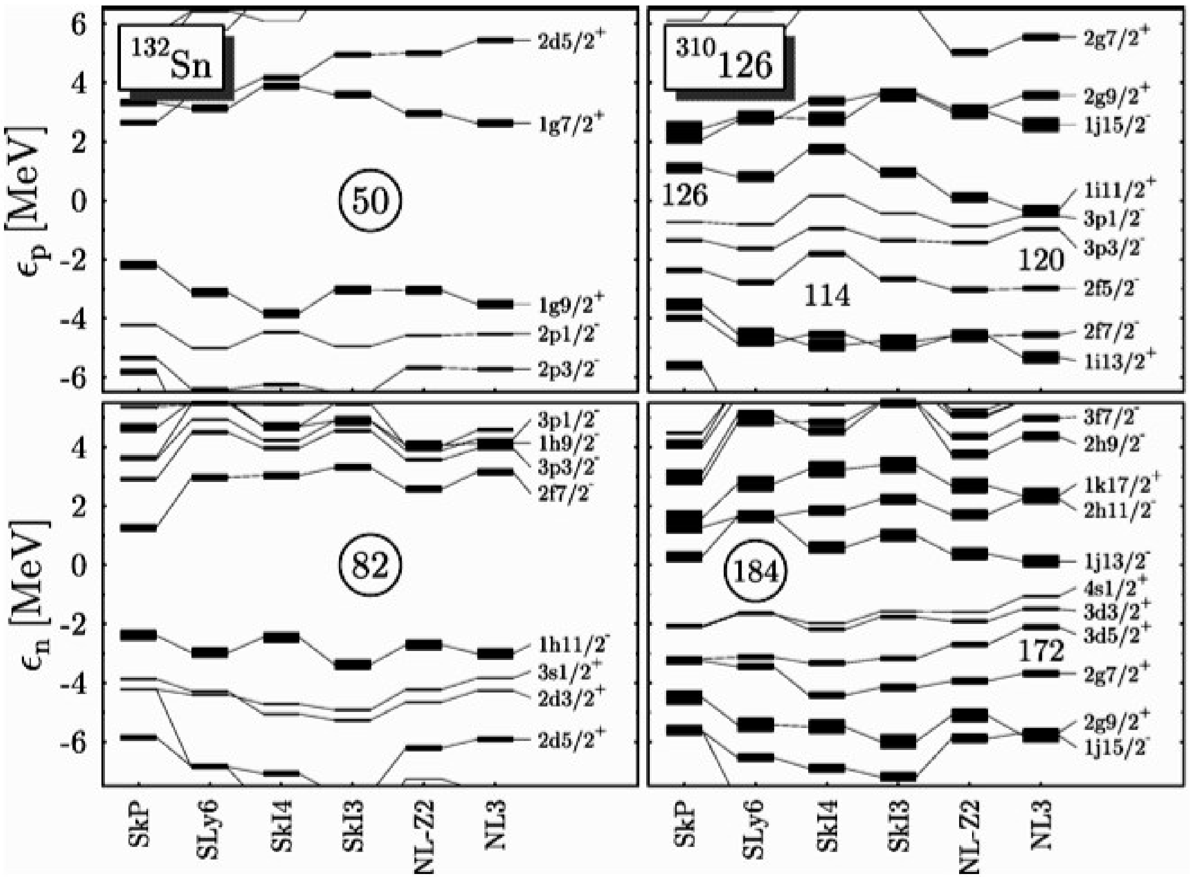




Effect of spin orbit contribution cancelled or reversed

Splitting $2f_{5/2}$ $2f_{7/2}$

# Complex nature of SHE

Level density increases
Spin orbit → orbitals flipped
Low *j* orbitals → can modify significantly the gap but not drastically the binding energies → smooth island of stability

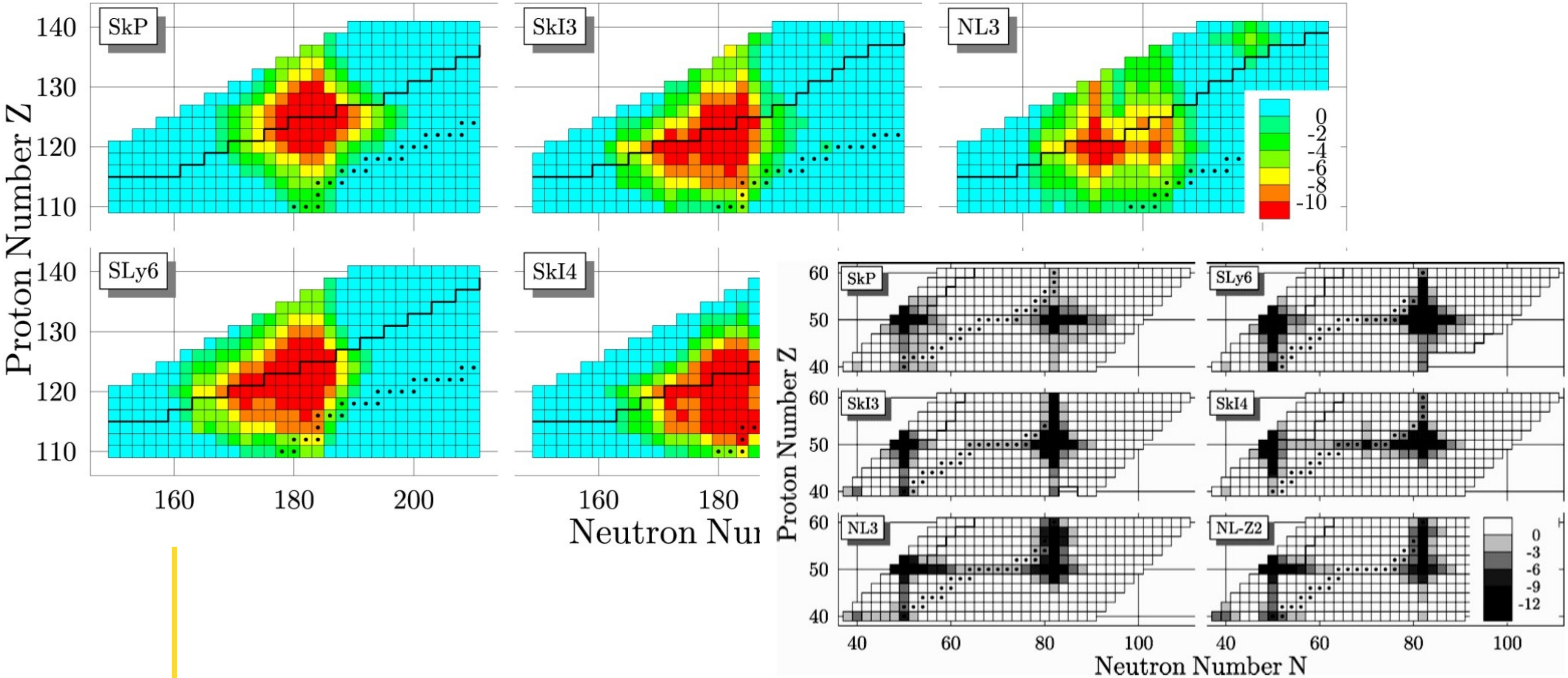



M. Bender et al., Phys. Lett. B 515 (2001) 42

# Theoretical challenges

Doubly magic character of predicted SHE not as marked as lighter Nuclei such as $^{48}$Ca, $^{208}$Pb, …

Island of stability smooth and not well localized.



# Deformed nuclei

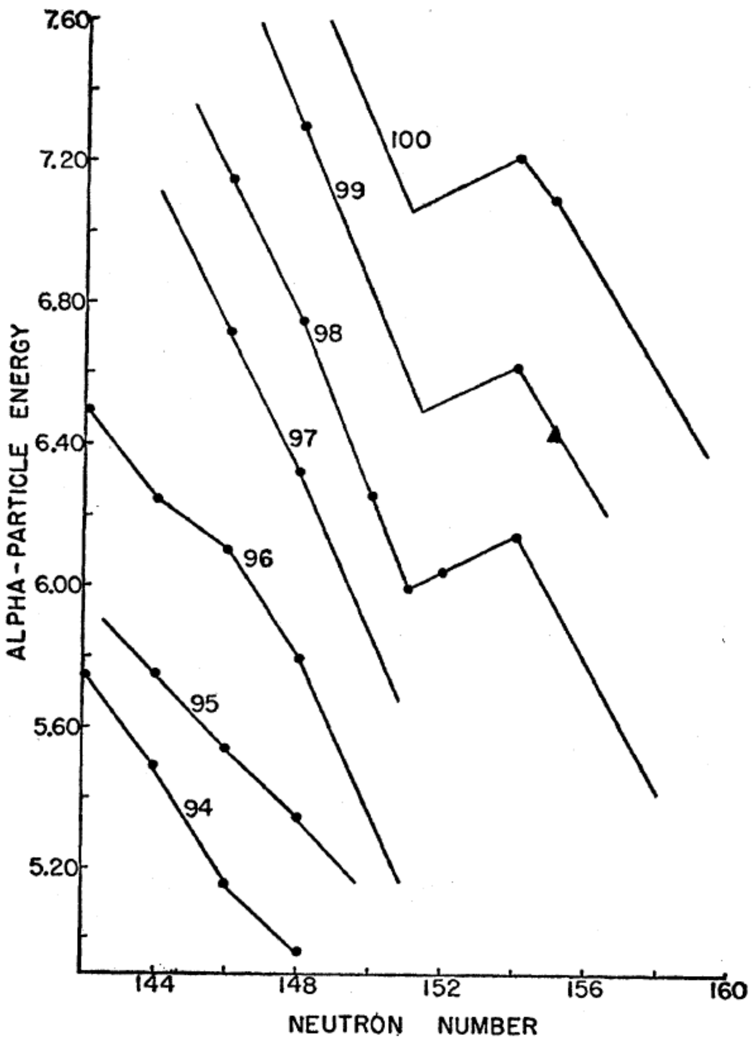
First evidence by Schüler and Schmidt (1935) in $^{151,153}$Eu, atomic spectroscopy → atomic structure is influenced by the nuclear deformation

Townes systematics 1949 of electric quadrupole moments

1950 : spheroidal model by J. Rainwater, unified model by Bohr and Mottelson

1954 : Nilsson deformed shell model by S.G. Nilsson

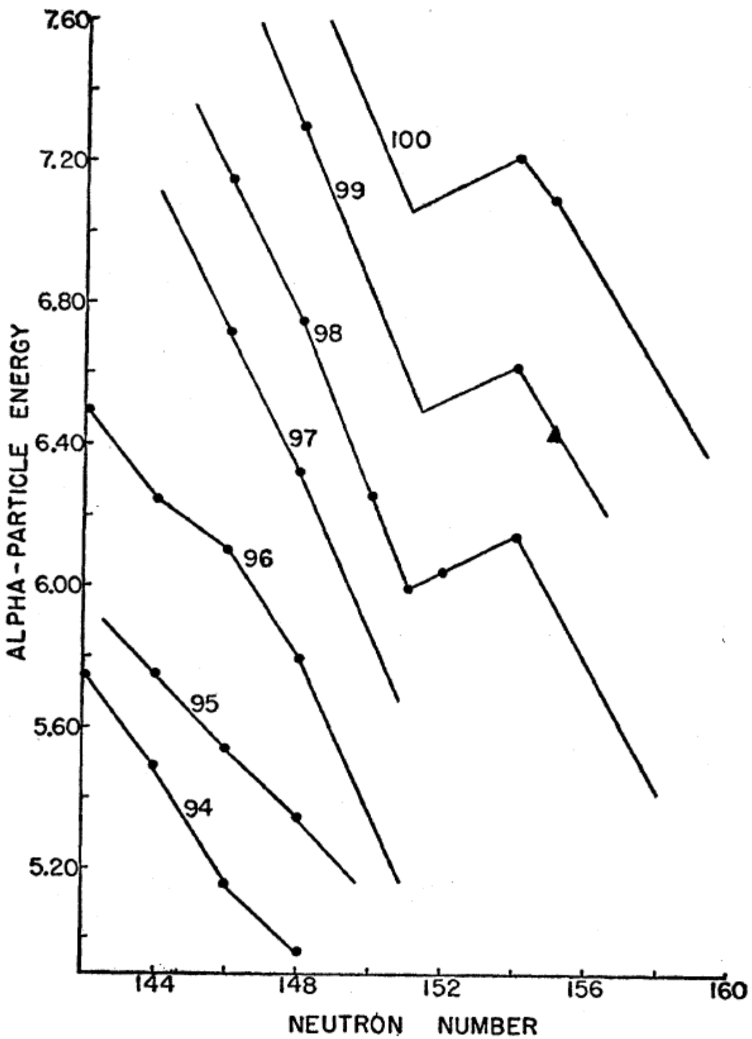
# Ghiroso systematics of α-decay energies

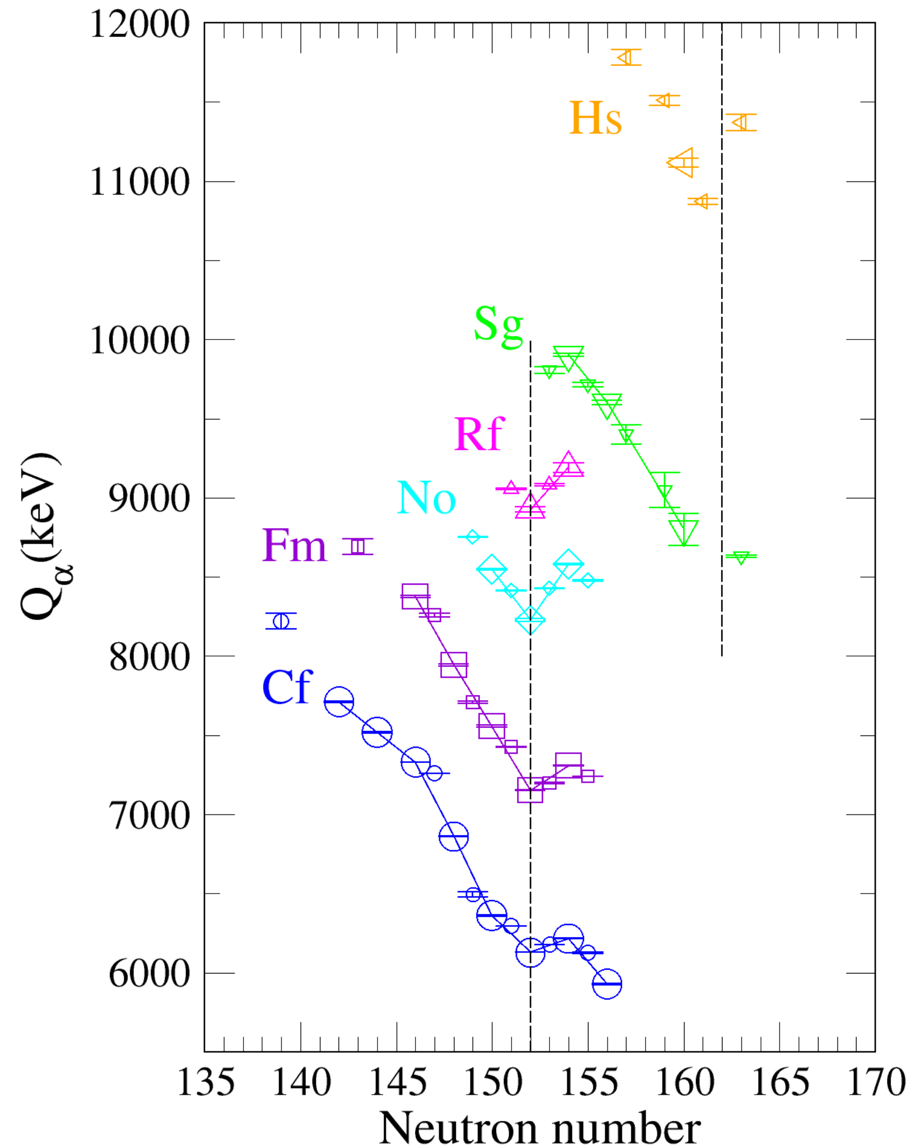



pletion in the process of the filling of levels in the simple single-particle shell model may be an oversimplification because this is just the region where the strong surface coupling caused by large spheroidal distortion[10–13] or configuration interaction[14–18] of several nucleons may be important. In this connection one might expect on the basis of either the Bohr-Mottelson[12] strong surface coupling model or the de-Shalit-Goldhaber[15] configuration interaction arguments regarding trends of first excited state energies, that if the nucleon configuration at $N=152$ involves only completely filled levels, the first excited state energies should approach a maximum as is observed in the closing of other shells[19–21]; the experimental evidence so far indicates that this is not the case.[4,22] Thus it seems that the 152-neutron subshell may be of a fundamentally different nature than the major closed shells.

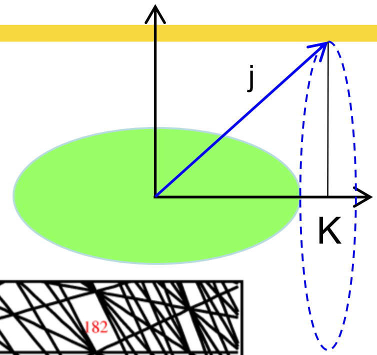
PR 95 (1954) 293

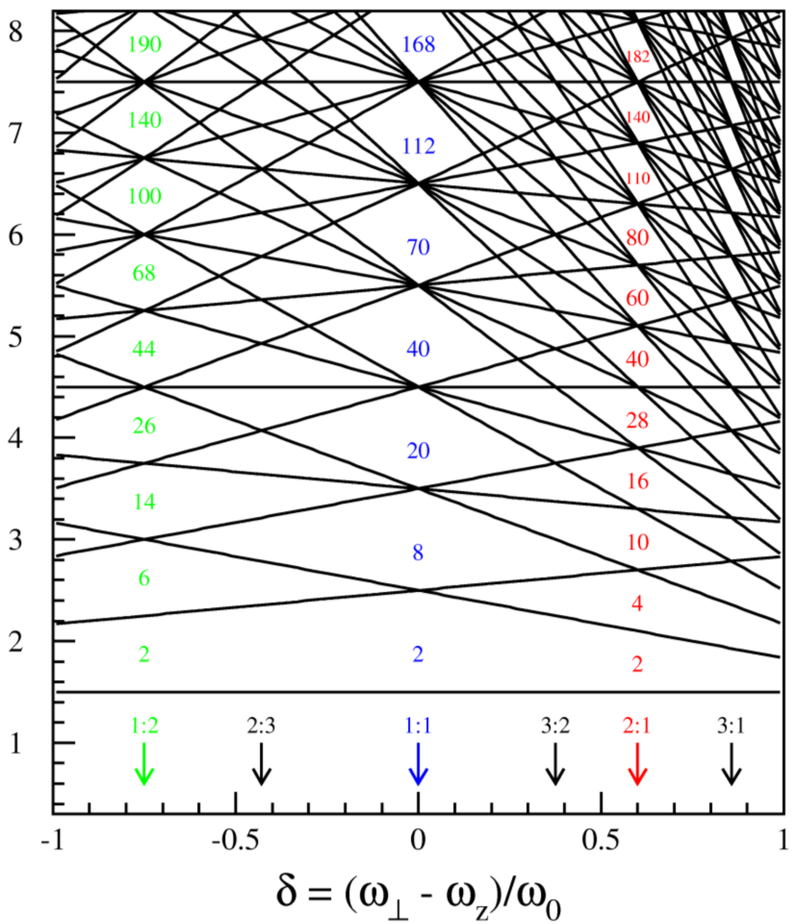
# α-decay energies

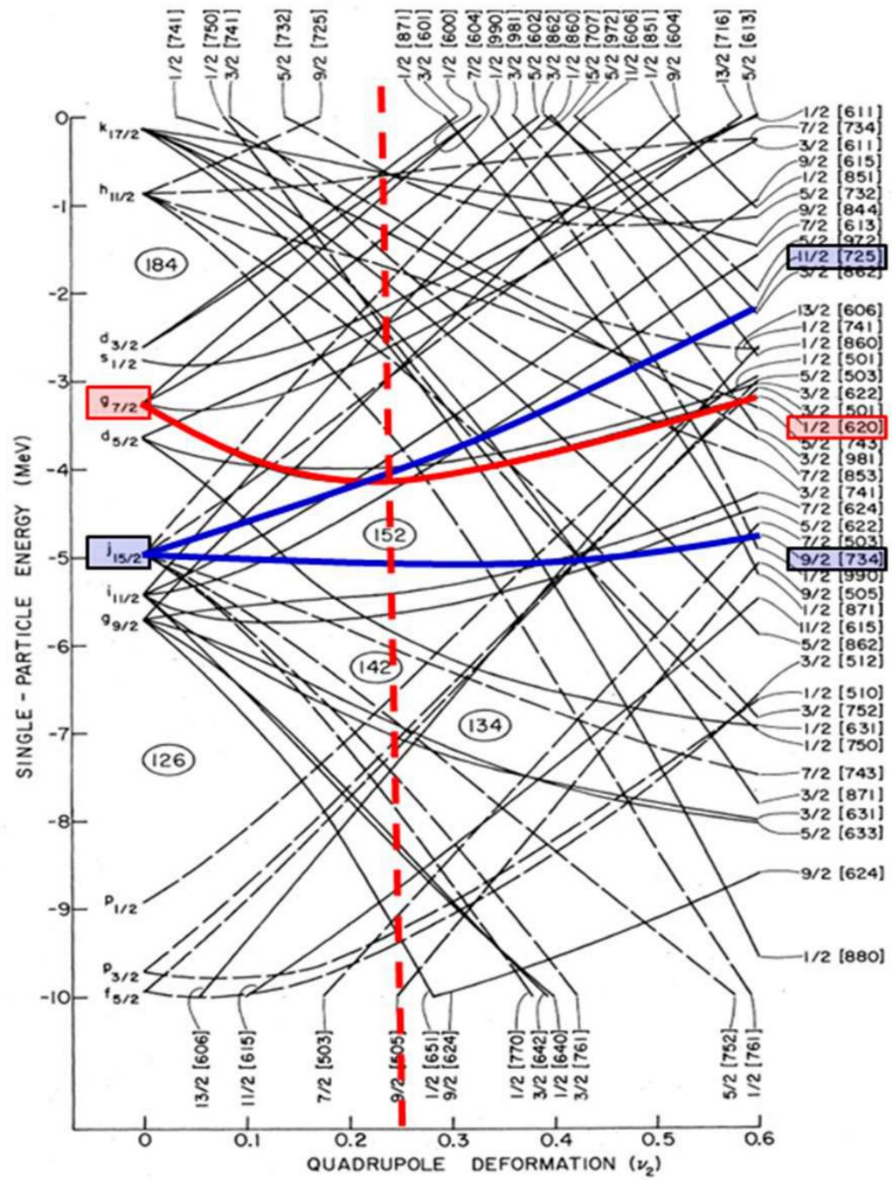


# Harmonic oscillator → Nilsson Model



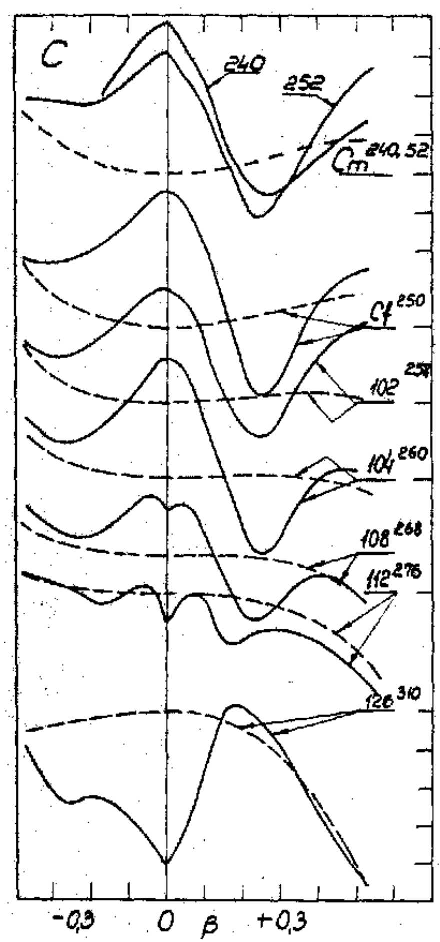



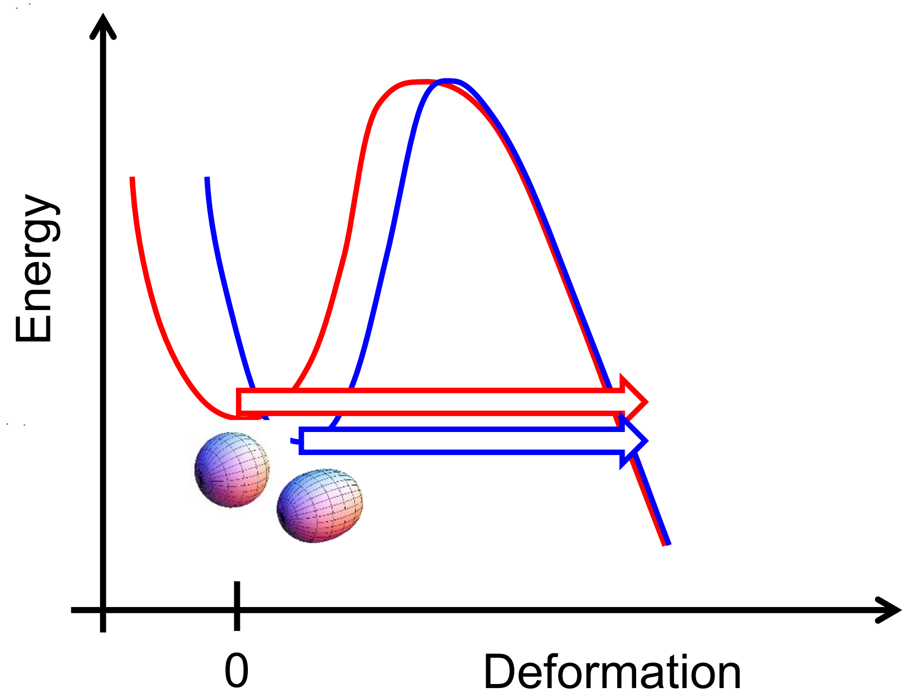

Chasman et al. Rev. Mod. Phys. 49 (1977) 833

# The Strutinsky method

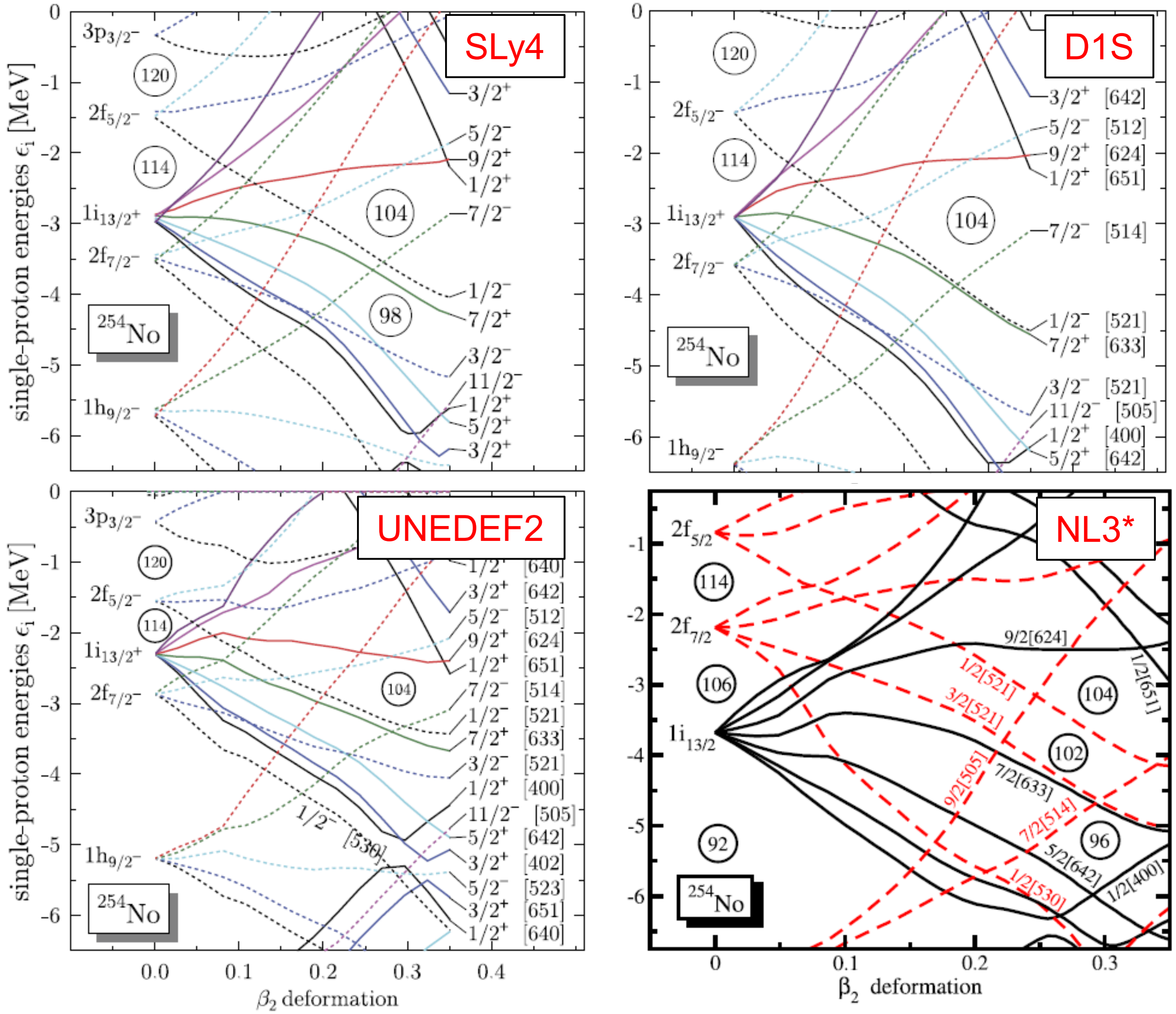
Energy = macroscopic + shell correction. NPA 95 (1967) 420



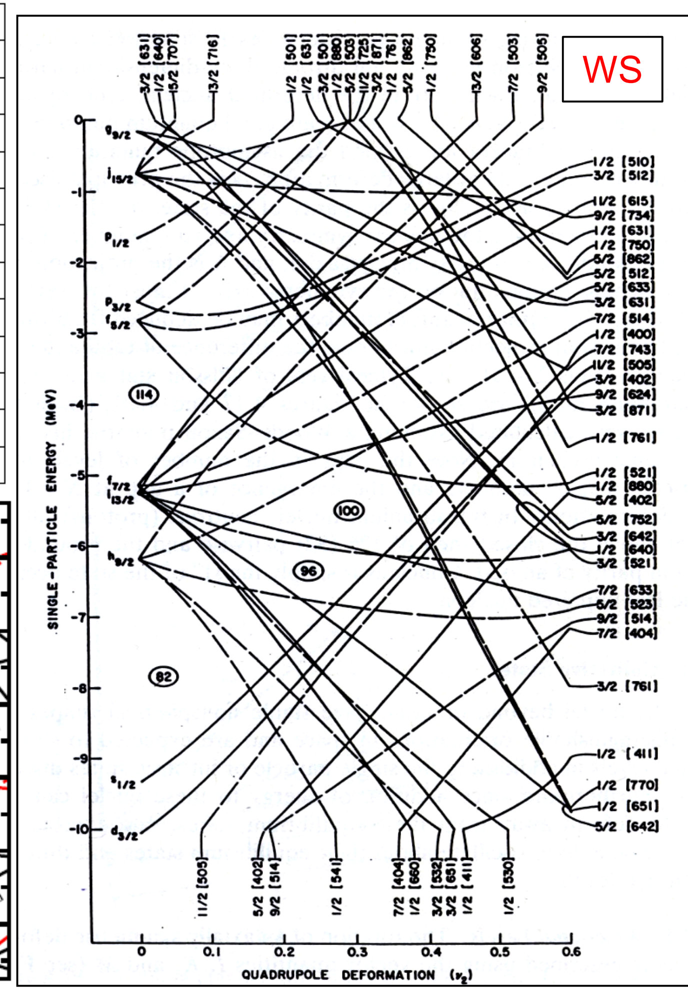

Consequence on fission lifetimes:
Deformed vs spherical nucleus → shorter fission lifetime for the same barrier height



# Predictions around $^{250}$Fm Z=100, N=152

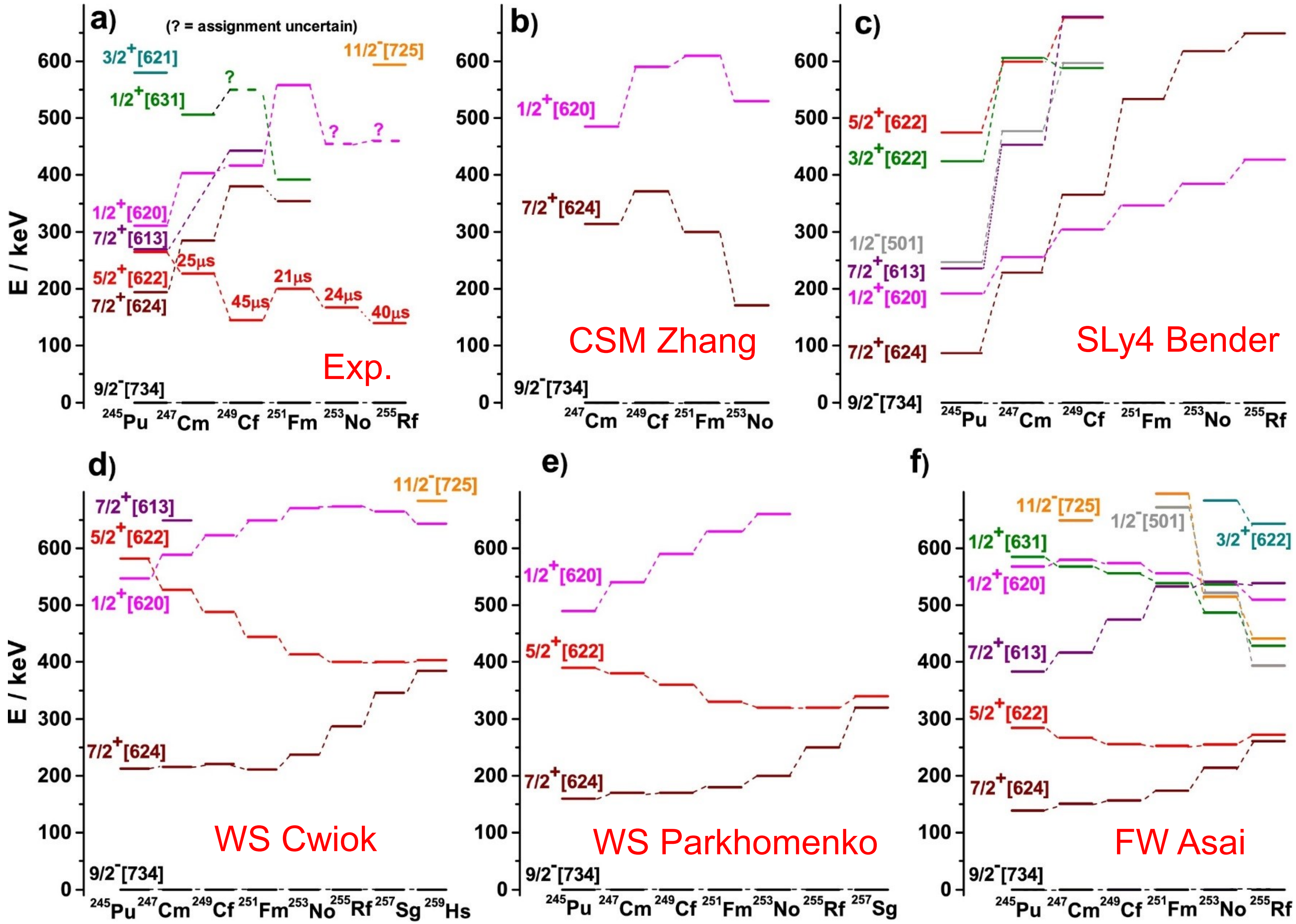



Dobaczewski et al. NPA 944 (2015) 388




R.R. Chasman et al.,
Rev. Mod. Phys. 49, 833 (1977)

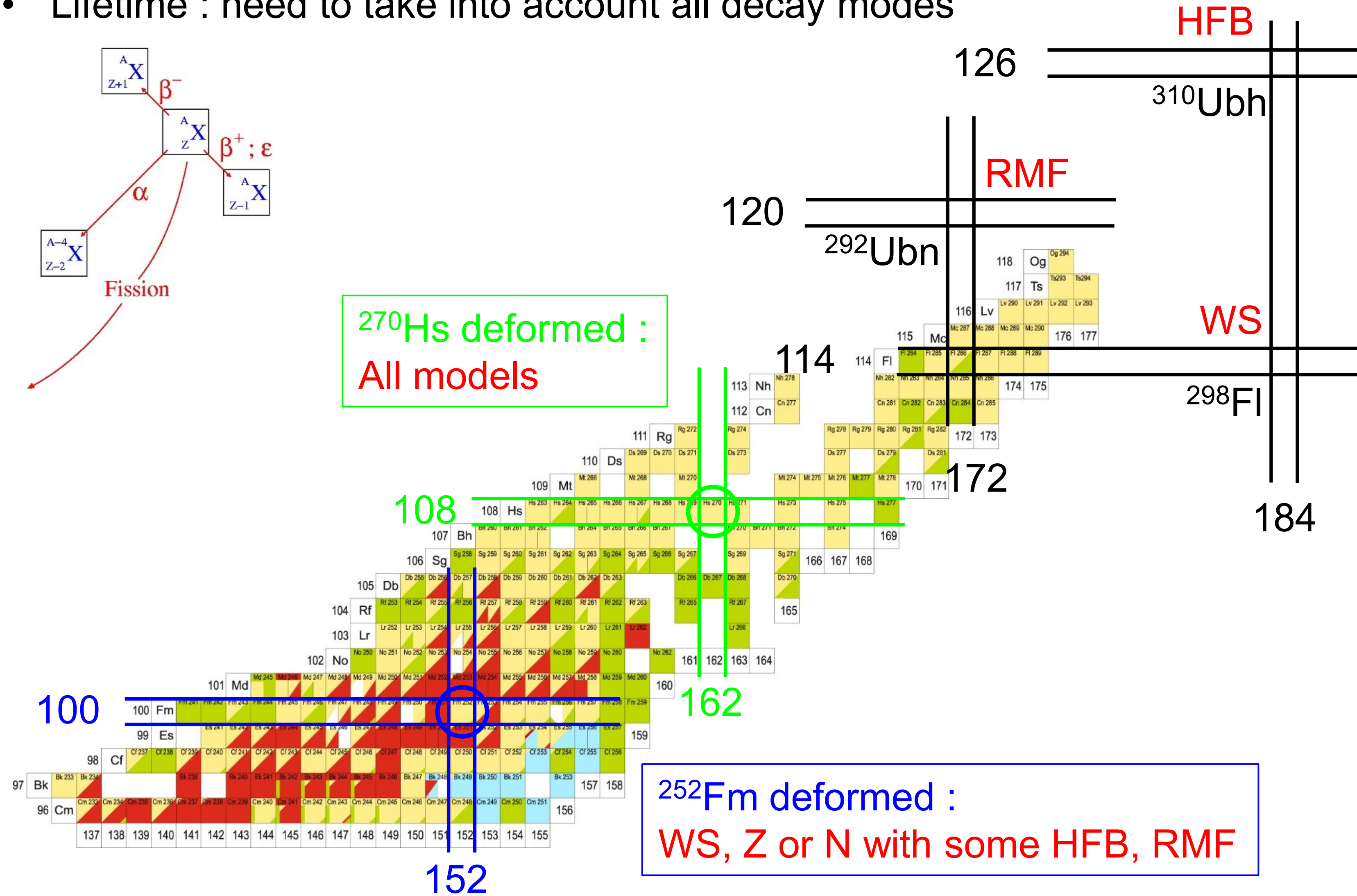
# Spectroscopic data vs theory. N=151




Asai et al. NPA 944 (2015) 308

# Where is the island of stability ?

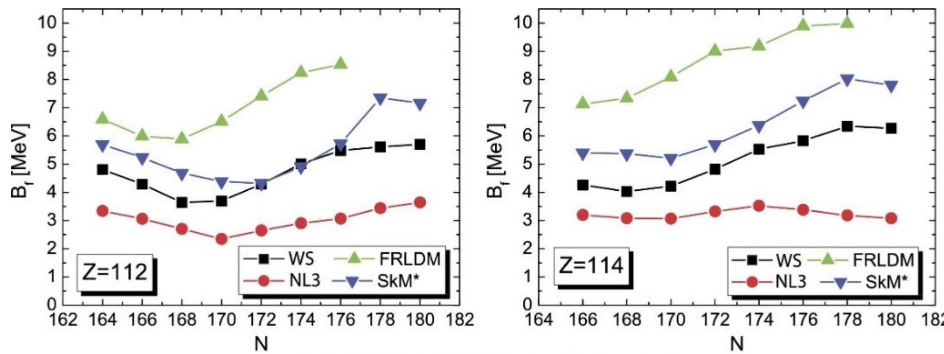
- Shell corrections : disagreement between models (even around $^{252}$Fm)
- Lifetime : need to take into account all decay modes



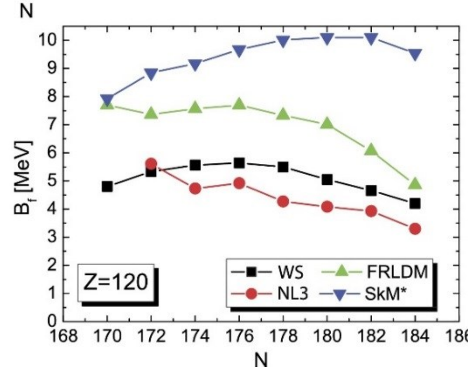
# Fission

Fission lifetime calculation : a tremendously difficult task.

1: Which model for shell corrections : phenomenological WS – MHO, effective forces Skryme or RMF ?




(Remember lifetime is ~ an exponential function of the fission barrier)




Baran et al.
NPA 944 (2015) 442

2: nuclei explores several degrees of freedom before reaching the saddle point.

3 : fission is a dynamical process; calculation of static energy potentials is not enough.

# Mendelevium

https://www.youtube.com/watch?v=DrssJRb301k

# Mendelevium

## New Element Mendelevium, Atomic Number 101*

A. Ghiorso, B. G. Harvey, G. R. Choppin, S. G. Thompson, and G. T. Seaborg

*Radiation Laboratory and Department of Chemistry, University of California, Berkeley, California*

(Received April 18, 1955)

We have produced and chemically identified for the first time a few atoms of the element with atomic number 101. Very intense helium ion bombardments of tiny targets of $99^{253}$ have produced a few spontaneously fissionable atoms which elute in the *eka*-thulium position on a cation resin column.

$^{253}Es(\alpha,n)^{256}Md$ target ~ $10^9$ atoms, Iα ~ $10^{14}$ pps, 17 spontaneous fission detected

Last element identified after chemical separation

For heavier elements, breakthroughs needed :

- drop of the cross-section and lifetime
- heavy ion beam needed
- more efficient « physical » separation needed

# Mendelevium

## New Element Mendelevium, Atomic Number 101*

A. Ghiorso, B. G. Harvey, G. R. Choppin, S. G. Thompson, and G. T. Seaborg

*Radiation Laboratory and Department of Chemistry, University of California, Berkeley, California*

(Received April 18, 1955)

We have produced and chemically identified for the first time a few atoms of the element with atomic number 101. Very intense helium ion bombardments of tiny targets of $99^{253}$ have produced a few spontaneously fissionable atoms which elute in the *eka*-thulium position on a cation resin column.

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Last element identified after chemical separation

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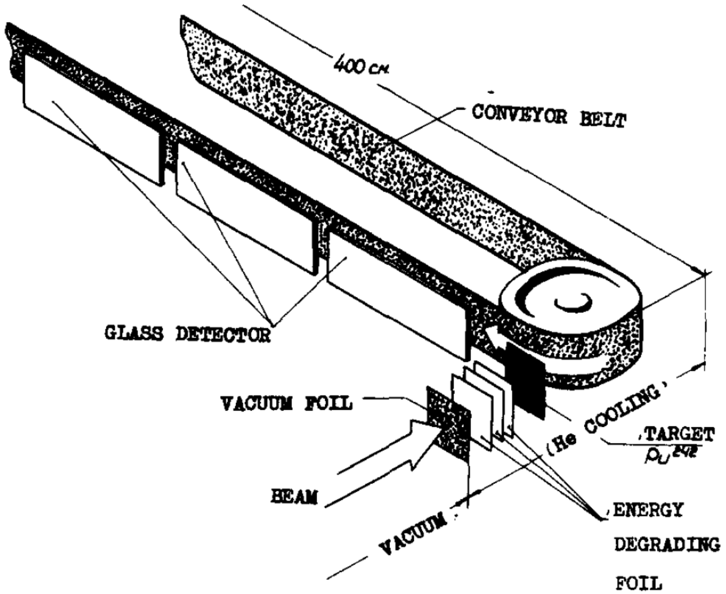
- drop of the cross-section and lifetime
- heavy ion beam needed
- more efficient « physical » separation needed

# The Rf (Z=104) example - Dubna


1964 : G.N. Flerov *et al.*, Dubna
Phys. Lett. 13 (1964) 73
$^{242}Pu(^{22}Ne,4n)^{260}104$
Detection of spontaneous fission using a conveyor belt system
Fission detector = glass detector: fission tracks measured offline
Spatial distribution of track : implantation-decay correlation and → lifetime
Measurement of a 0,3 s fission activity attributed to $^{260}104$
(however incorrect interpretation)



# The Rf (Z=104) example - Berkeley

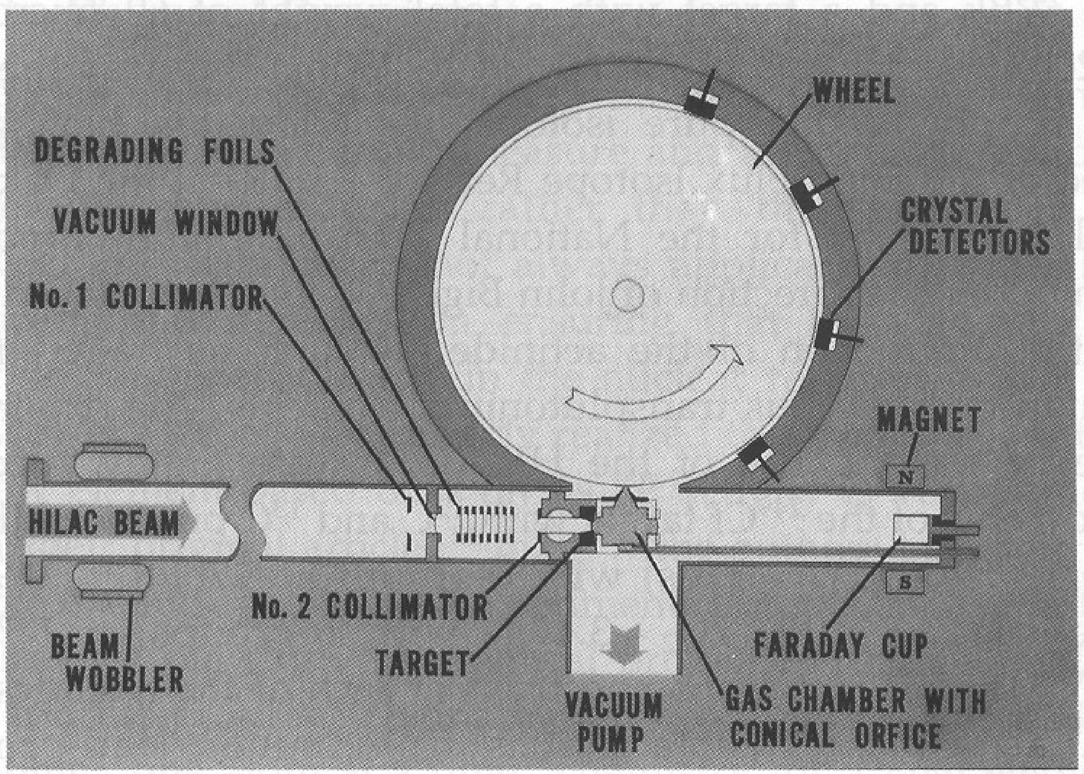
The Ghiroso Vertical Wheel.

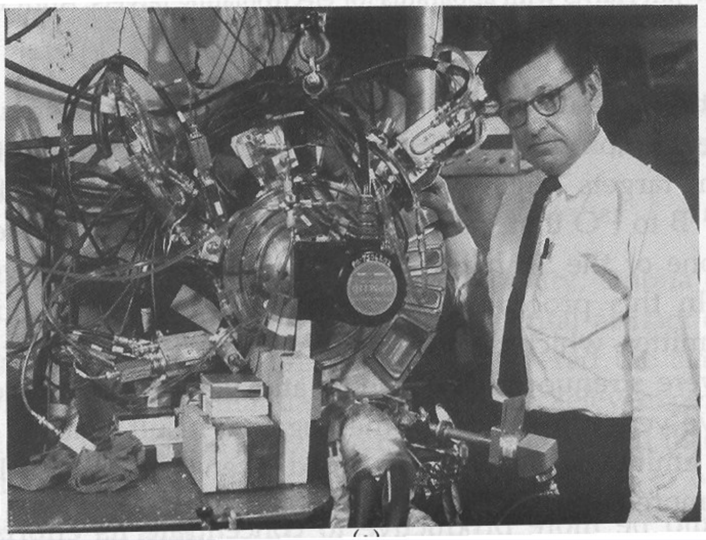
$^{249}Cf + ^{12,13}C \rightarrow ^{257,259}Rf \rightarrow No$

Parent-daughter correlations : genetic correlations

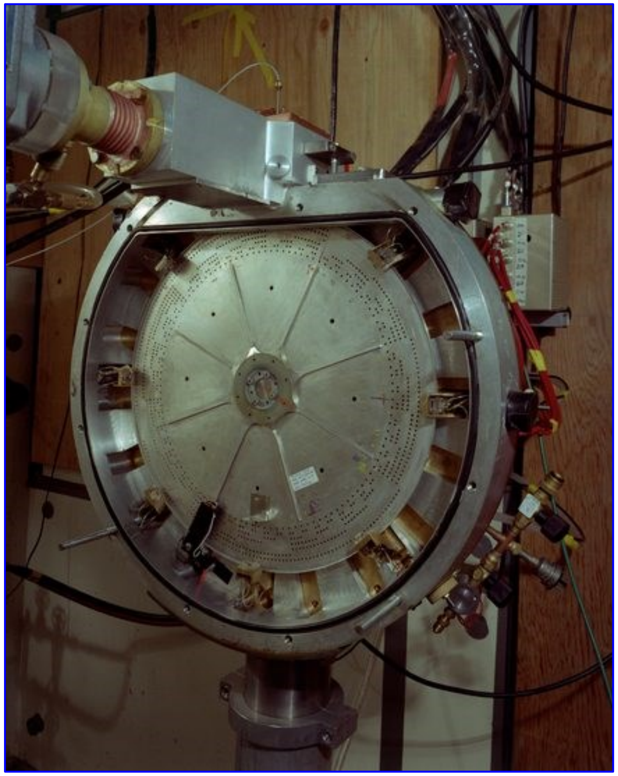
Detection using Si detectors.

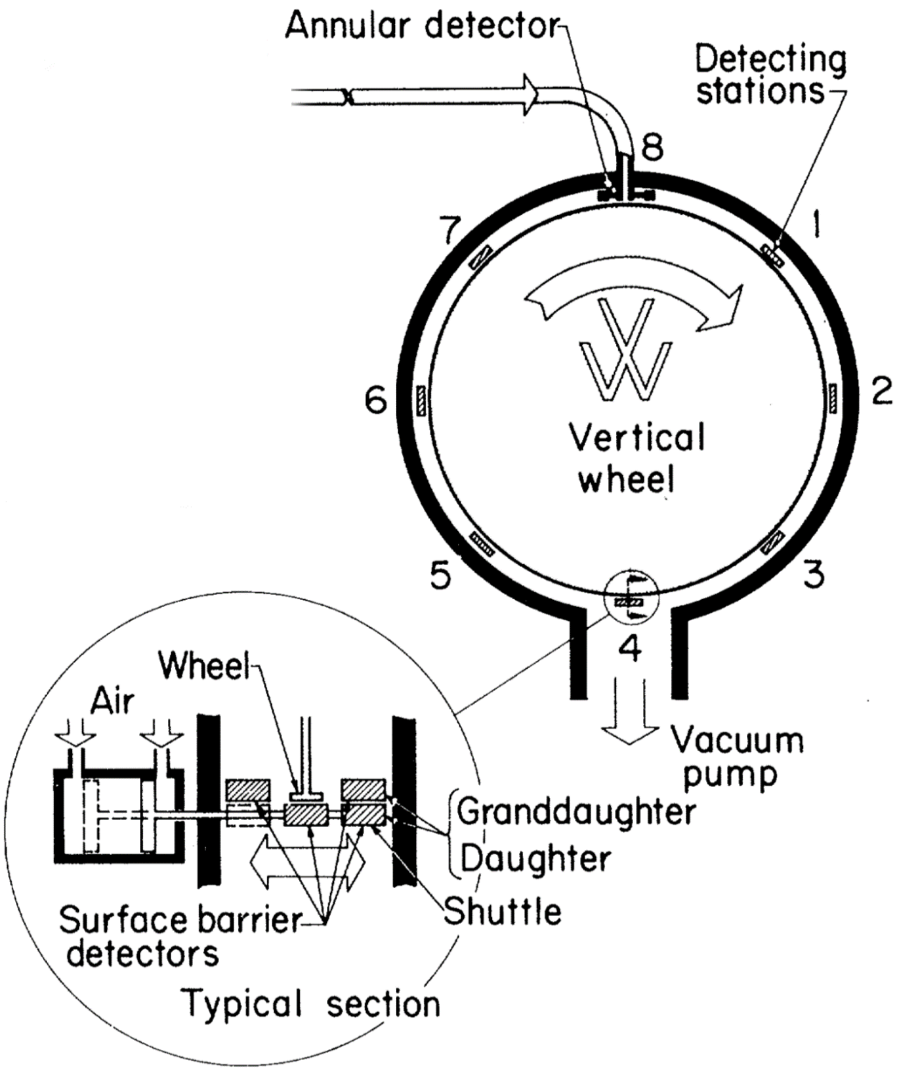
PRL 22 (1969) 1317



# The VW in detail



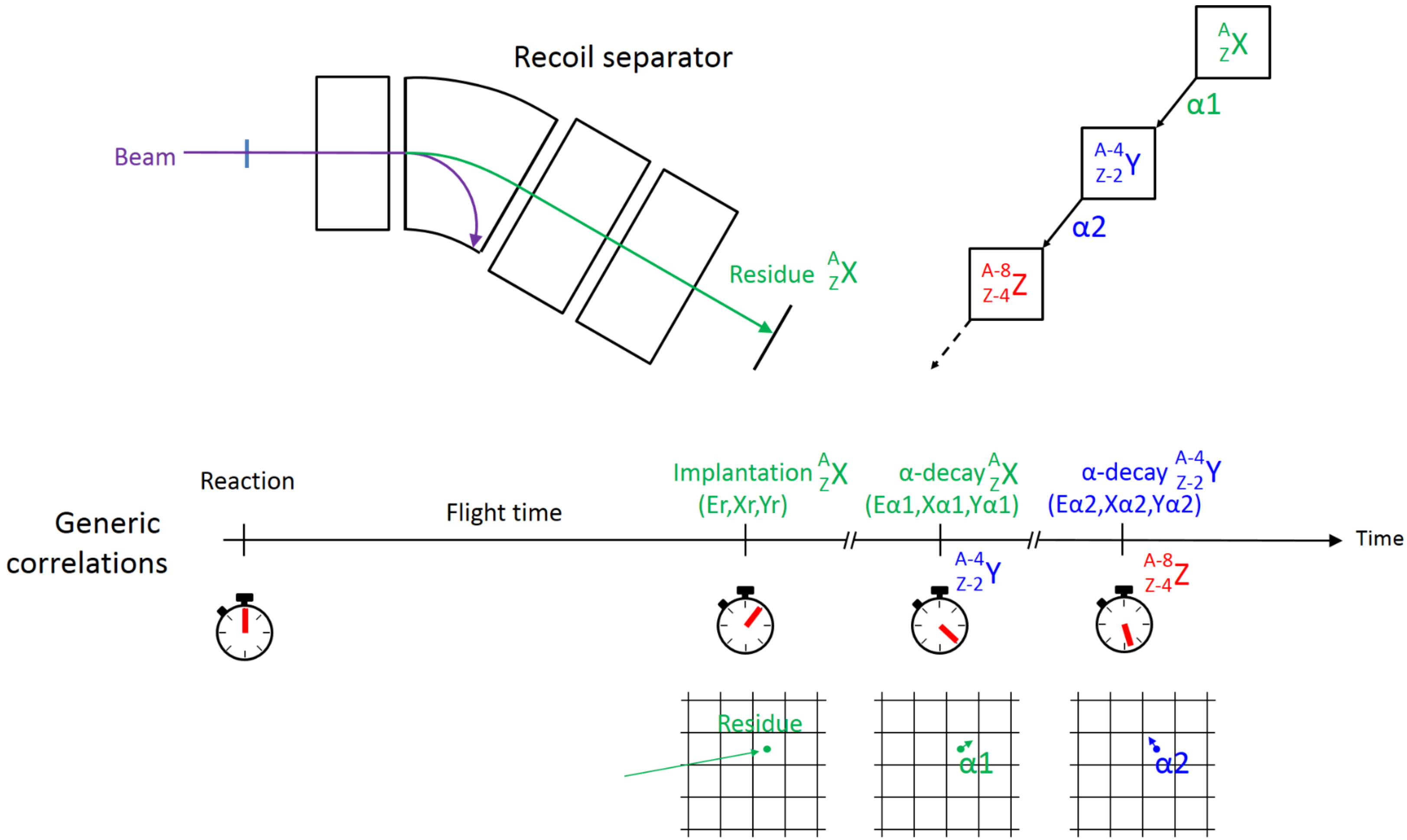



Variant using the gas-jet technique
(used for the discovery of Sg Z=106)
PRL 33 (1974) 1490

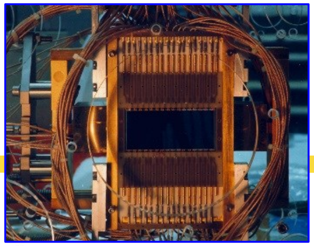
# Modern view of genetic correlations



Requirement: recoil at the detection station with as little as possible contaminants (direct or scattered beam, scattered target, unwanted reaction channels) → use of a recoil separator

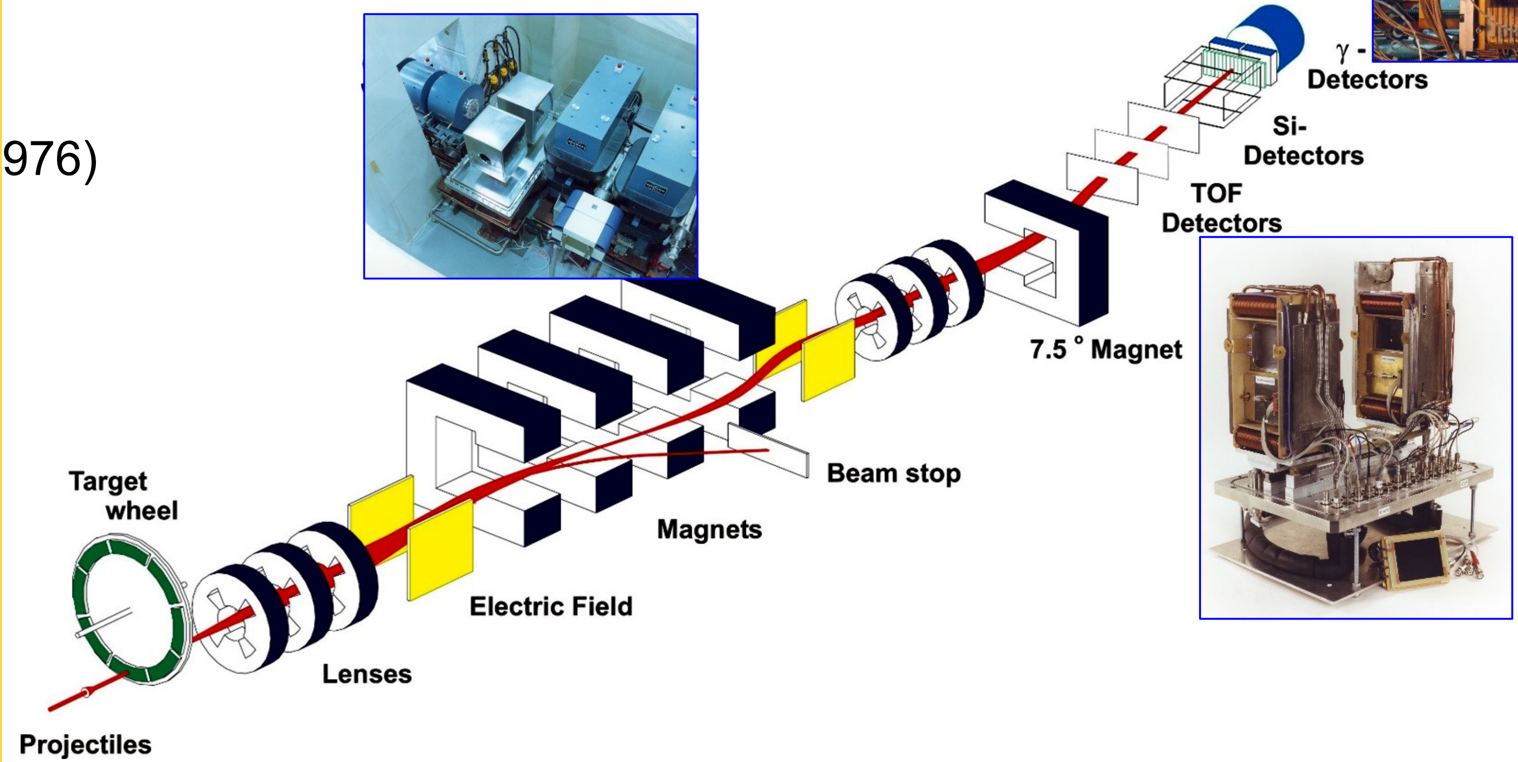


# Separator : SHIP



universite PARIS-SACLAY

SHIP (1976)




SHIP, GSI. Principle = velocity filter.
Typical transmission for Ca+Pb reaction : ~ 30 %
Discovery of Z=107-112
by S. Hofmann, G. Münzenberg et al

G. Münzenberg

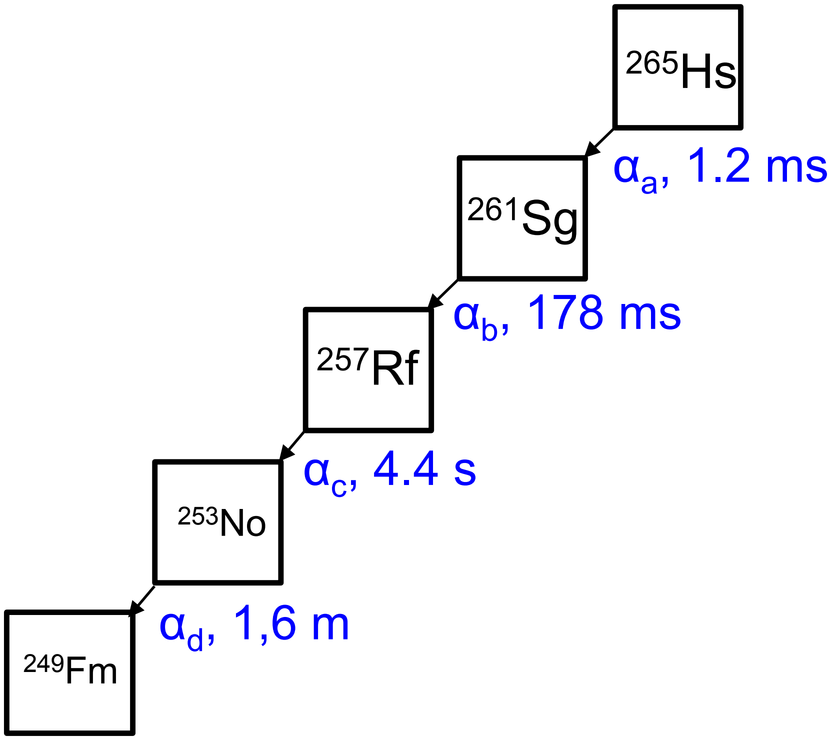
S. Hofmann

# $_{107}Bh$, $_{108}Hs$, $_{109}Mt$, $_{110}Ds$, $_{111}Rg$, $_{112}Cn$

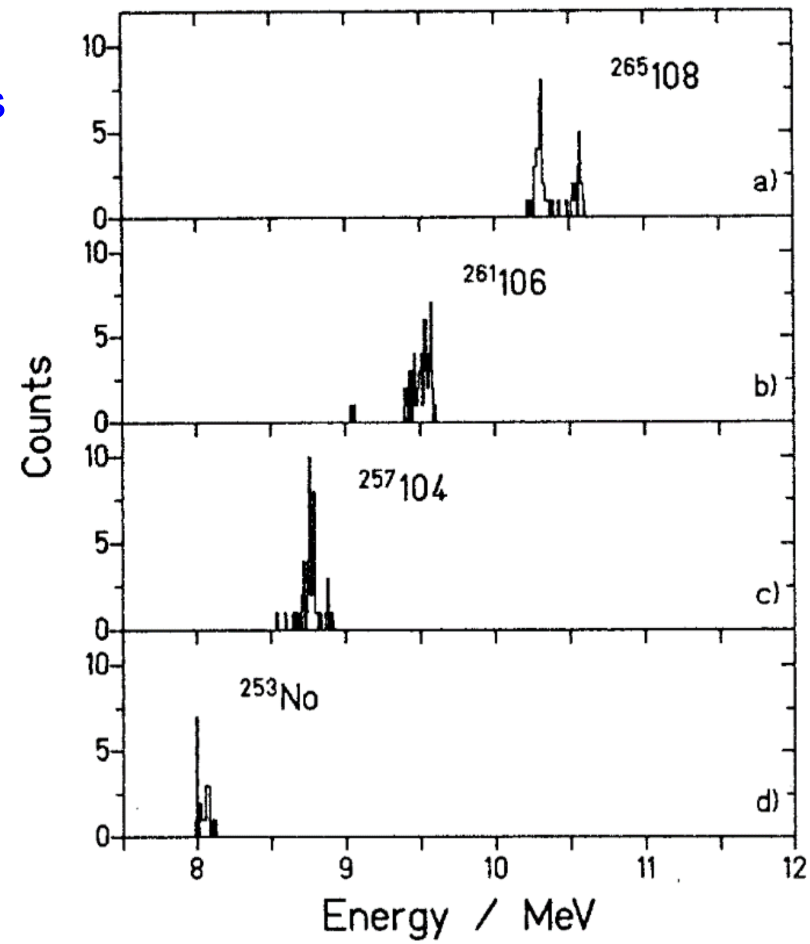
70th : G.S.I.; S.H.I.P. (P. Ambruster); 1975 : first UNIversal Linear ACcelerator beam

- 1981 $_{107}Bh$ (G. Münzenberg *et al.* ZPA 300 (1981) 107)
  $^{209}Bi(^{54}Cr,1n)^{262}Bh \rightarrow {}^{258}Db \rightarrow \ldots \rightarrow {}^{250}Fm$
- 1982 $_{109}Mt$ (G. Münzenberg *et al.* ZPA 309 (1982) 89)
  $^{209}Bi(^{58}Fe,1n)^{266}Mt \rightarrow {}^{262}Bh \rightarrow {}^{258}Db$
- 1984 $_{108}Hs$ (G. Münzenberg *et al.* ZPA 318 (1984) 235)
  $^{208}Pb(^{58}Fe,1n)^{265}Hs \rightarrow {}^{261}Sg \rightarrow {}^{257}Rf$
- 1994 $_{110}Ds$, $_{111}Rg$ (S. Hofmann *et al.)*
  $^{208}Pb(^{62}Ni,n)^{269}Ds \rightarrow {}^{265}Hs \rightarrow \ldots$ ZPA 350 (1995) 277
  $^{209}Bi(^{64}Ni,n)^{272}Rg \rightarrow {}^{268}Mt \rightarrow \ldots$ ZPA 350 (1995) 281
- 1996 $_{112}Cn$ (S. Hofmann *et al.* ZPA 354 (1996) 229)
  $^{208}Pb(^{70}Zn,1n)^{277}Cn \rightarrow {}^{273}Ds \rightarrow \ldots$

# Example of genetic correlations



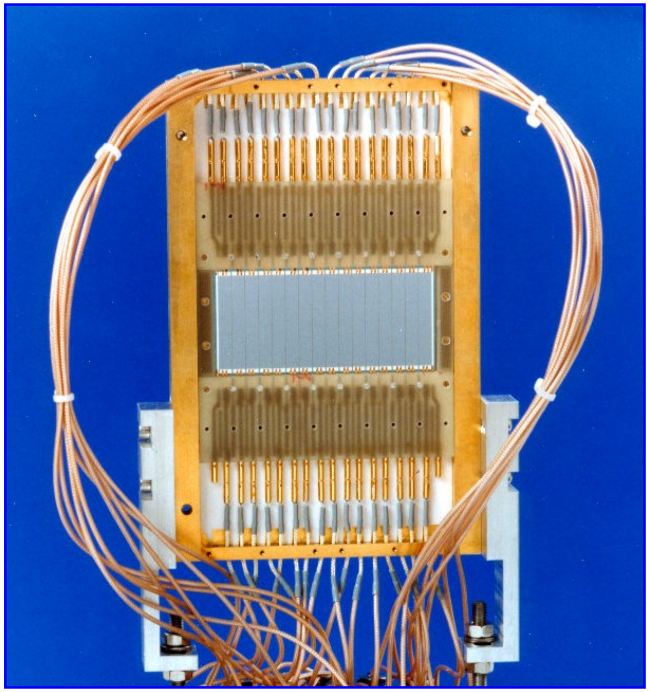

$^{208}$Pb($^{58}$Fe,1n)$^{265}$Hs, $\sigma$~65 pb




Position sensitivity of the implantation detector needed : total counting rate much larger than Implantation decay rate

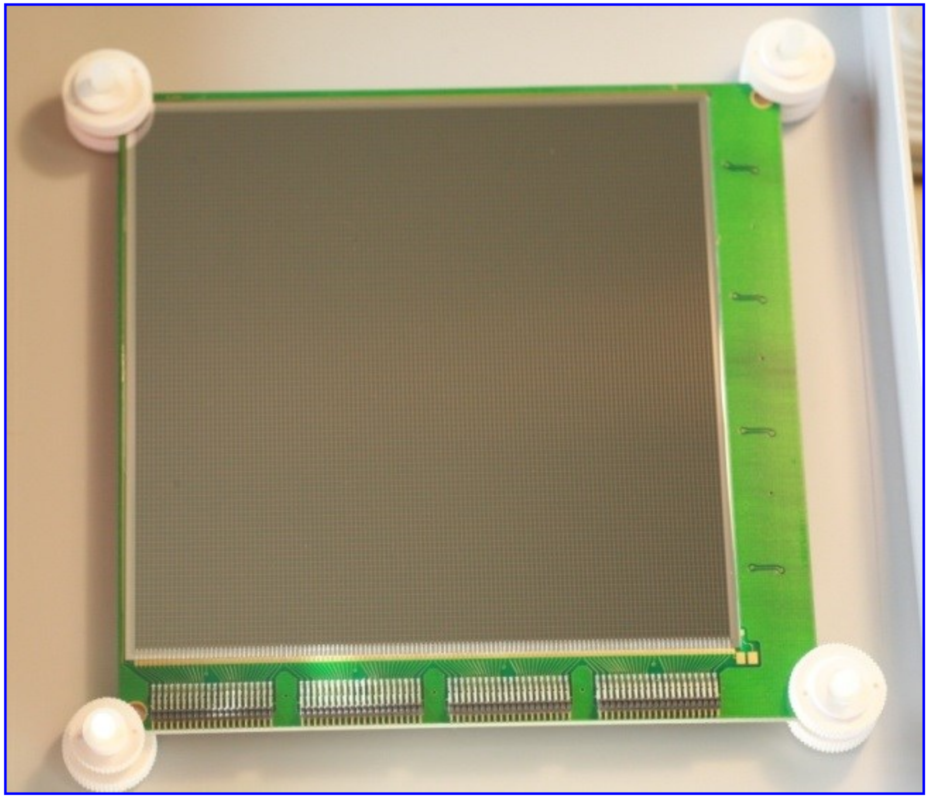
Hofmann et al., ZPA 350 (1995) 277

# Position sensitive Si detectors



1980 's : position sensitivity
= strips + charge division
eg SHIP (picture), RITU

DSSD = Double-sided Silicon Strip Detector
used in most modern focal plane detectors



Si detector for VAMOS & S3 (GANIL),
SHELS (Dubna)
10x10 cm$^2$, 128(X)+128(Y) strips

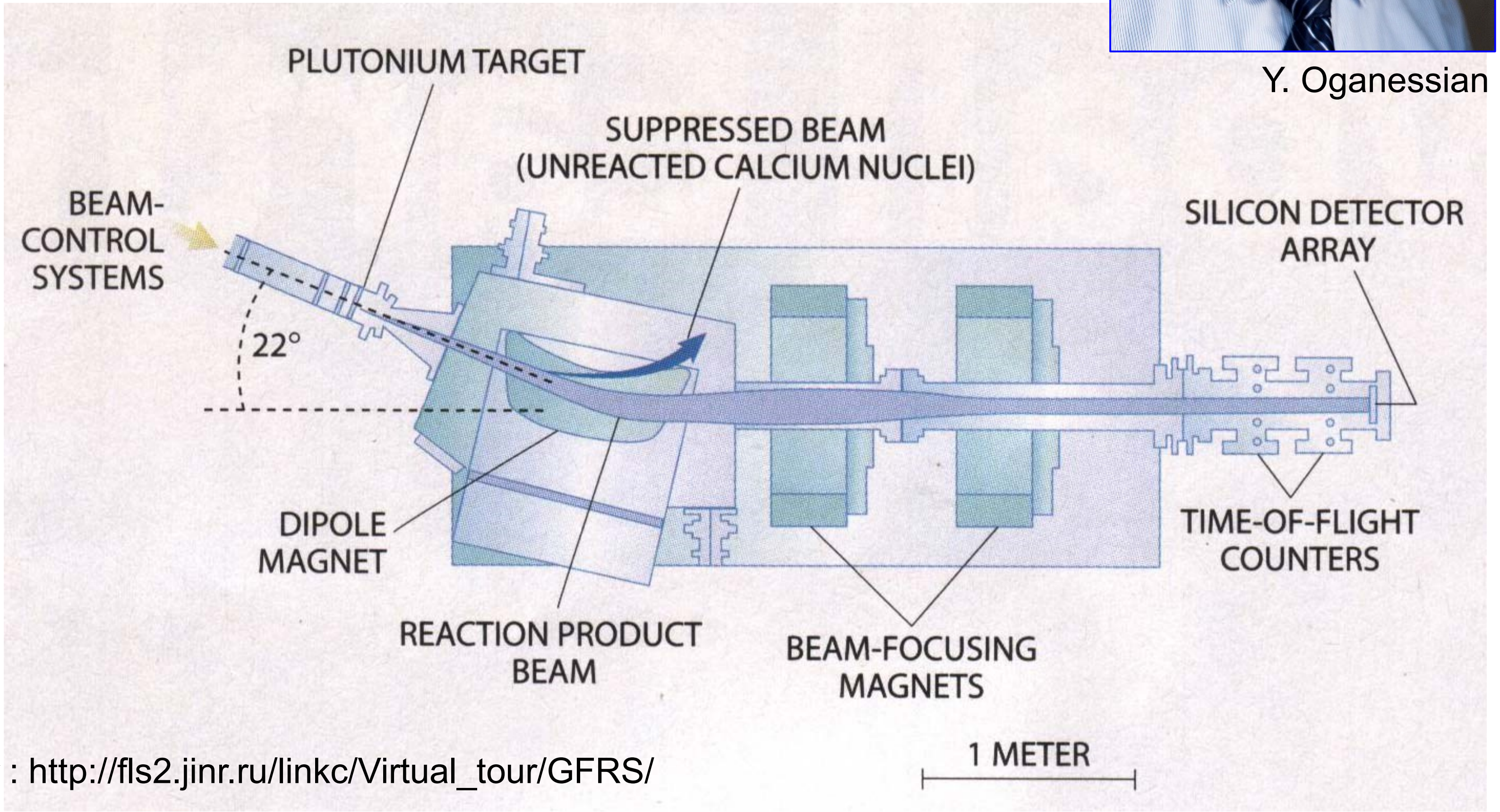
# DGFRS

DGFRS Dubna gas-filled recoil separator (1989)

Discovery of elements 114-118 by Oganessian et al.

Typical transmission for Ca+Pb : ~ 45 %

Y. Oganessian

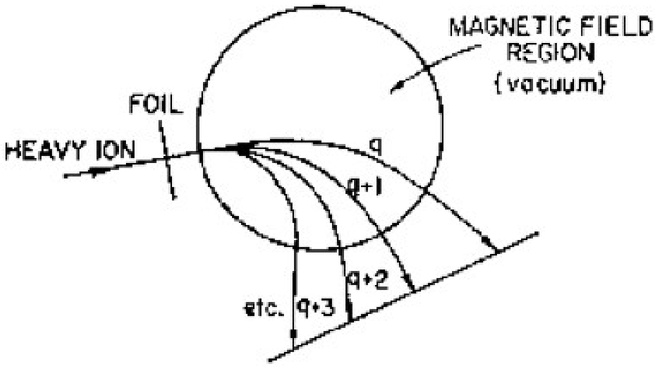



Virtual tour : http://fls2.jinr.ru/linkc/Virtual_tour/GFRS/

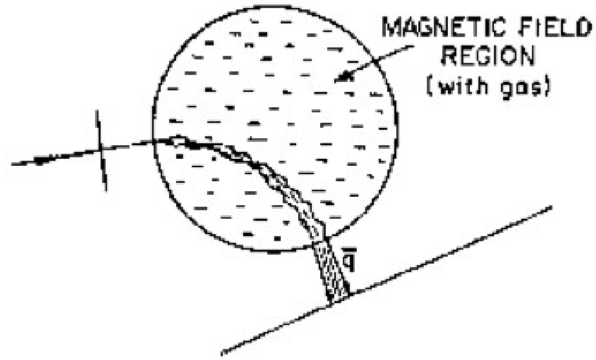
# The principle of a gas-filled separator

Ion in a magnetic field :
$B\rho = Av/q$

Charge exchange with the gas : average charge state
$\langle q \rangle = v/v_0 \, Z^{1/3}$ (Bohr)
$\rightarrow B\rho \sim A / Z^{1/3}$
→ charge state focussing
→ no velocity dependence (to first order)



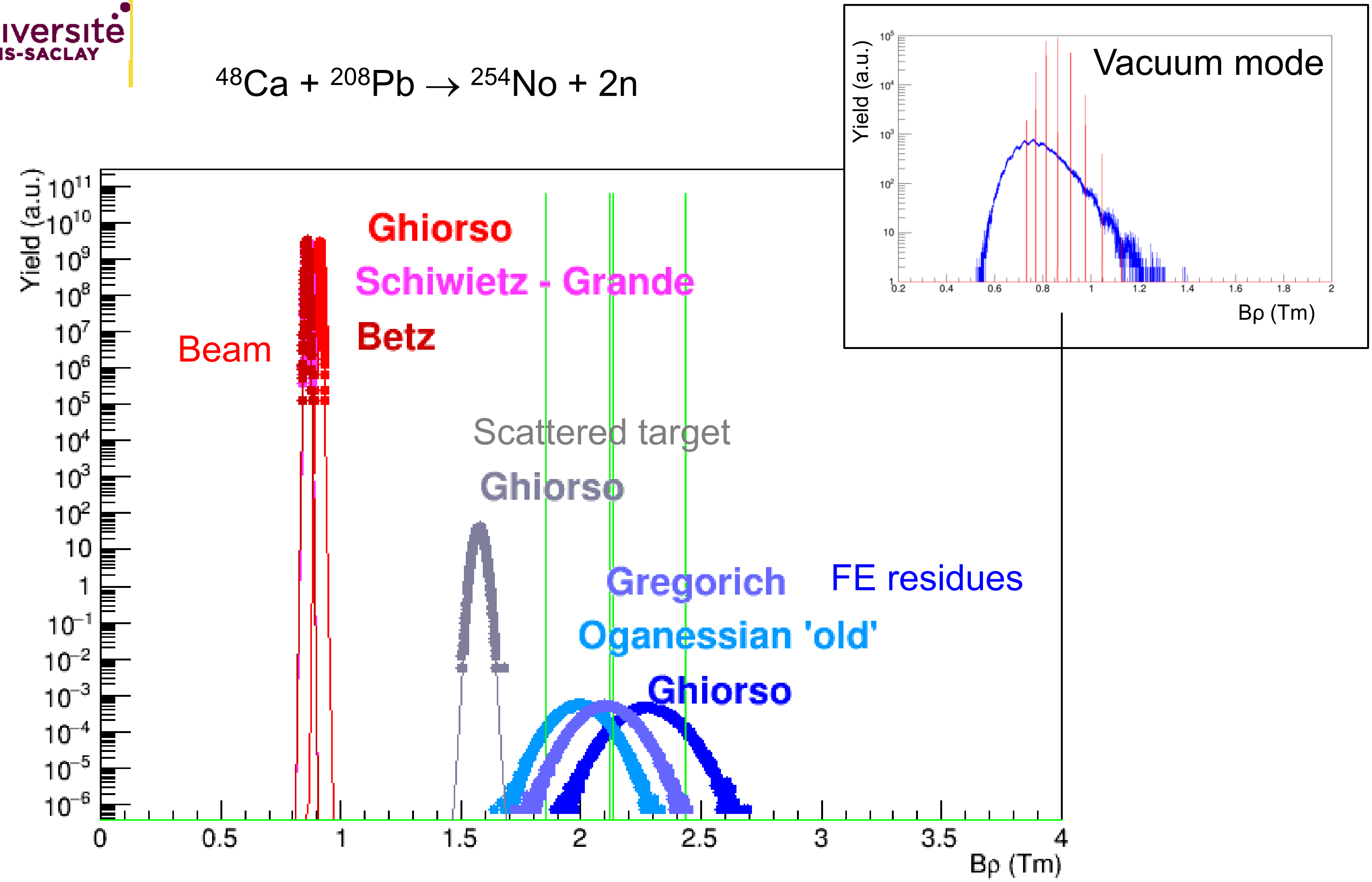

- High transmission
- Target cooling
- No mass selection
- Ion slowing down



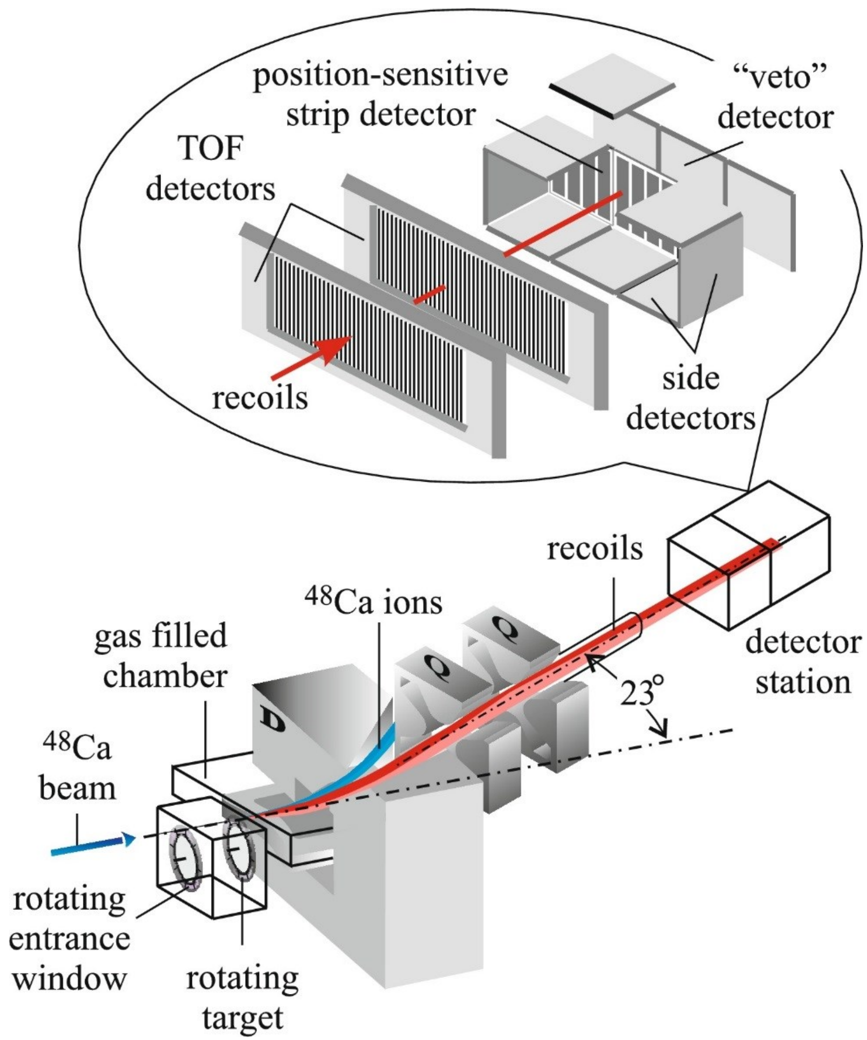

RITU (Jyväskylä), BGS (Berkeley),
DGFRS (Dubna), TASCA(GSI),
GARIS (RIKEN), SHANS (Lanzhou),
AGFA (ANL), VAMOS-GFS (GANIL soon)
He gas used in most cases

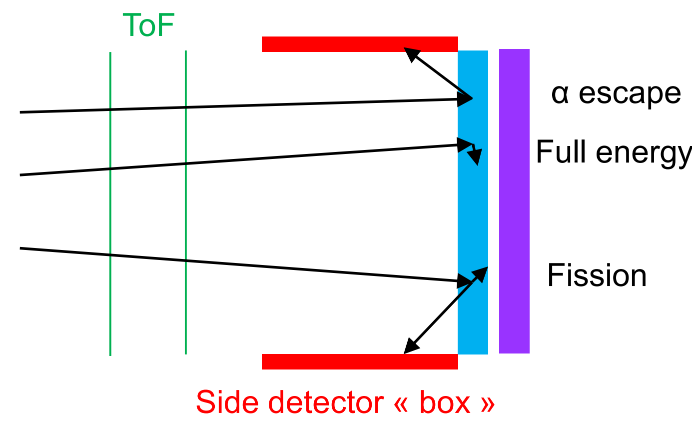
# Magnetic rigidity Bρ in He gas and vacuum

$^{48}Ca + ^{208}Pb \rightarrow ^{254}No + 2n$



# DGFRS and Z=118

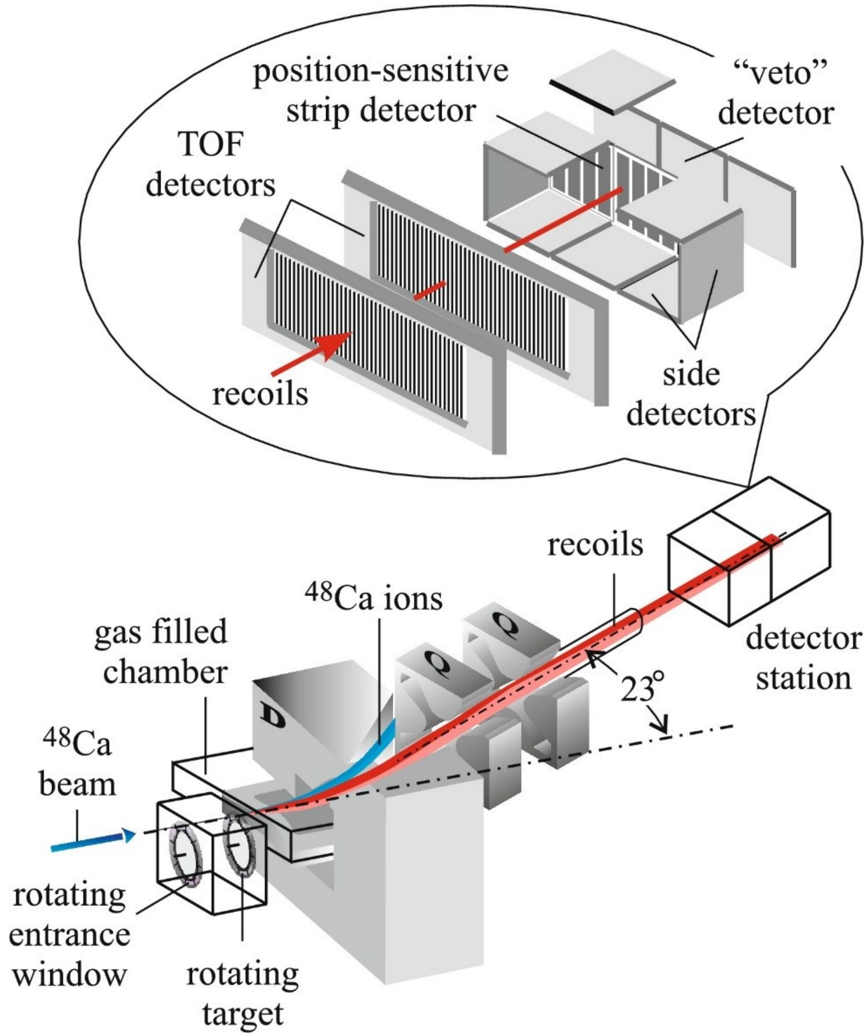



- Implantation in the strip detector (few µm depth)
- Kinematic identification (ToF, E) or (ToF, ΔE)
- « veto detector » : punch through
- Incoming detector : TOF and Si
- Decay : Si and no TOF
- Alpha decay or fission using strip detector AND side detector (veto or sum)

Oganessian, Utyonkov NPA 944 (2015) 62

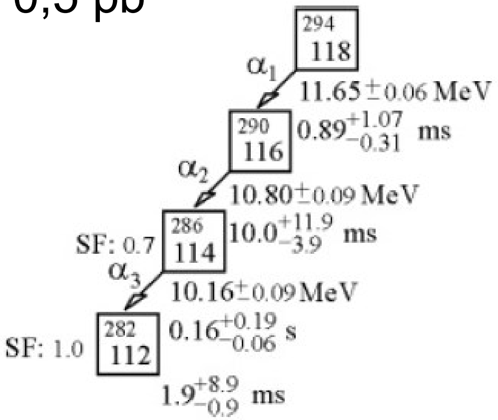
# DGFRS and Z=118




4 decay chains observed

$^{249}$Cf($^{48}$Ca,3n)$^{294}$Og

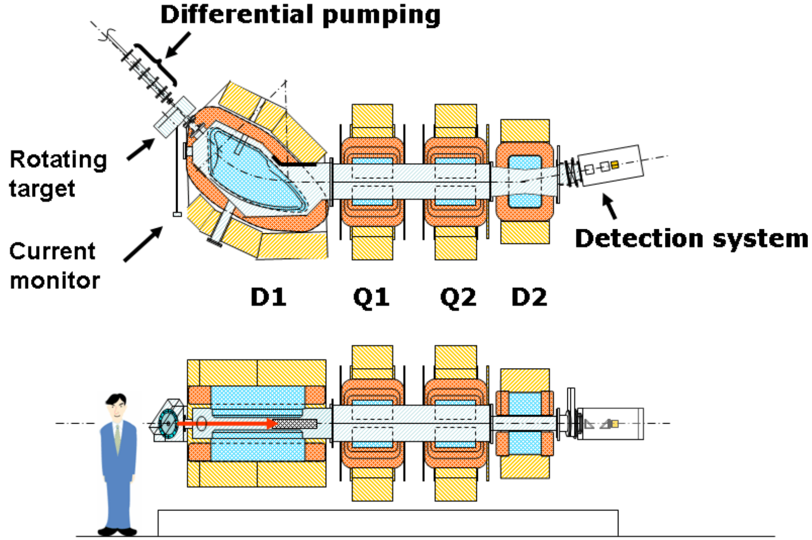
σ ~0,5 pb

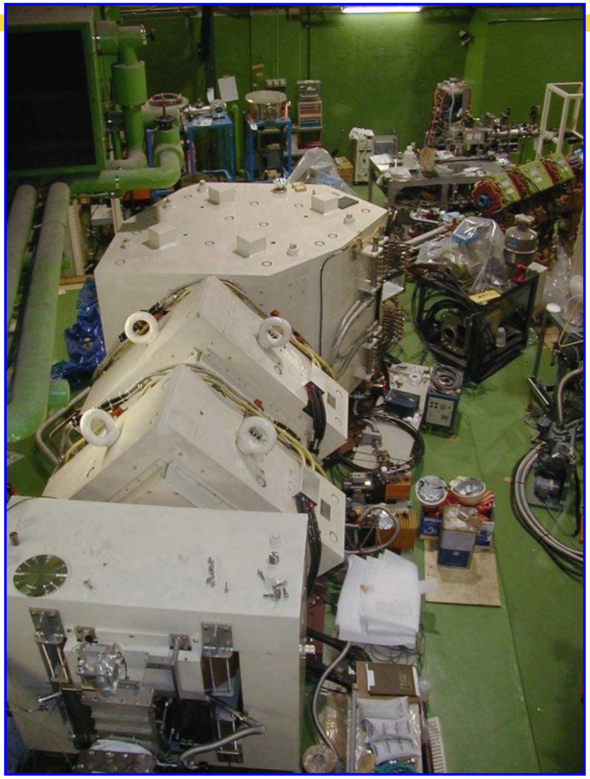


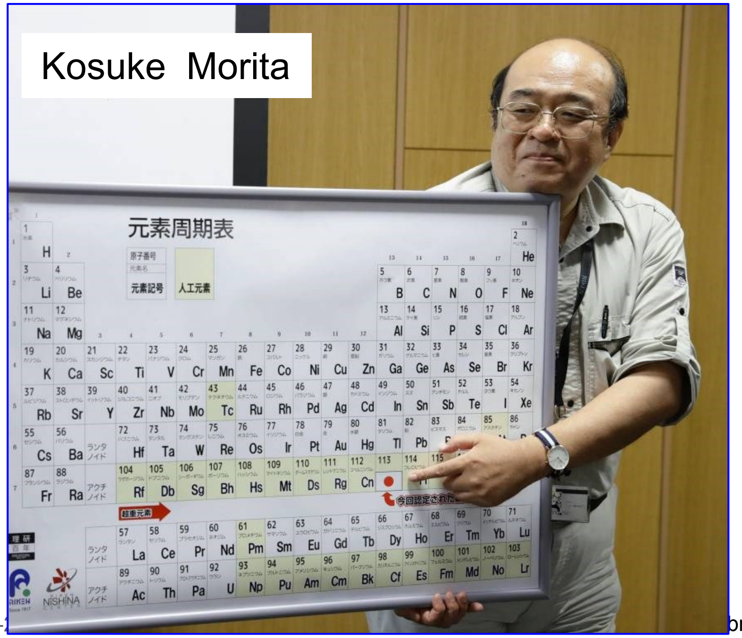

Y. Oganessian et al.
PRC 7 (2006) 044602

# GARIS, Riken

Overview of the gas-filled recoil ion separator GARIS






Discovery of Nh, Z=113

$^{209}Bi(^{70}Zn,n)^{278}Nh$ σ ~ 22 fbarn

3 events, 553 days of beam time

K. Morita et al. J. Phys. Soc. Jpn. 81 (2012) 103201

# Spectroscopy after alpha decay

Reminder probability of alpha decay.

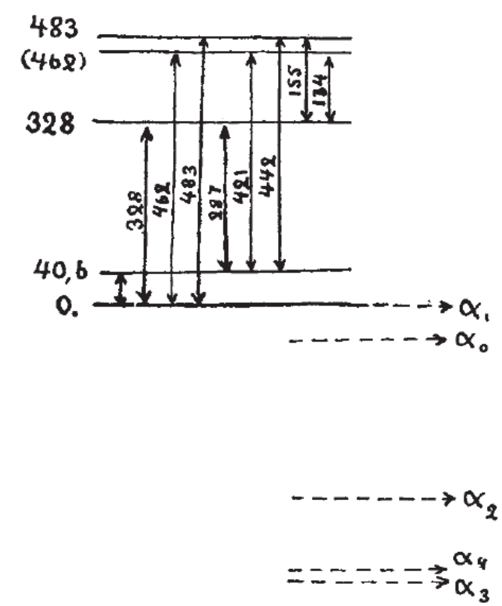
Macroscopic part :

- Decay probability increases with Z and Eα, decreases with mass and with transferred angular momentum

S. Rosenblum

Microscopic part :

- prefers states similar initial and final wave function




- Alpha decay fine structure from 'thorium C' ($^{212}$Bi discovered in 1929 by S. Rosenblum

  C. R. Acad. Sci. 188 (1929) 1401

- Interpretation by G. Gamow (using also gamma-rays from Black) as population of excited states i the daughter nucleus

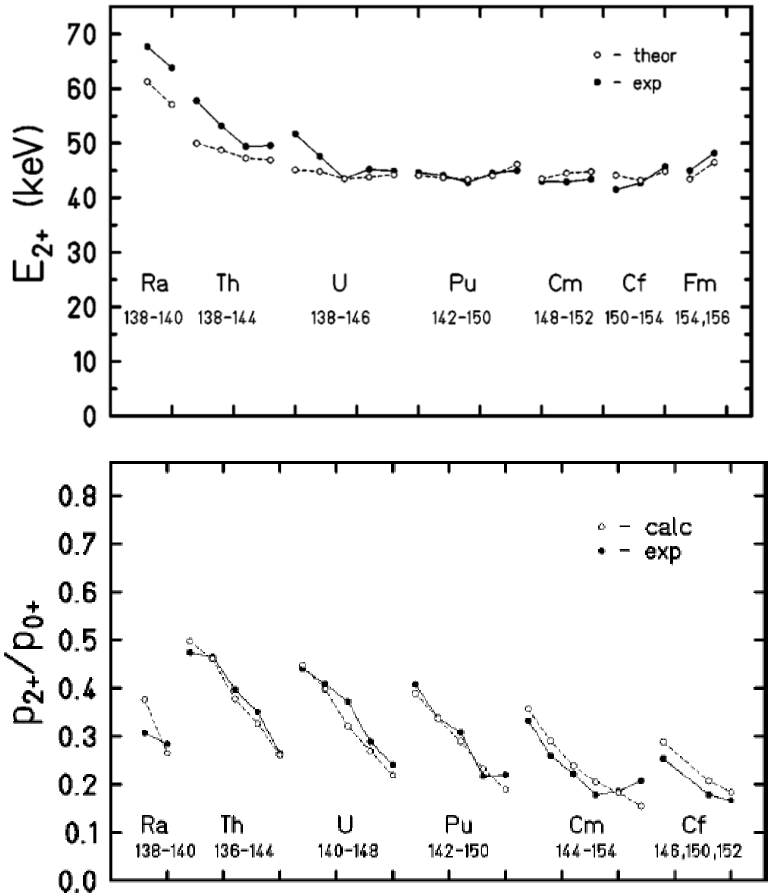
  Nature 126 (1930) 397

→ Alpha decay is a tool for spectroscopy

Gamow, Nature 126 (1930) 397

# Trivial case : α-decay in even-even nuclei

- 0+ →0+ transition favoured
- then 0+ →2+ 20-30 %




$E_{2+}$ energy

→ moment of inertia $\mathfrak{I}$

$$E(I) = \frac{\hbar^2}{2\mathfrak{I}}\, I\,(I+1)$$

→ deformation of the nucleus

However, no access to high angular momenta states

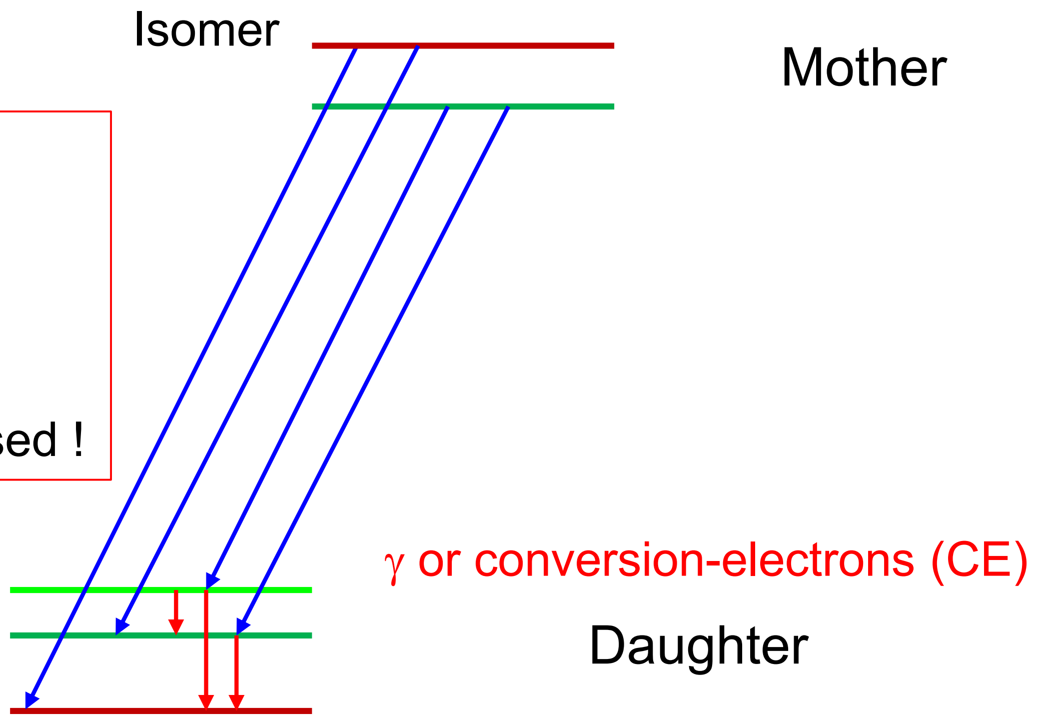
→ High-spin states prompt spectroscopy

Sobiczewski, Muntian and Patyk PRC 63 (2001) 034306

# More complex case (odd nuclei)

Odd nuclei :
In most cases the g.s. α-decay does not fed the daugther g.s.

Daughter g.s. can be missed !




Goal: deduce (at least)

- Qα
- level energies
- Spin and parity of levels (including g.s.)
    - α,γ,e- coincidences
    - Energies and multipolarities of the gamma and CE
    - Alpha decay hindrance factor

# Alpha decay hindrance factor (HF)

HF = $T_{\frac{1}{2}}(\text{exp.})$ / $T_{\frac{1}{2}}(\text{theo.}, no\ nuclear\ structure, even - even)$

$T_{\frac{1}{2}}(\text{exp.})$ = partial lifetime of the α transition

Empirical HF rules (Loveland, Morrissey and Seaborg : Modern Nuclear Chemistry, Wiley, 2005)

- HF = 1-4 : same initial and final single-particle state
- HF = 4-10 : similar initial and final states
- HF = 10-100 : different single particle states, same parity, same spin projection
- HF = 100-1000 : different single particle states, parity change, same spin projection
- HF > 1000 : different single particle states, parity change, spin flip

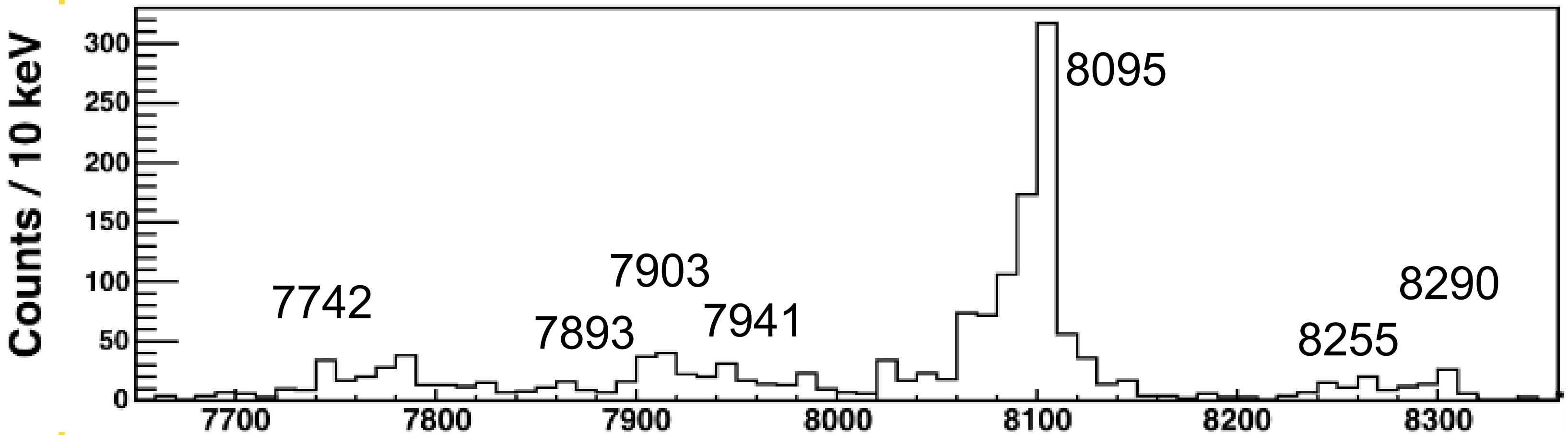
# $^{255}$No as an example

SHIP, GSI. Hessberger et al, EPJA 29 (2006) 165

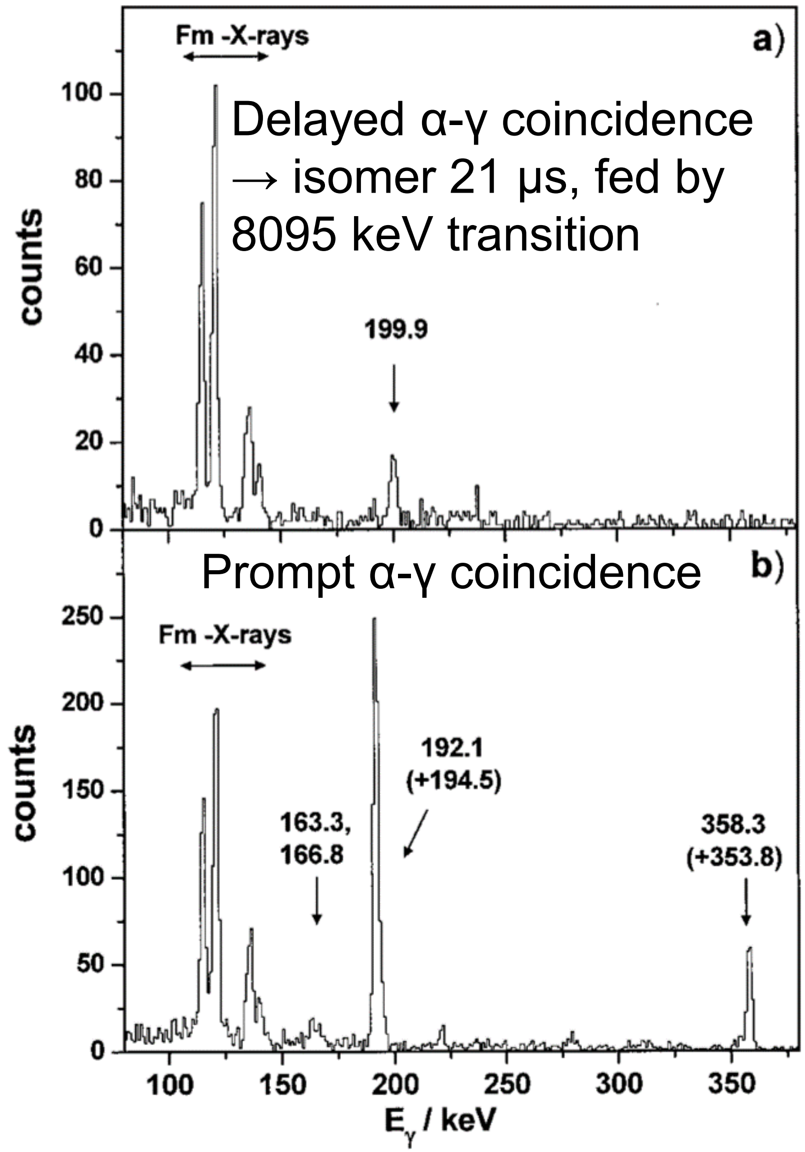
- Choice of the reaction :
  - $^{208}$Pb($^{48}$Ca,1n)$^{255}$No σ~140 nb, but contaminated by $^{208}$Pb($^{48}$Ca,2n)$^{254}$No σ~2 µb
  - $^{238}$U($^{22}$Ne,5n)$^{255}$No σ~100 nb
  - $^{209}$Bi($^{48}$Ca,2n)$^{255}$Lr → (37%) $^{255}$No σ~200 nb

Setup = Silicon strip detector 80x35 mm$^2$, 300µm thick + Ge “clover” detector

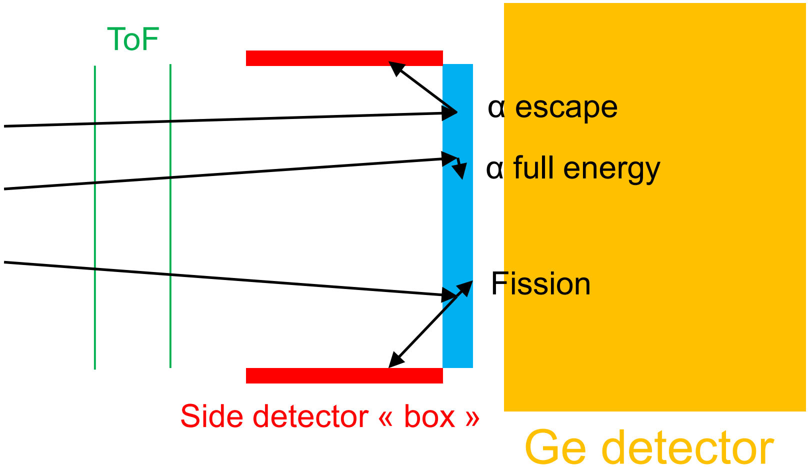
Data a complementary. Cleanest alpha spectra from Ne+U reaction

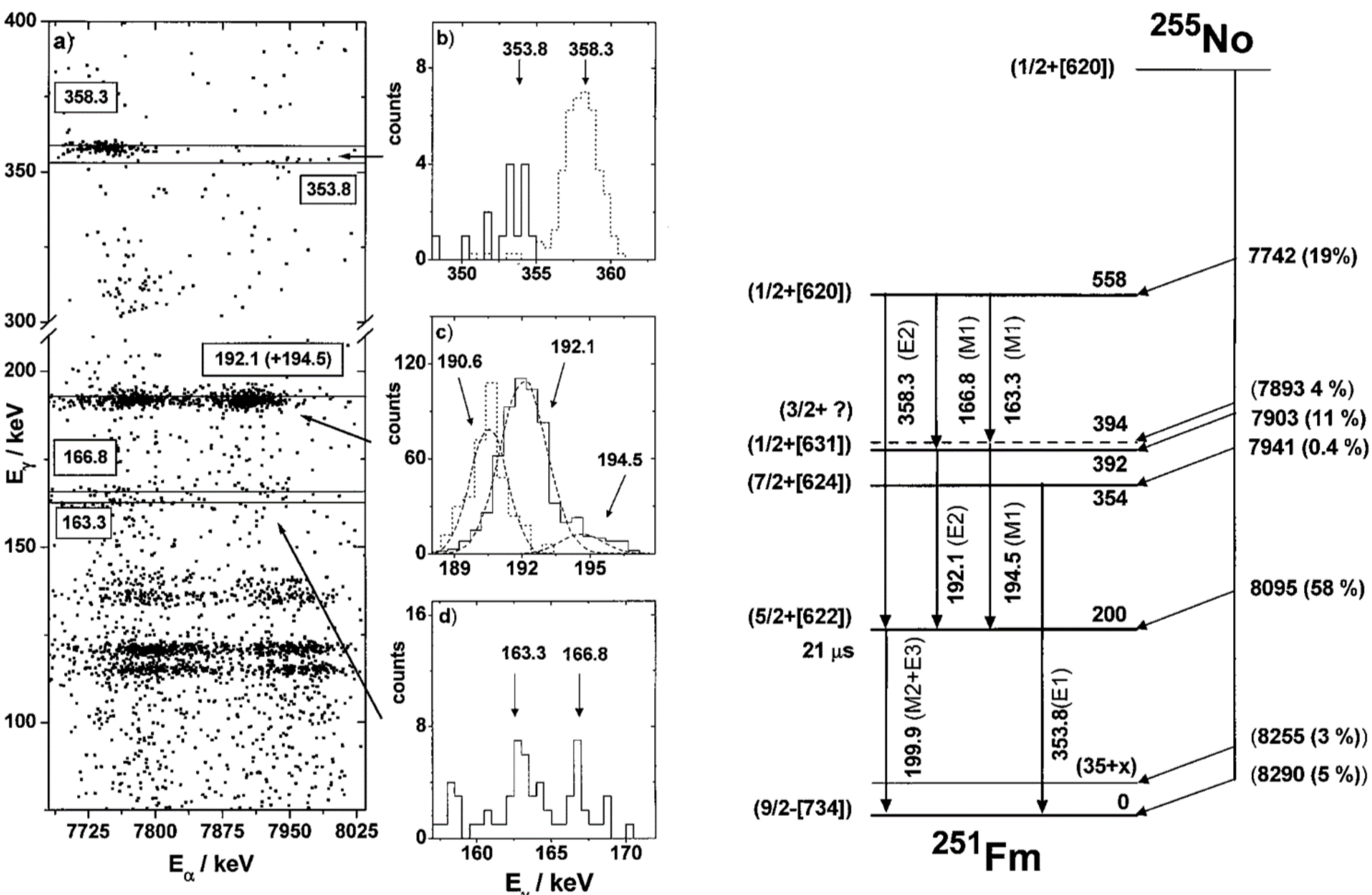


# Gamma-rays from $^{251}$Fm after α decay of $^{255}$No




Conversion 199,9 keV
K conversion : fluorescence yield ωk~ 1
→ γ/K X-rays provides conversion coefficient
→ mixed E2/M3 transition

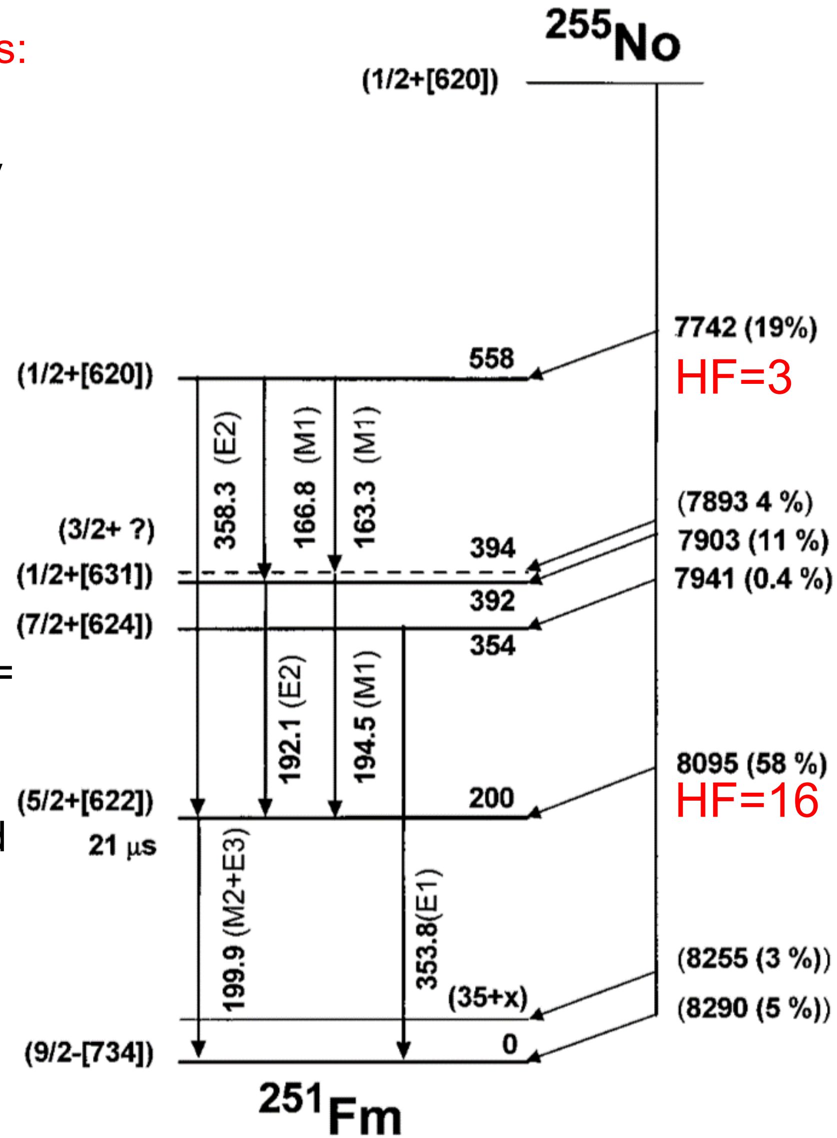




a)
358.3
353.8
192.1 (+194.5)
166.8
163.3
400
350
300
200
150
100
7725
7800
7875
7950
8025
Eγ / keV
Eα / keV
b)
353.8
358.3
counts
8
4
0
350
355
360
c)
120
190.6
192.1
194.5
counts
60
0
189
192
195
d)
16
163.3
166.8
counts
8
0
160
165
170
Eγ / keV
255No
(1/2+[620])
7742 (19%)
558
(1/2+[620])
358.3 (E2)
166.8 (M1)
163.3 (M1)
(7893 4 %)
(3/2+ ?)
394
7903 (11 %)
(1/2+[631])
7941 (0.4 %)
392
(7/2+[624])
354
192.1 (E2)
194.5 (M1)
8095 (58 %)
(5/2+[622])
200
21 μs
199.9 (M2+E3)
353.8(E1)
(8255 (3 %))
(35+x)
(8290 (5 %))
(9/2-[734])
0
251Fm

Several arguments used to built the level scheme and assign multipolarities:

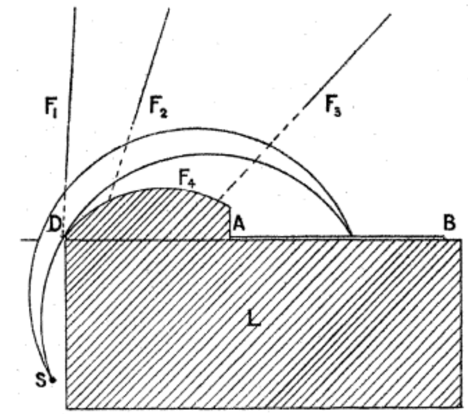
- Previous experiments
- States predicted by theory (usually single particle states predicted at low are indeed present, energy accuracy is few 100 keV).
- α-γ coincidences
- Hindrance factor (most intense transition does change the wave function in this example)
- X-ray intensity (conversion)
- Energy balance e.g. 166.8+192,1 = 358.3
- Intensity balance eg 166,8 transition must be highly converted
- Lifetime vs Weisskopf
- Branching ratio (Alaga rules)
- Energy summing of converted transition with α line (see below)



# Internal electron conversion

1911 : Bayer, Hahn and Meitner observe a fine structure in the ($\beta$) decay of 'radium B' and 'C' ($^{214}$Pb and $^{214}$Bi). Phys. Zeit. 12 (1911) 1019

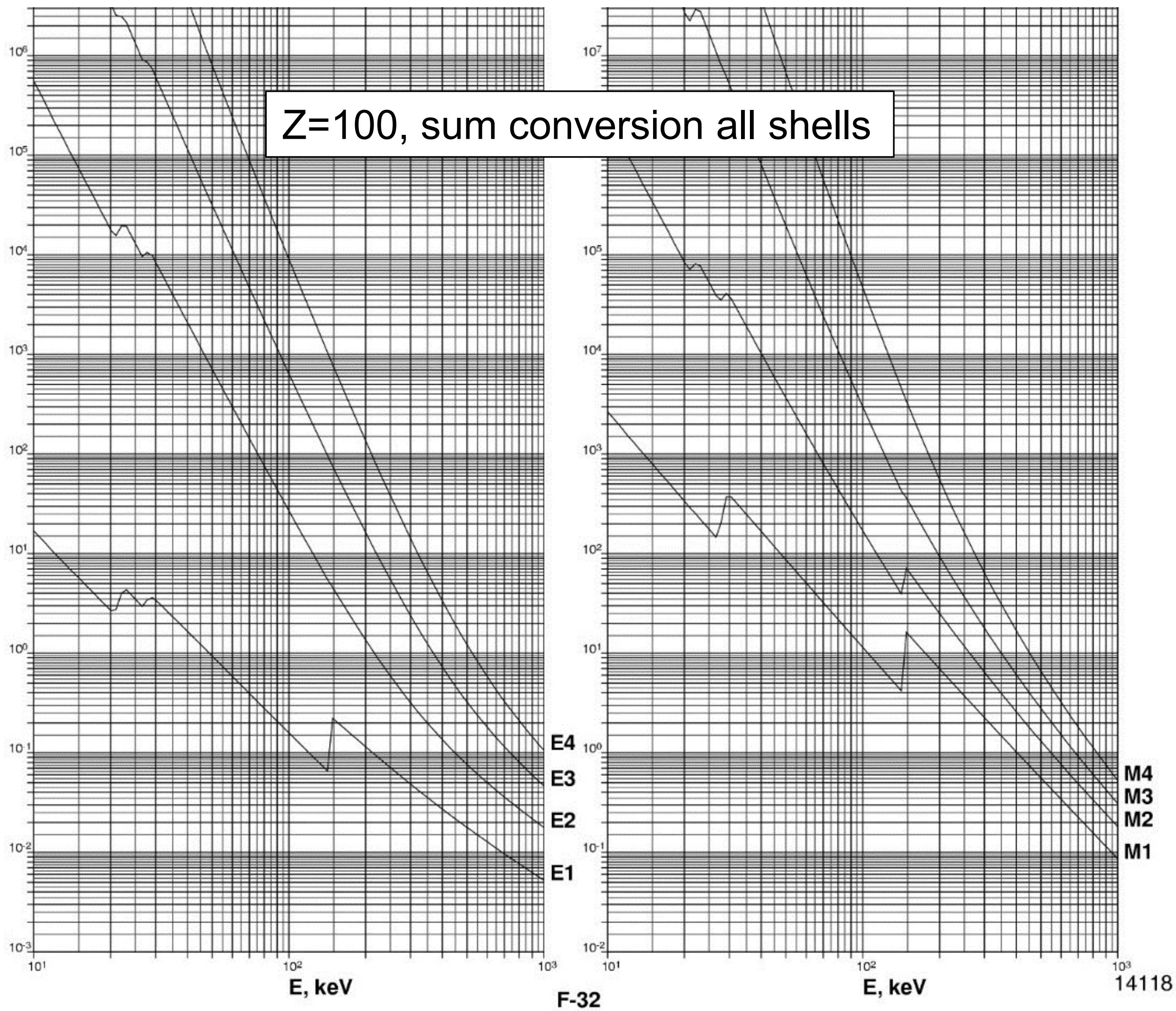
1921 : Ellis. Effect corresponds in 'radium B' to internal electron conversion.
Proc. Roy. Soc. Lond. A 99 (1921) 261




- Radiative transition → gamma. E(gamma) = E(transition)
- Conversion : electron ejected from the atom
  E(electron) = E(transition) - E(electron binding energy)
  Several shells → several electron lines

Conversion coefficient $\alpha$=I(electron)/I($\gamma$)
$\alpha$ ↑ when Z ↑
$\alpha$ ↑ when E ↓
$\alpha$ ↑ when ΔI ↑

# Internal electron conversion



Irfu

université PARIS-SACLAY

# Example No, E(transition = 200 keV)

Bricc code Kibédi et al. NIM A 589 (2008) 202
http://bricc.anu.edu.au/

| Shell | E(ce) | E1 | M1 | E2 | M2 | E3 | M3 | E4 | M4 | E5 | M5 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Tot | | 1.188E-01 | 7.692E+00 | 1.568E+00 | 2.757E+01 | 1.874E+01 | 1.020E+02 | 1.535E+02 | 6.146E+02 | 1.080E+03 | 4.387E+03 |
| K | 50.70 | 8.900E-02 | 5.912E+00 | 1.294E-01 | 1.635E+01 | 1.969E-01 | 2.305E+01 | 2.748E-01 | 2.732E+01 | 3.661E-01 | 3.086E+01 |
| L1 | 170.78 | 1.216E-02 | 1.146E+00 | 9.104E-02 | 6.275E+00 | 9.434E-01 | 2.741E+01 | 6.779E+00 | 1.203E+02 | 4.106E+01 | 5.371E+02 |
| L2 | 171.72 | 6.345E-03 | 1.773E-01 | 6.762E-01 | 9.702E-01 | 9.326E+00 | 5.467E+00 | 7.602E+01 | 2.972E+01 | 5.066E+02 | 1.572E+02 |
| L3 | 178.15 | 3.723E-03 | 3.807E-03 | 2.642E-01 | 8.797E-01 | 2.713E+00 | 2.175E+01 | 1.984E+01 | 2.361E+02 | 1.247E+02 | 2.003E+03 |
| L-tot | | 2.223E-02 | 1.327E+00 | 1.031E+00 | 8.125E+00 | 1.298E+01 | 5.463E+01 | 1.026E+02 | 3.862E+02 | 6.724E+02 | 2.697E+03 |
| M1 | 192.33 | 2.856E-03 | 2.795E-01 | 2.723E-02 | 1.683E+00 | 3.192E-01 | 8.349E+00 | 2.541E+00 | 4.199E+01 | 1.706E+01 | 2.153E+02 |
| M2 | 192.77 | 1.566E-03 | 4.871E-02 | 1.883E-01 | 2.872E-01 | 2.801E+00 | 1.758E+00 | 2.486E+01 | 1.044E+01 | 1.814E+02 | 6.053E+01 |
| M3 | 194.27 | 9.980E-04 | 1.084E-03 | 7.944E-02 | 2.711E-01 | 8.411E-01 | 7.190E+00 | 6.342E+00 | 8.558E+01 | 4.139E+01 | 8.005E+02 |
| M4 | 194.95 | 5.586E-05 | 5.804E-05 | 1.346E-03 | 5.283E-03 | 2.912E-02 | 1.392E-01 | 1.566E+00 | 2.165E+00 | 3.363E+01 | 2.572E+01 |
| M5 | 195.24 | 5.702E-05 | 3.116E-05 | 5.151E-04 | 2.340E-04 | 3.581E-02 | 5.972E-02 | 1.062E+00 | 3.531E+00 | 1.719E+01 | 7.502E+01 |
| M-tot | | 5.533E-03 | 3.294E-01 | 2.968E-01 | 2.247E+00 | 4.026E+00 | 1.750E+01 | 3.638E+01 | 1.437E+02 | 2.906E+02 | 1.177E+03 |

Measurement of conversion coefficient → mulitpolarity.
(ambiguous in some cases however)
Even better : measurement of conversion on several subshells

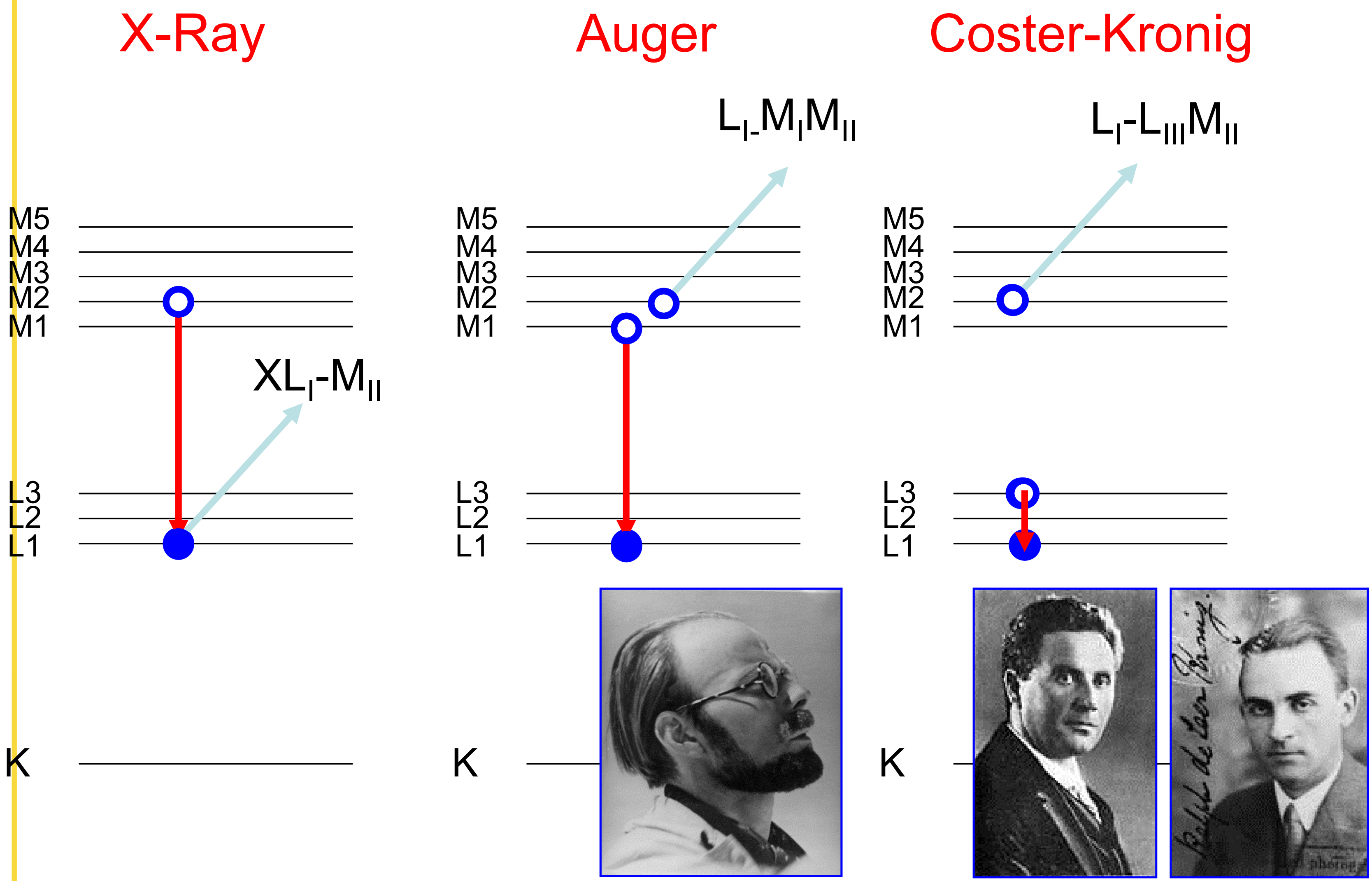
# After internal conversion…

Internal conversion

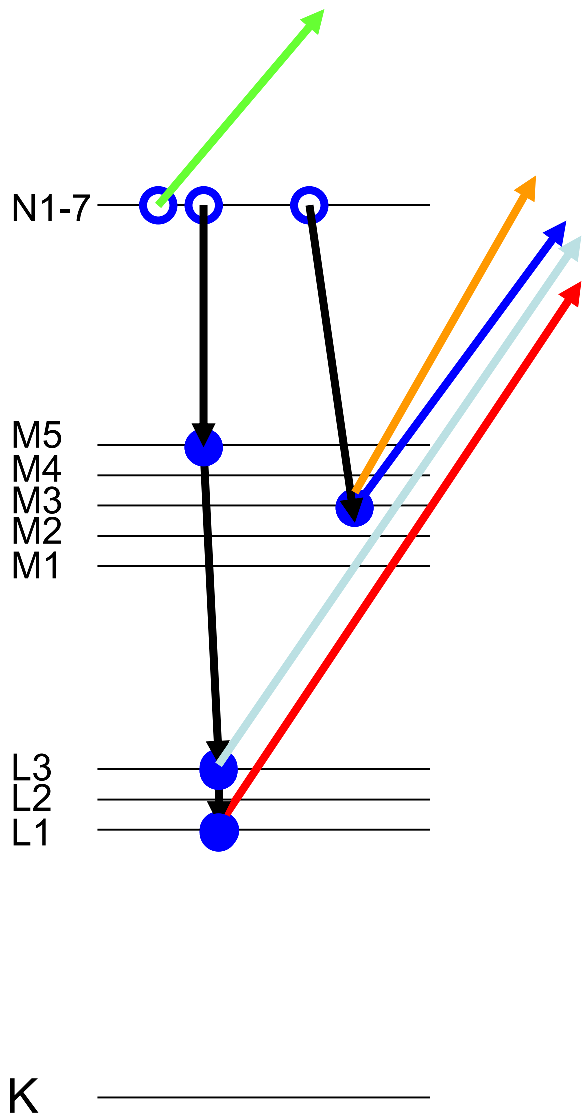
→ vacancy in the atomic shell

→ rearrangement of the atomic shell followed by electron (Auger, Coster-Kroning) and/or X-ray emission

# Atomic effects



# Example (Z=99 conversion 50 keV M1)



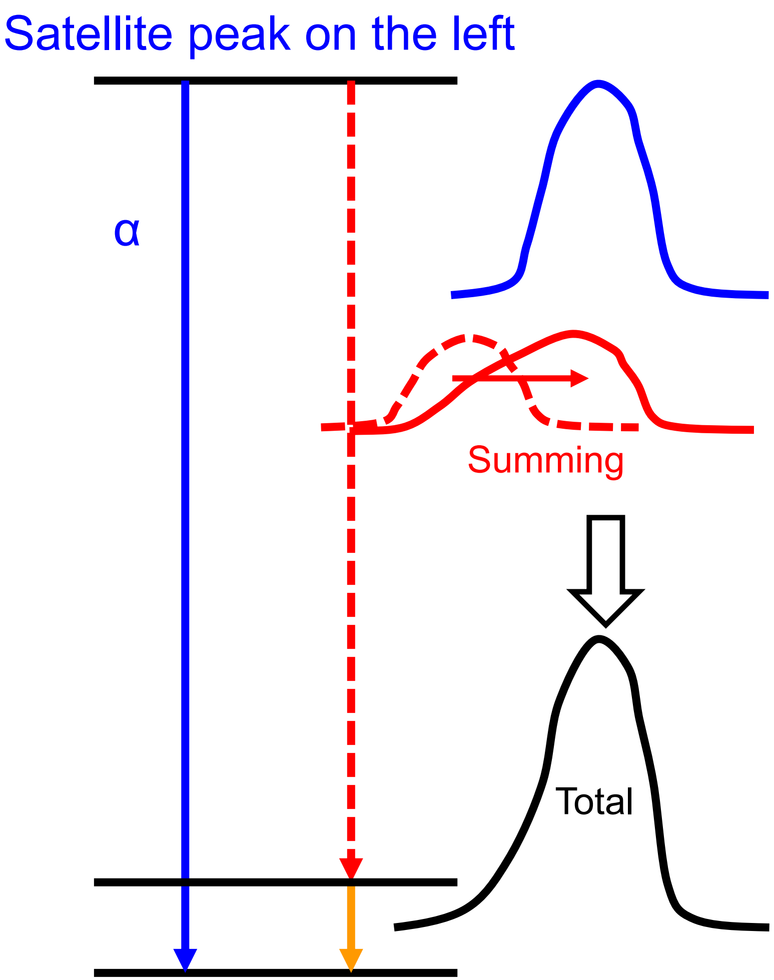

| | |
|---|---|
| 1 Conversion $L_{I}$ | 23.2 |
| 2 Coster-Kronig $L_{I}$-$L_{III}M_{III}$ | 1.1 |
| 3 X $L_{III}$-$M_{V}$ | 16.0 |
| 4 X $M_{III}$-$N_{I}$ | 3.4 |
| 5 Auger $M_{V}$-$N_{V}N_{VII}$ | 2.9 |

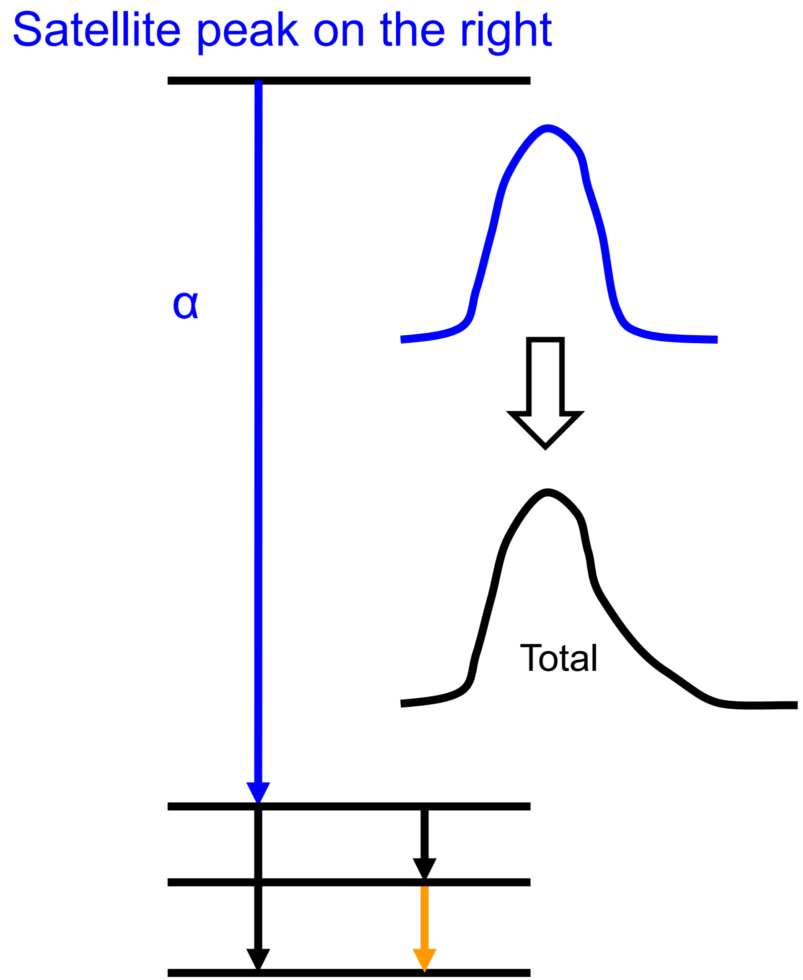
And so on…

These atomic transitions are emitted in coincidence with the α decay and will (partially) be detected in the implantation detector
→ summing

# Summing

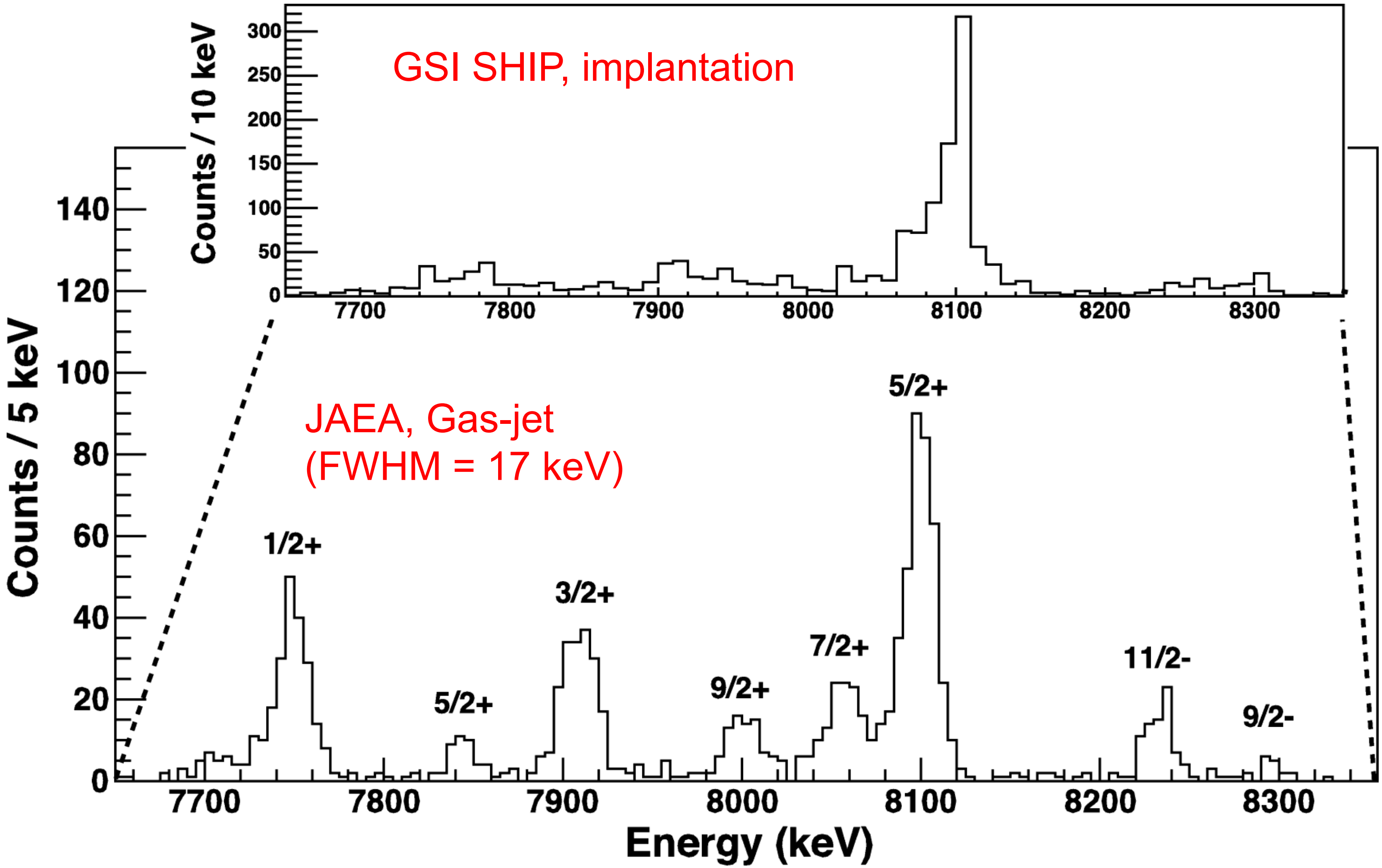





Alpha spectra have to be taken with care !

Simulation (eg Geant4) needed to understand alpha spectra and account properly for the shape of alpha spectra. See eg NIMA 589 (2008) 230

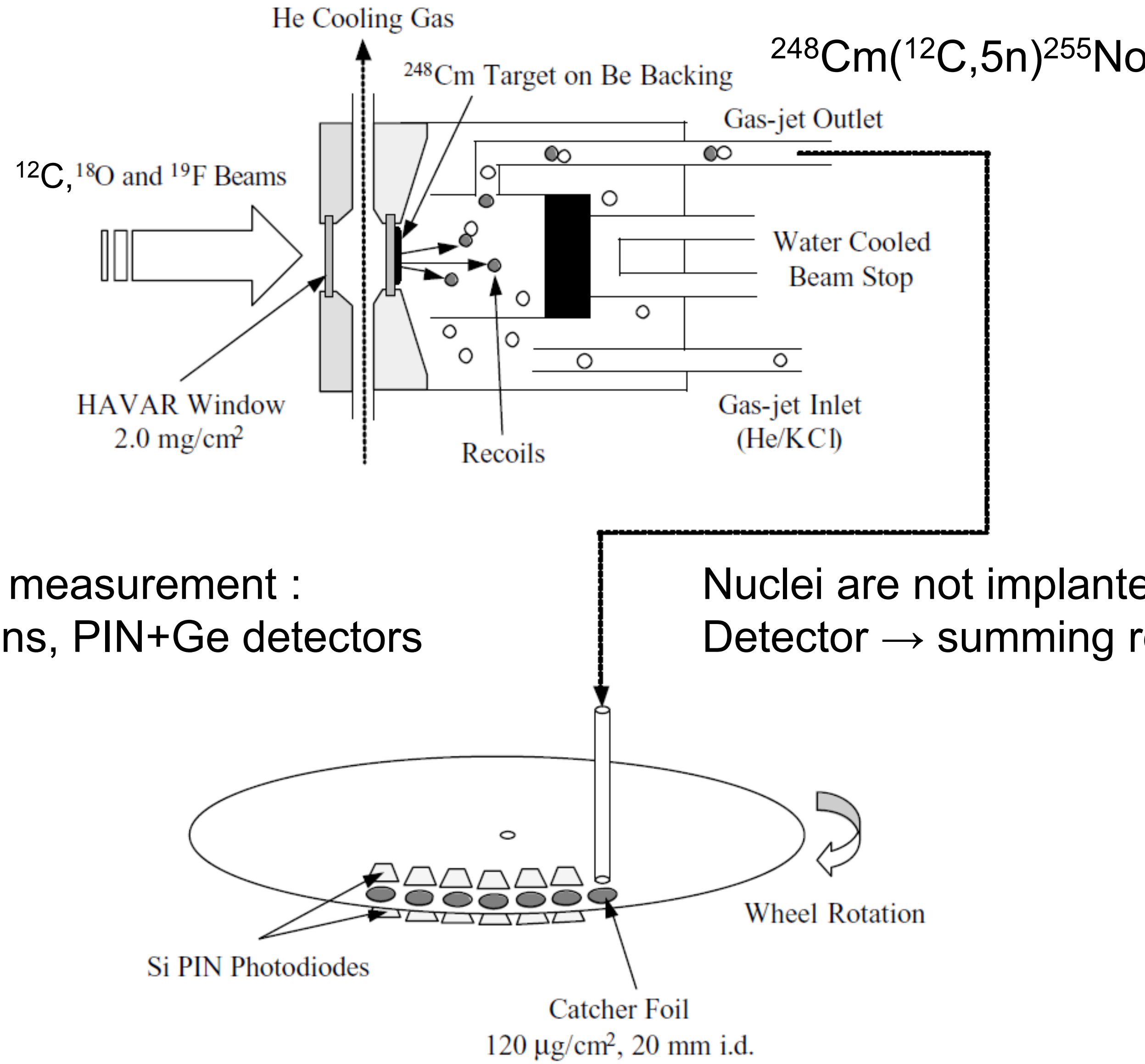



Asai et al. NPA 944 (2015) 308

# $^{255}$No at JAEA, gas-jet technique



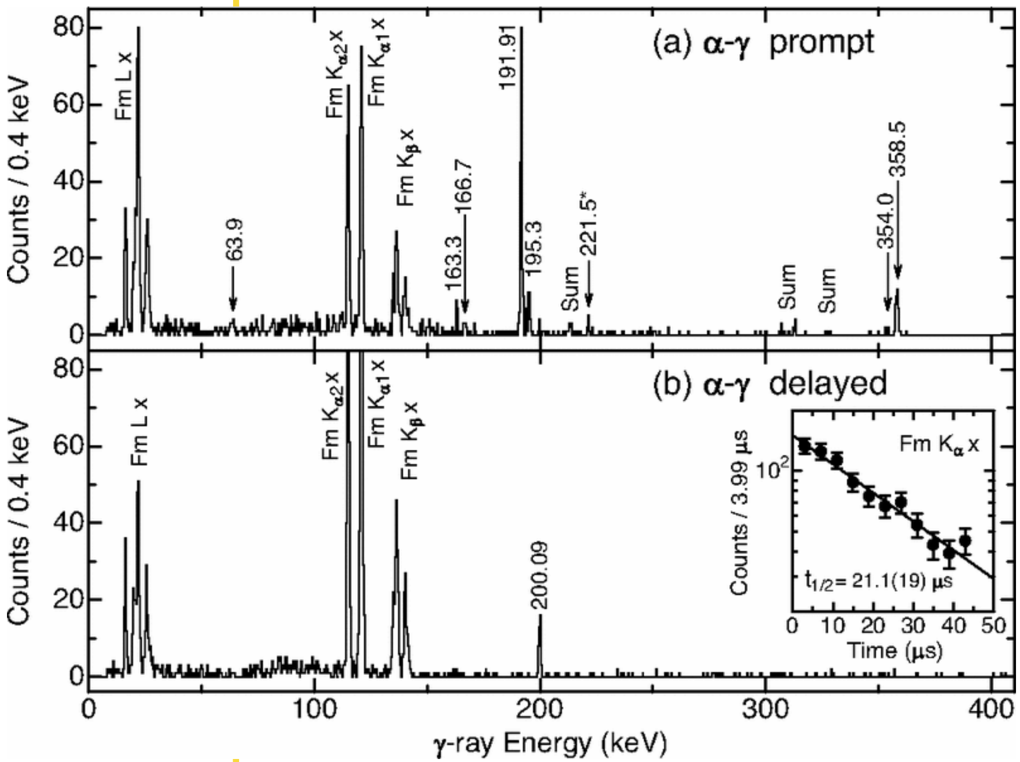
$^{248}Cm(^{12}C,5n)^{255}No$

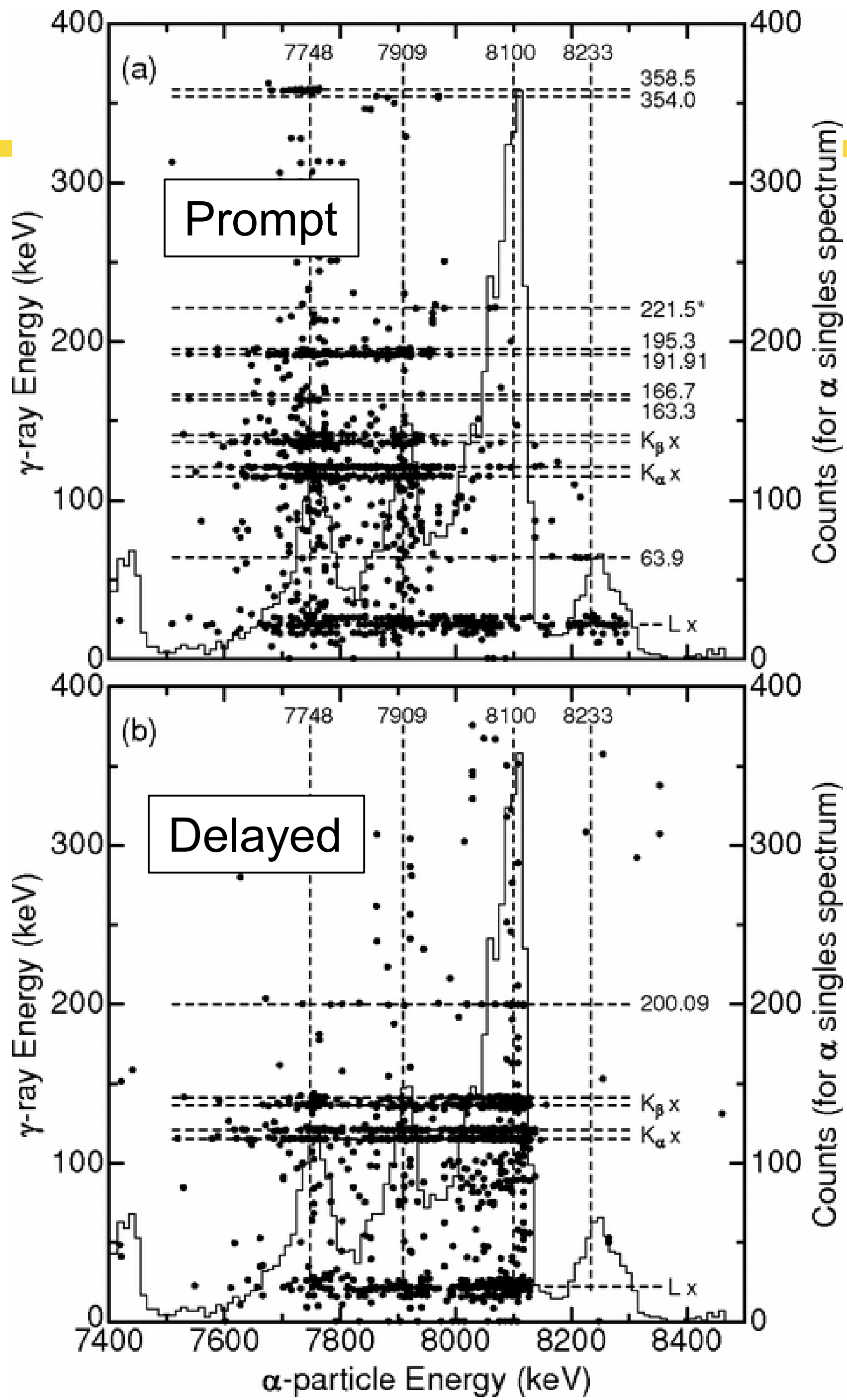



Variant for α-γ measurement :
only two stations, PIN+Ge detectors

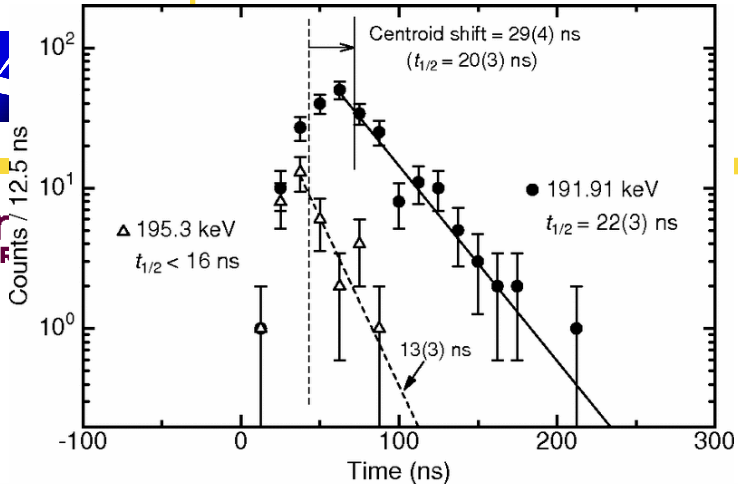
Nuclei are not implanted in the Si Detector → summing reduced

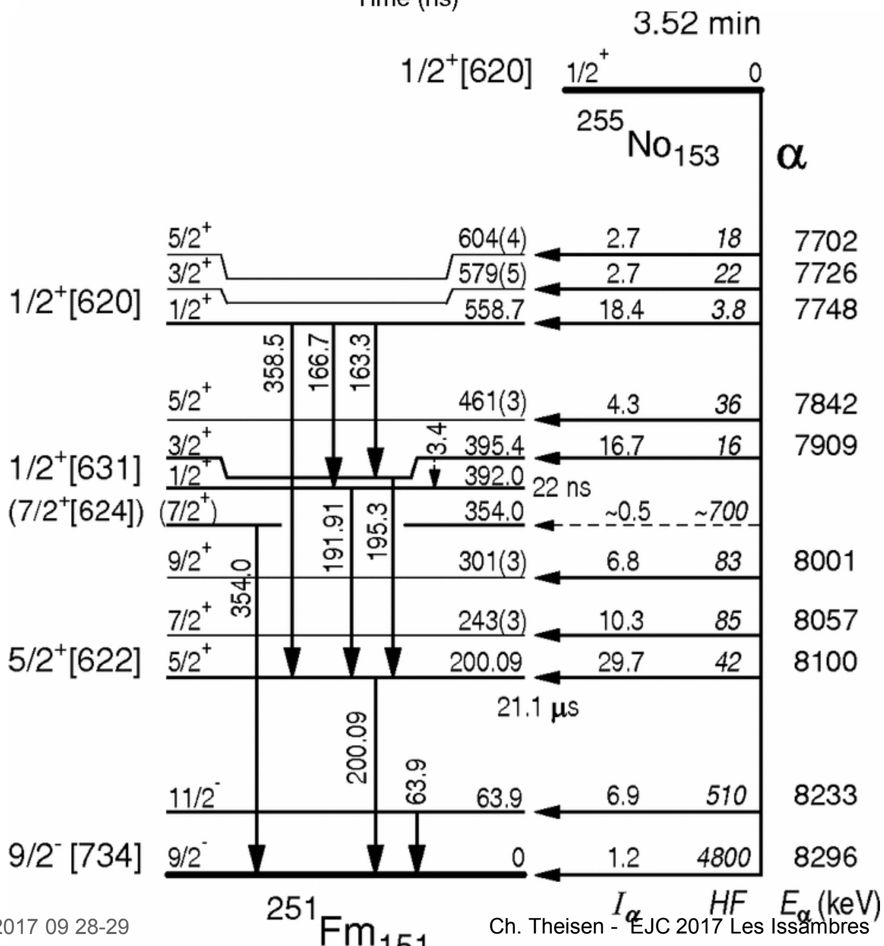
Nagame et al. J. Radiochem. Sci 3 (2002) 85

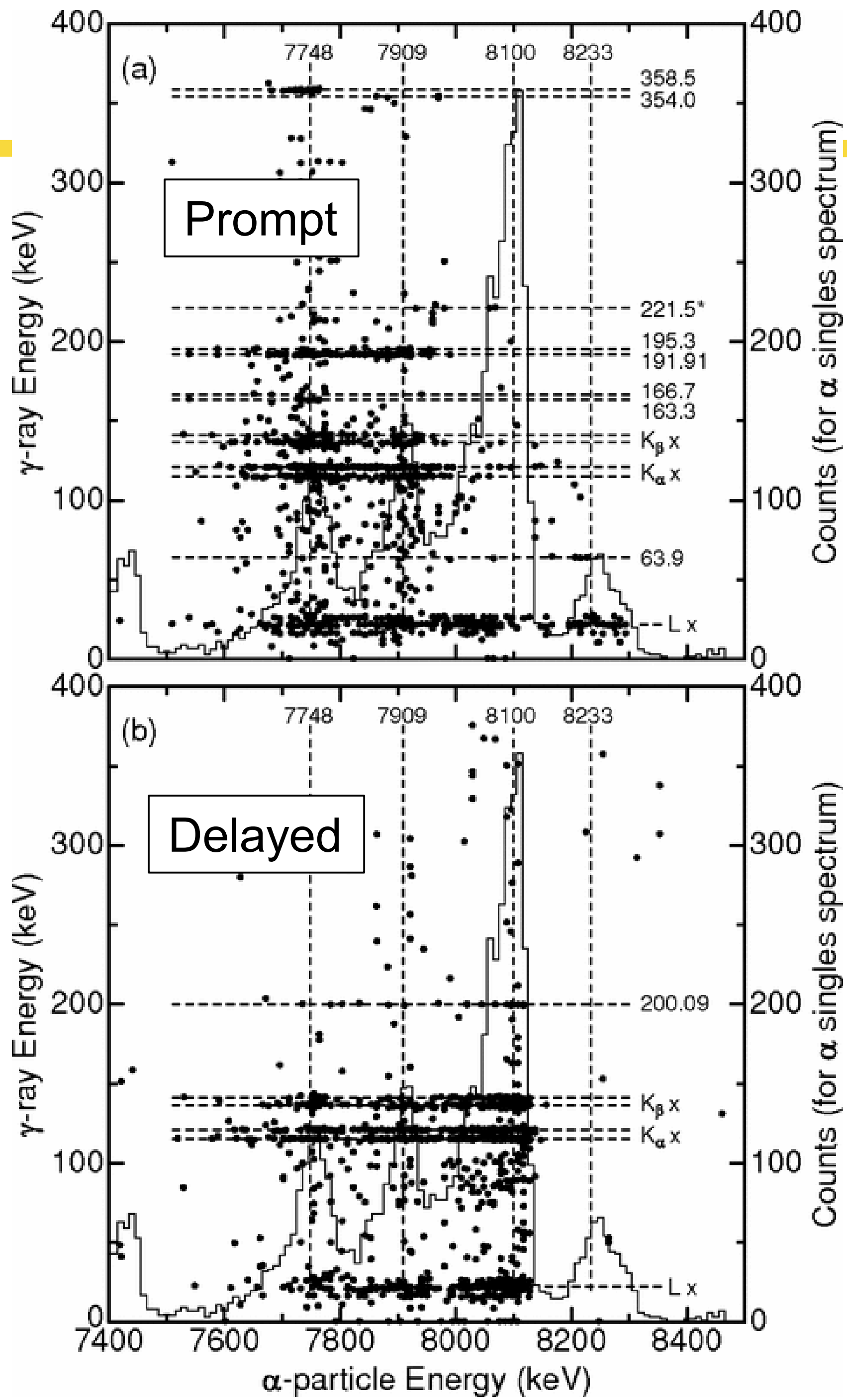



Asai et al. PRC 83 (2011) 014315

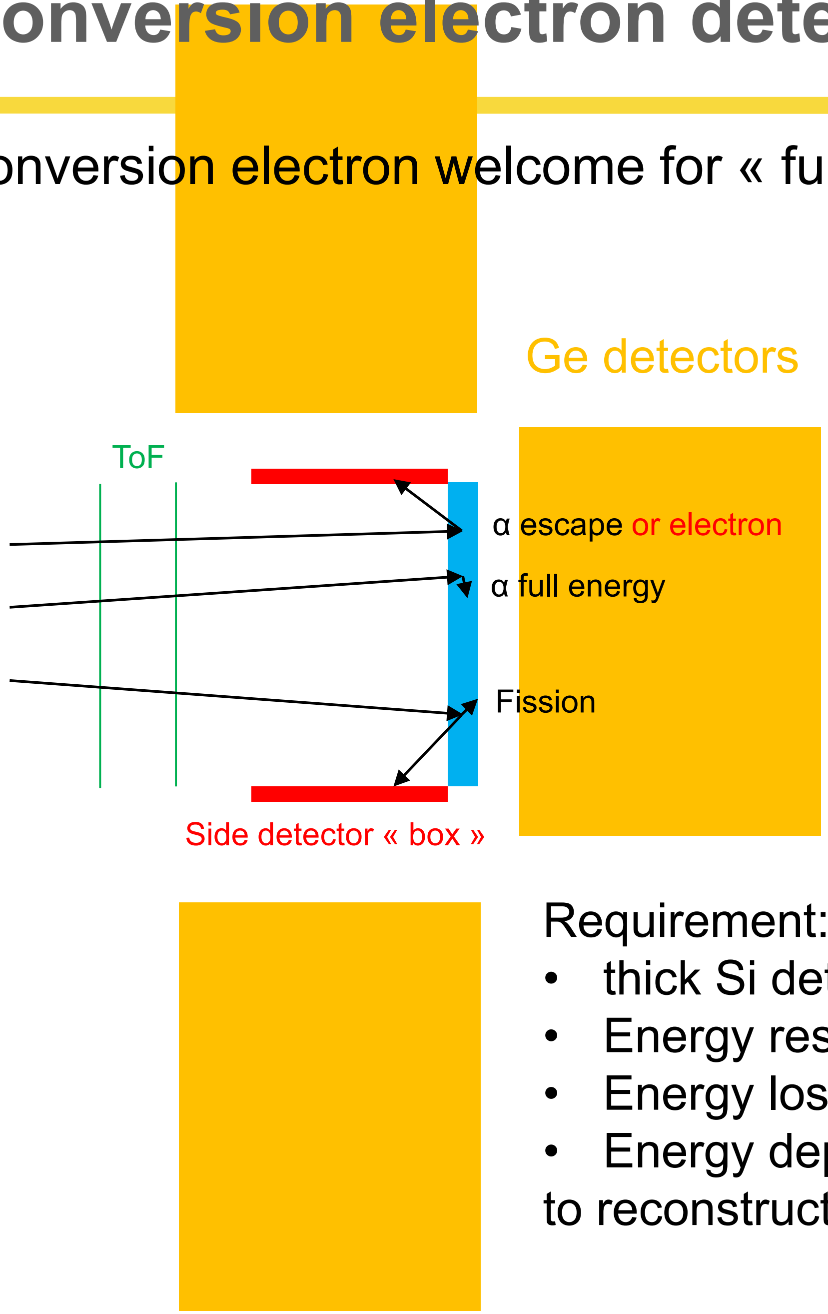

Centroid shift = 29(4) ns
($t_{1/2}$ = 20(3) ns)
● 191.91 keV
$t_{1/2}$ = 22(3) ns
△ 195.3 keV
$t_{1/2}$ < 16 ns
13(3) ns
Counts / 12.5 ns
Time (ns)


3.52 min
1/2+[620]
1/2+ 0
255No153
α
5/2+ 604(4) 2.7 18 7702
3/2+ 579(5) 2.7 22 7726
1/2+[620] 1/2+ 558.7 18.4 3.8 7748
358.5
166.7
163.3
5/2+ 461(3) 4.3 36 7842
3/2+ 395.4 16.7 16 7909
1/2+[631] 1/2+ 392.0 22 ns
3.4
(7/2+[624]) (7/2+) 354.0 ~0.5 ~700
191.91
195.3
9/2+ 301(3) 6.8 83 8001
354.0
7/2+ 243(3) 10.3 85 8057
5/2+[622] 5/2+ 200.09 29.7 42 8100
21.1 µs
200.09
63.9
11/2- 63.9 6.9 510 8233
9/2- [734] 9/2- 0 1.2 4800 8296
251Fm151
Iα HF Eα (keV)


(a)
Prompt
7748 7909 8100 8233
358.5
354.0
221.5*
195.3
191.91
166.7
163.3
Kβ x
Kα x
63.9
L x
(b)
Delayed
200.09
γ-ray Energy (keV)
Counts (for α singles spectrum)
α-particle Energy (keV)

# Conversion electron detection

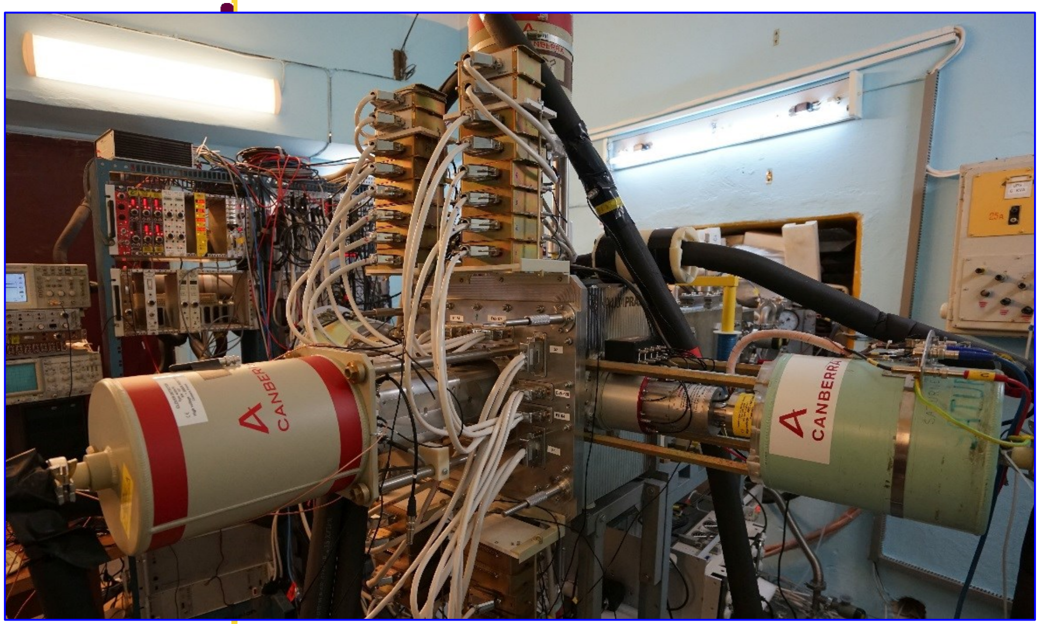
Conversion electron welcome for « full » spectroscopy

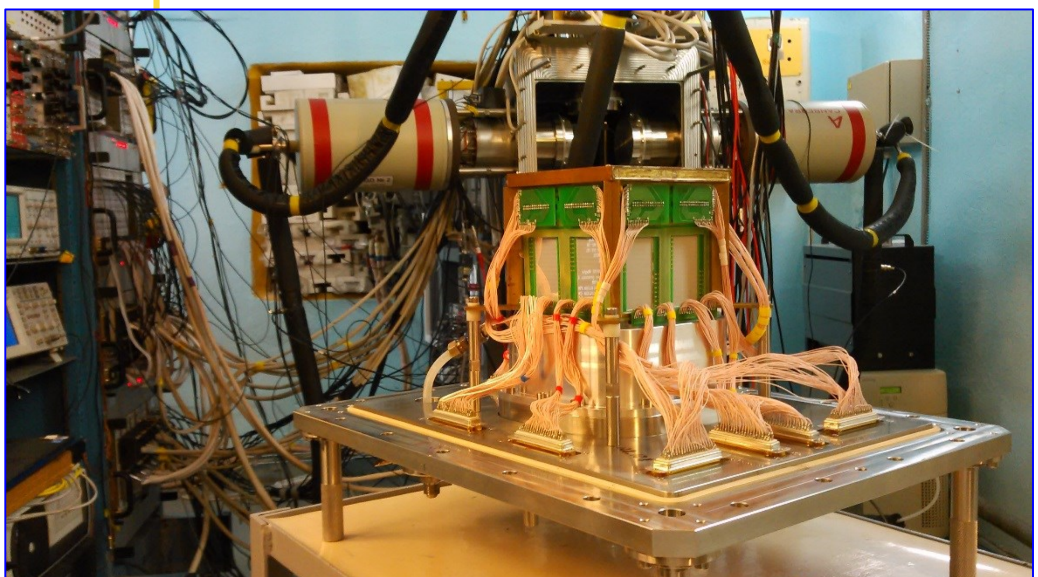


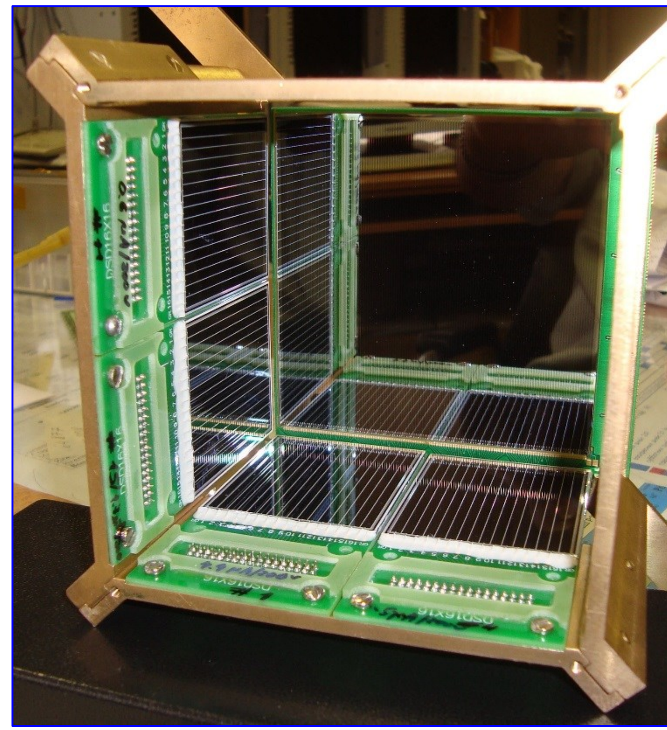

Requirement:

- thick Si detector (1 mm or more)
- Energy resolution few keV (cooling needed)
- Energy loss in dead layers → thin windows
- Energy deposited in implantation det. : need to reconstruct trajectory → position sensitivity

# GABRIELA@VASSILISSA-SHELS (Dubna)



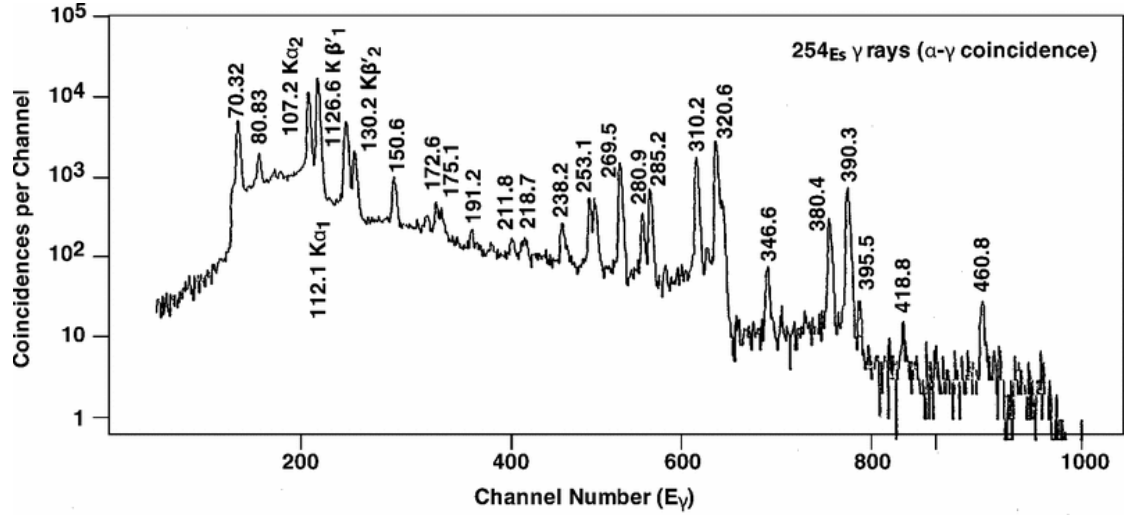


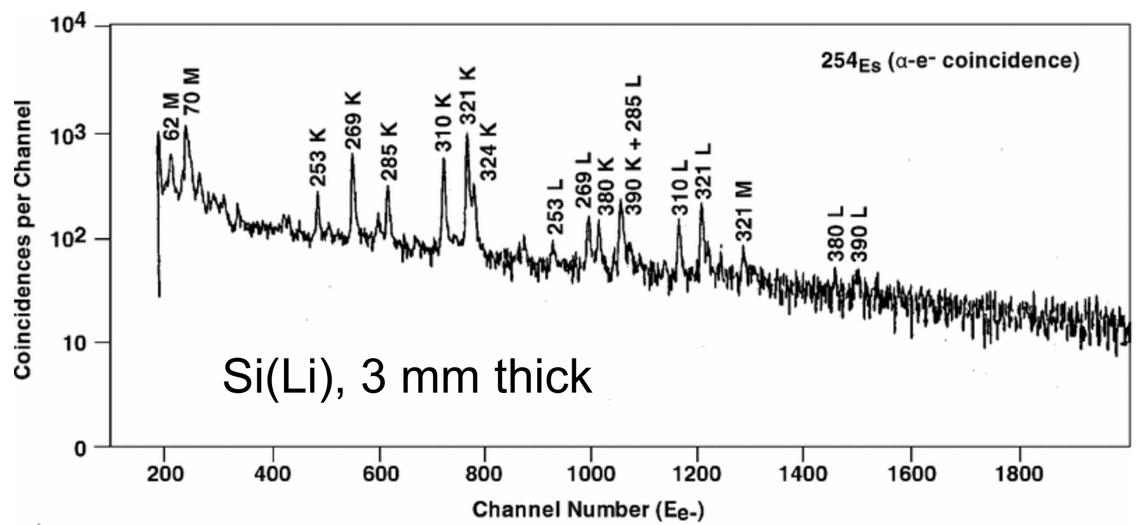
# Offline electron spectroscopy $^{250}Bk$



$^{254}Es$ source → $^{250}Bk$

Ahmad et al. PRC 77 (2008) 054302



# Identification using X-rays

- 1906 Charles Barkla : X-ray energy is characteristic of an element (→ nomenclature K, L, M, …).
- 1913 Henry Moseley. Linear relation between X-ray energy and Z

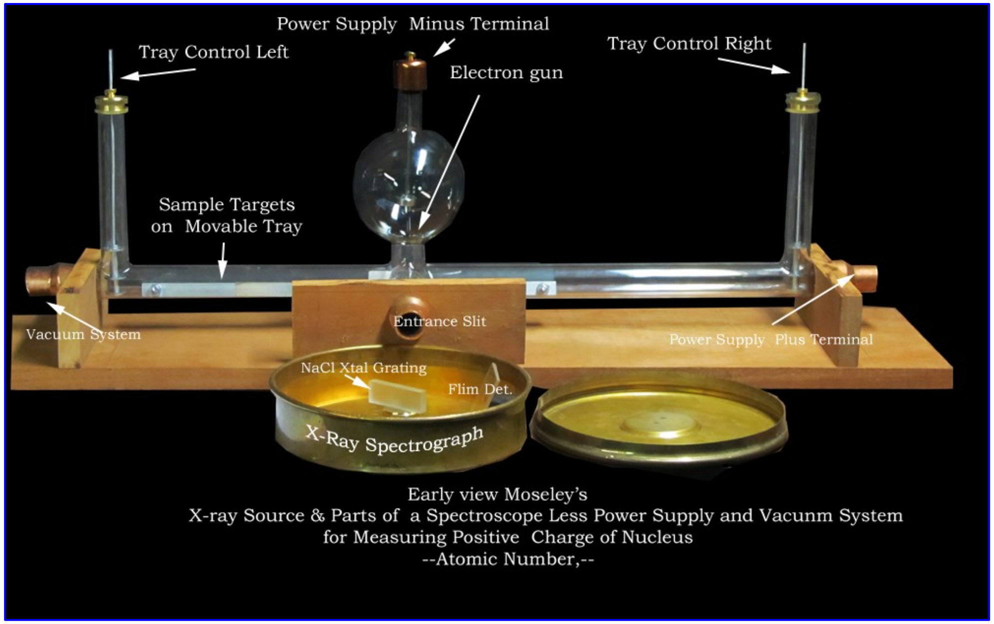
→ rearrange elements according to atomic number

→ gaps in gaps in the atomic number sequence at numbers 43, 61, 72, and 75

→ there must be exactly 15 lanthanide

Charles Barkla

Henry Moseley



# X-ray identification of Rf Z=104

1973 Bemis et al.

PRL 31 (1973) 647

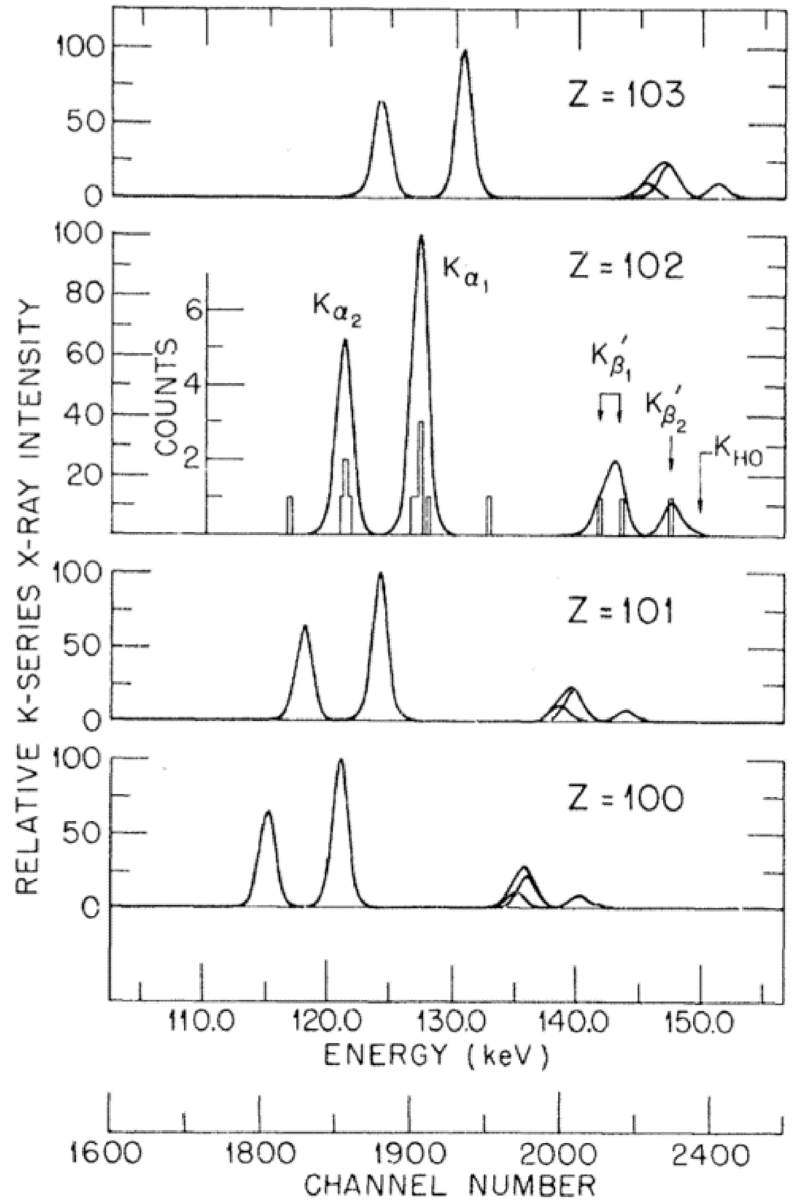
$^{249}Cf(^{12}C,4n)^{257}Rf$

Decay chain of Z=104

→ X-rays Z=102

Detector = planar Ge(Li)

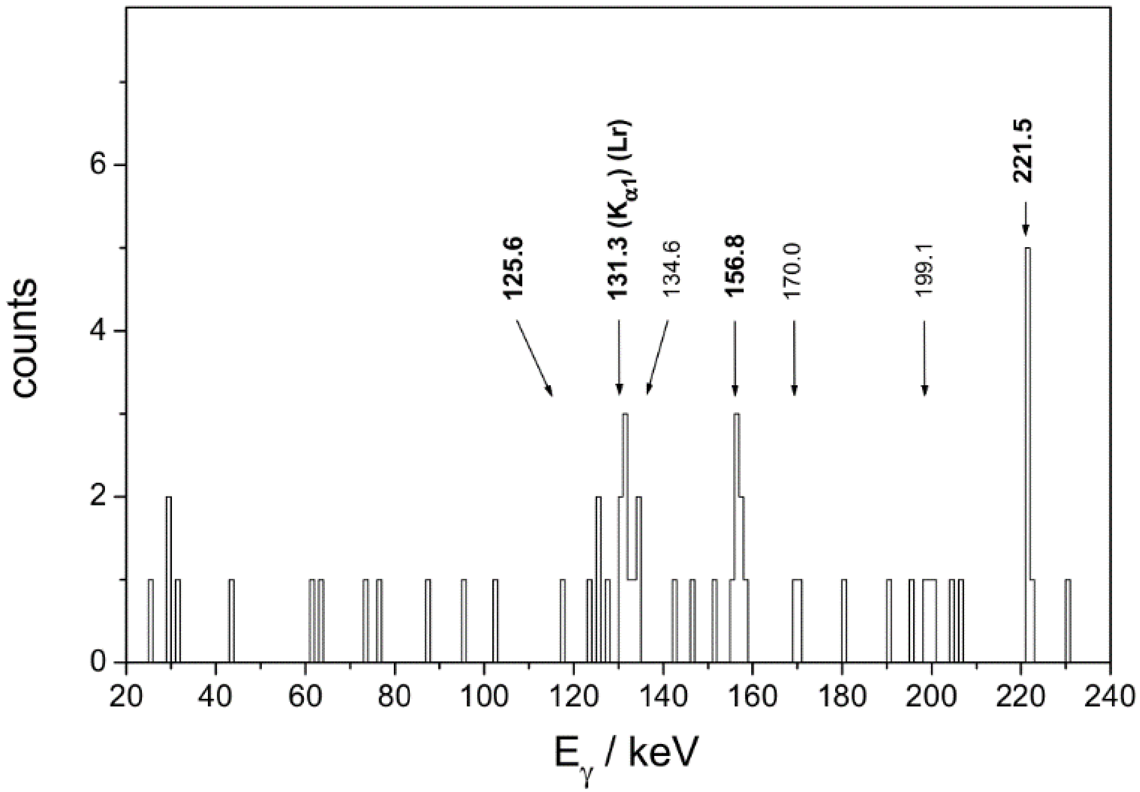
α-X-ray correlations



# X-ray Db

2009 Hessberger et al, SHIP. EPJA 41 (2009) 145

$^{209}Bi(^{54}Cr,1n)^{262}Bh$ ($\sigma$ ~ 290 pb) → $^{258}Db$



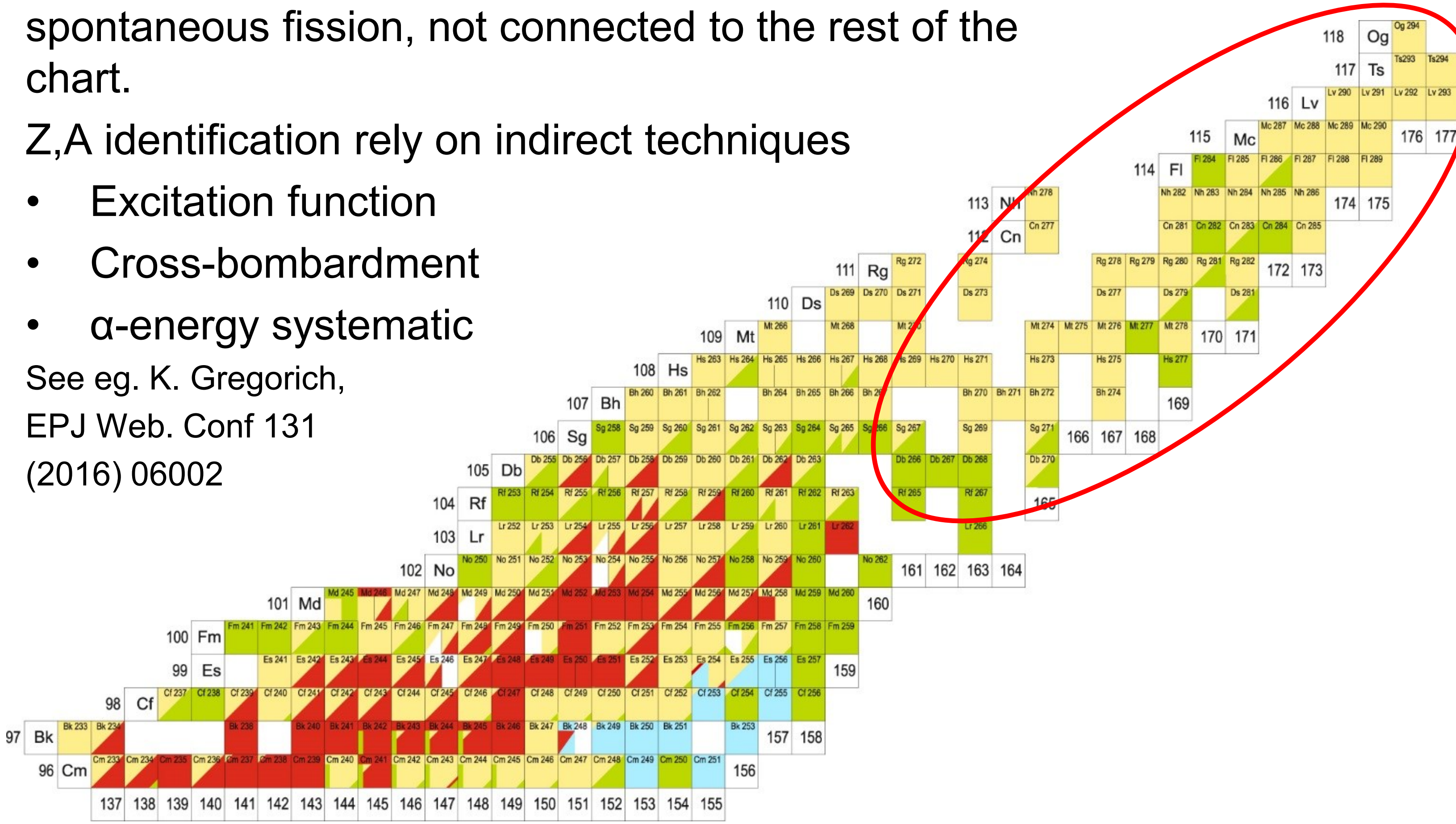

heaviest system for which X-ray α-decay coincidences have been observed ?

Hot fusion reaction : decay chains ending by spontaneous fission, not connected to the rest of the chart.

Z,A identification rely on indirect techniques

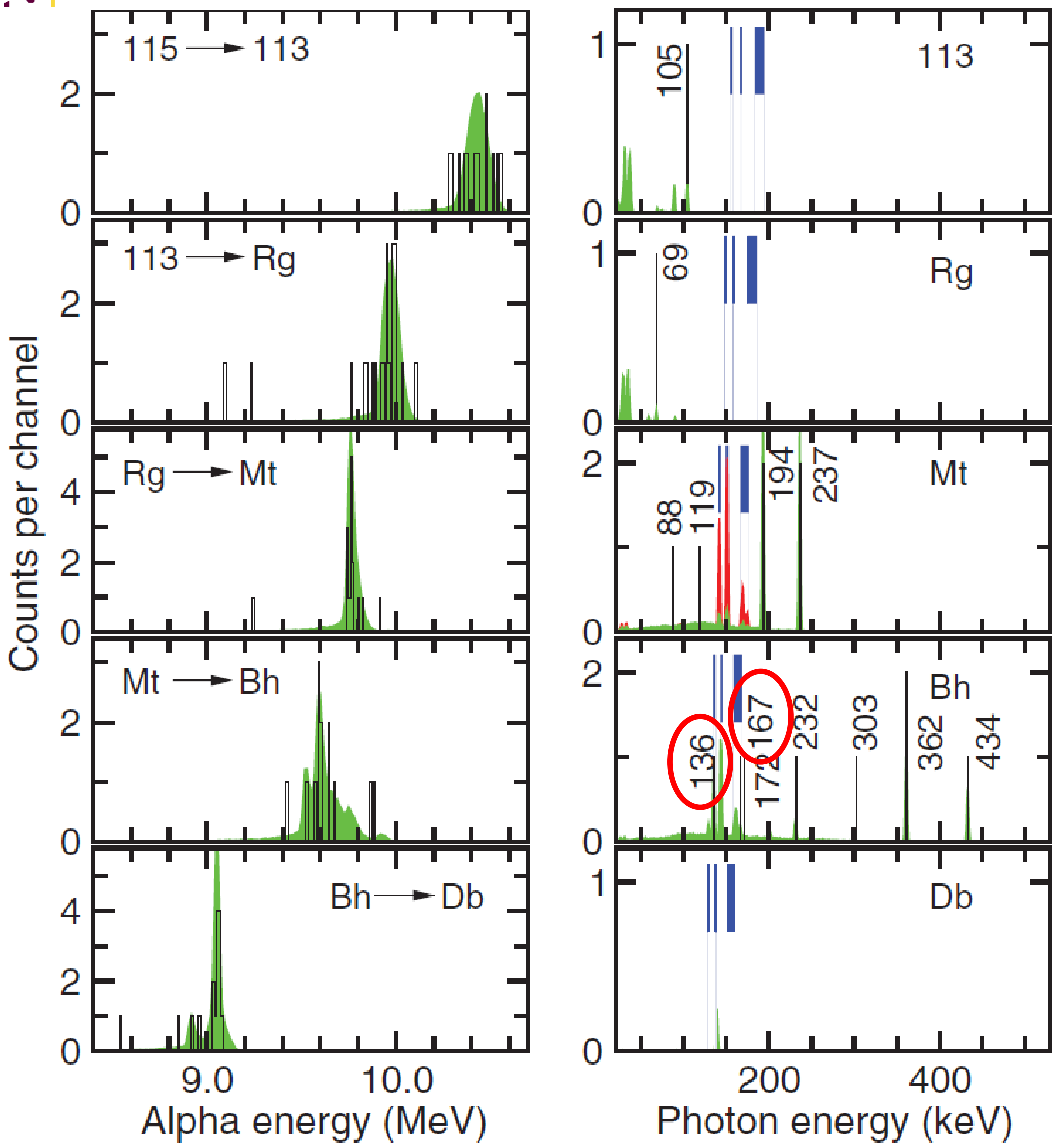
- Excitation function
- Cross-bombardment
- α-energy systematic

See eg. K. Gregorich, EPJ Web. Conf 131 (2016) 06002



# X-ray Identification of Z=115 (?)



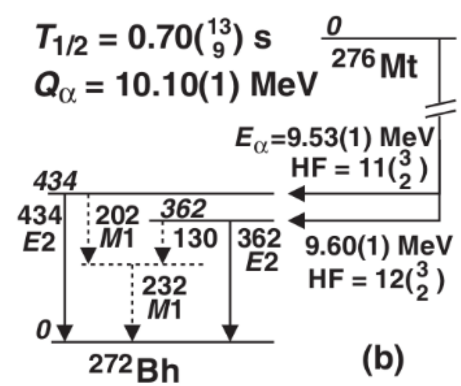



$^{243}Am(^{48}Ca,3n)^{288}115$ (σ~6 pb)
TASCA@GSI

D. Rudolf et al.,
PRL 111 (2013) 112502
[given as an example in NuPECC 2017 LRP]

Green (Red) = simulation

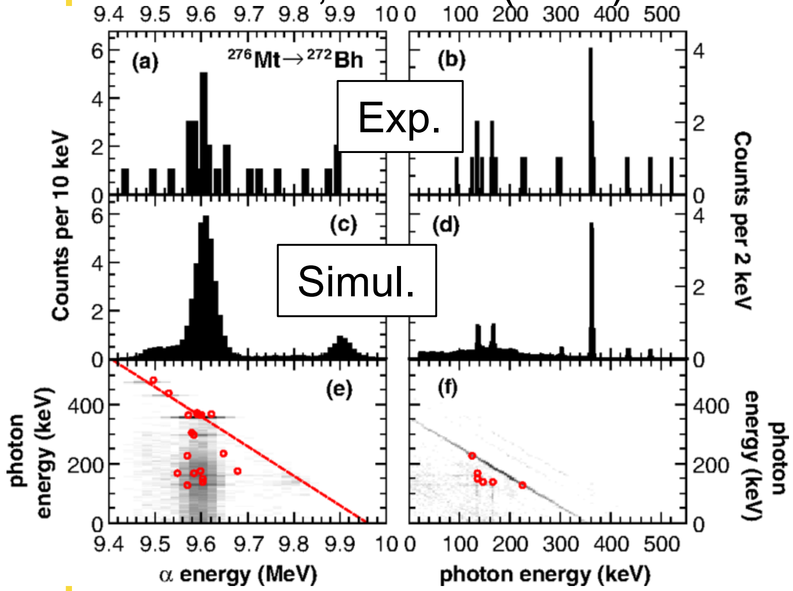
136 keV ~ $K_{\alpha 2}$ (Z=107)
167 keV ~ Kβ (Z=107)

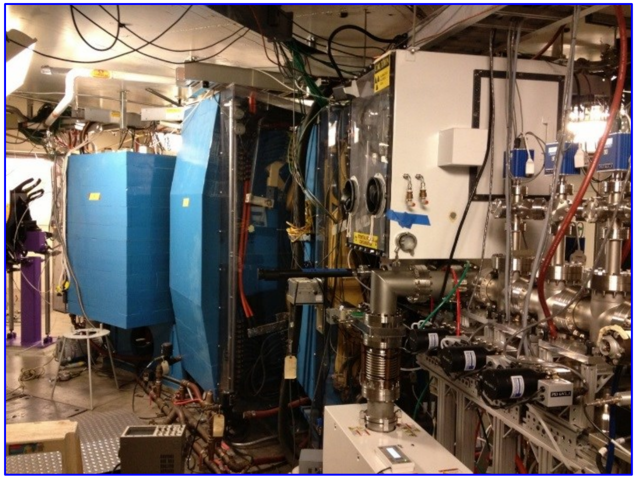


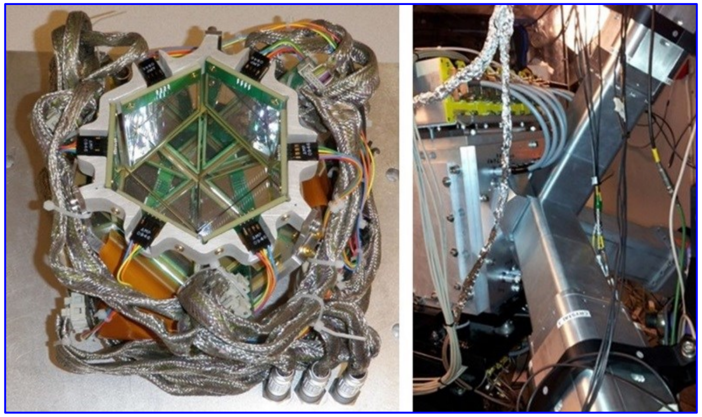
# $^{288}$115 decay chain at LBNL

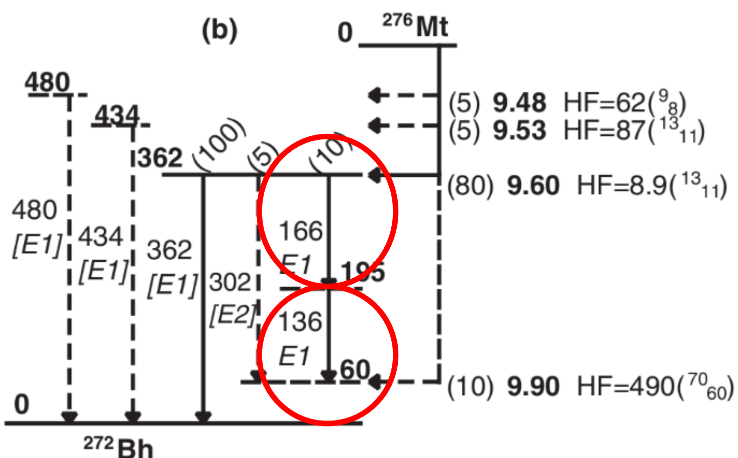
$^{243}$Am($^{48}$Ca,3n)$^{288}$115, BGS@LBNL

Gates et al, PRC 92 (2015) 021301








Data compatible with NO Bh X-rays.

# Isomers

- 1917. Isomerism predicted by F. Soddy.

  Nature 99 (1917) 433
- 1921. Discovery of isomerism by Otto Hahn.

Decay from ‘uranium X2’ to ‘uranium Z’ ($^{214}$Pa isomer decay).

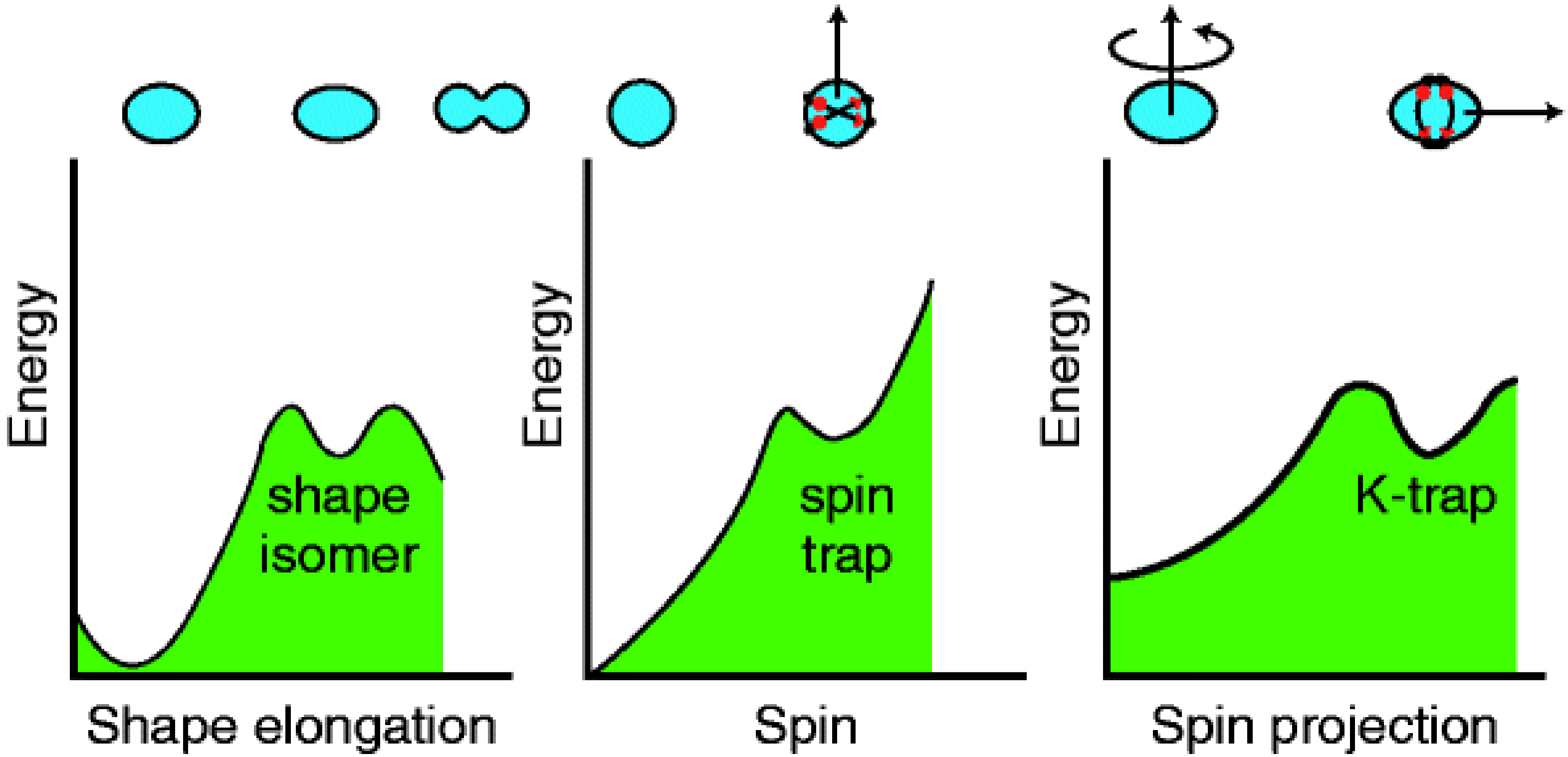
  Naturwissenschaften 9 (1921) 84
- 1935. Discovery of isomerism in artificial radioactivity ($^{80}$Br) by I. Kurchatov using neutron irradiation
- 1936. Explanation of isomers as spin traps by von Weiszäcker.

  Naturwissenschaften 24 (1936) 813

“There is no strict half-life requirement for a nuclear excited state to be designated an 'isomer', though it should at least be long lived compared to other states with similar angular momentum and excitation energy”

Walker and Xu, Phys. Scr. 91 (2016) 013010

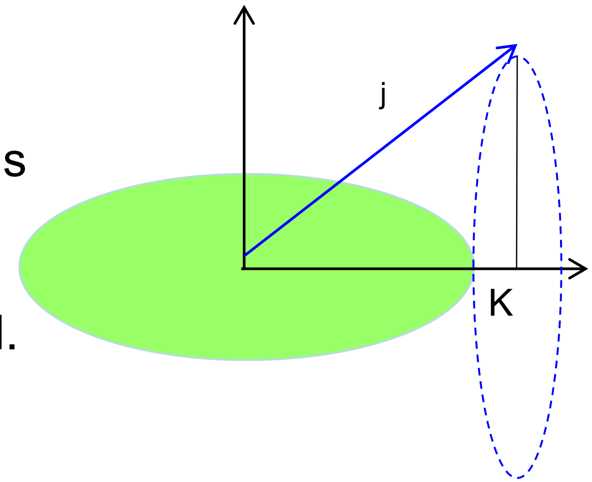
# Spin traps, shape isomers, K-isomers




Walker and Dracoulis, Nature 399 (1999) 35

# K-isomer

Decay of a high-K state
Selection rule : multipolarity λ of the transition must be larger than ΔK. If not, then transition is forbidden.

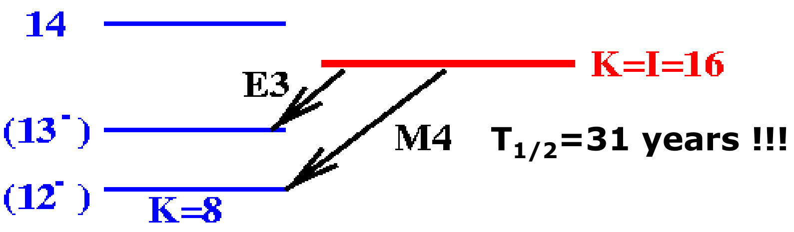



In real, transition is not forbidden but hindered.
Degree of K forbidness ν = ΔK – λ

Empirical rule : each degree of forbidness increases the lifetime by a factor of 100 compared to Weisskopf estimates.

$$F_W = \frac{T^{\gamma}_{1/2}(\text{experiment})}{T^{\gamma}_{1/2}(\text{Weisskopf})} \sim 100^{\nu}$$

Famous case : $^{178}$Hf




Recent review : Walker and Xu, Phys. Scr. 91 (2016) 013010

Irfu

# K isomers in heavy nuclei: an old story

université PARIS-SACLAY

PHYSICAL REVIEW C VOLUME 7, NUMBER 5 MAY 1973

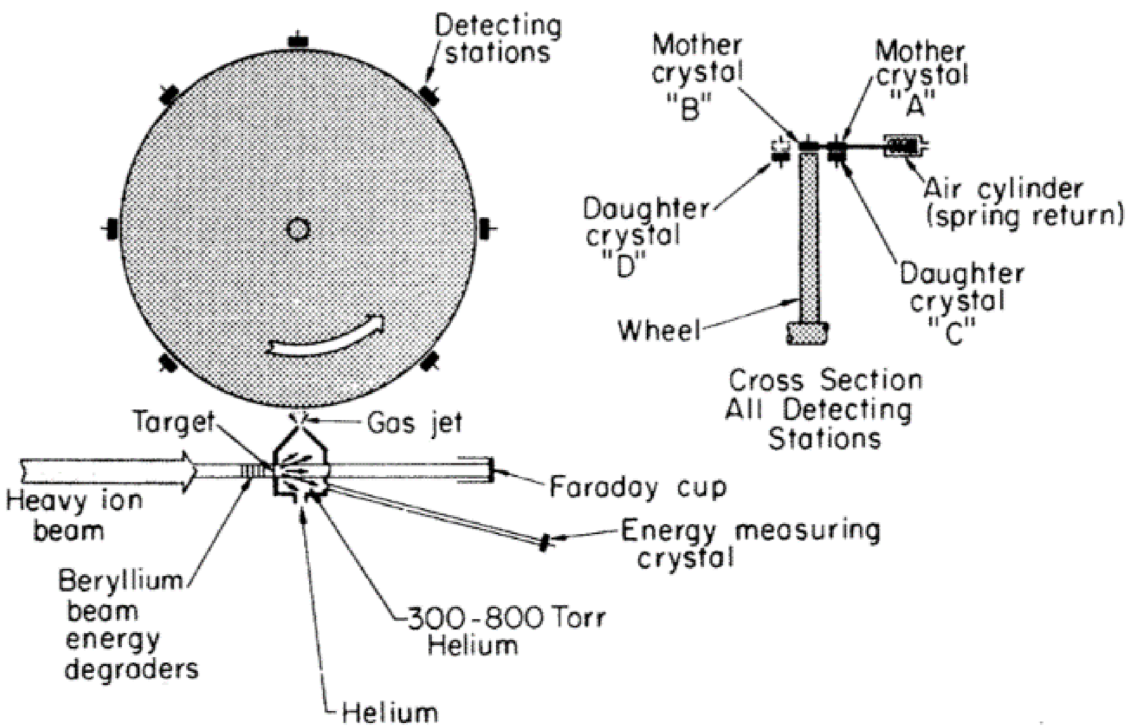
## Isomeric States in $^{250}$Fm and $^{254}$No†

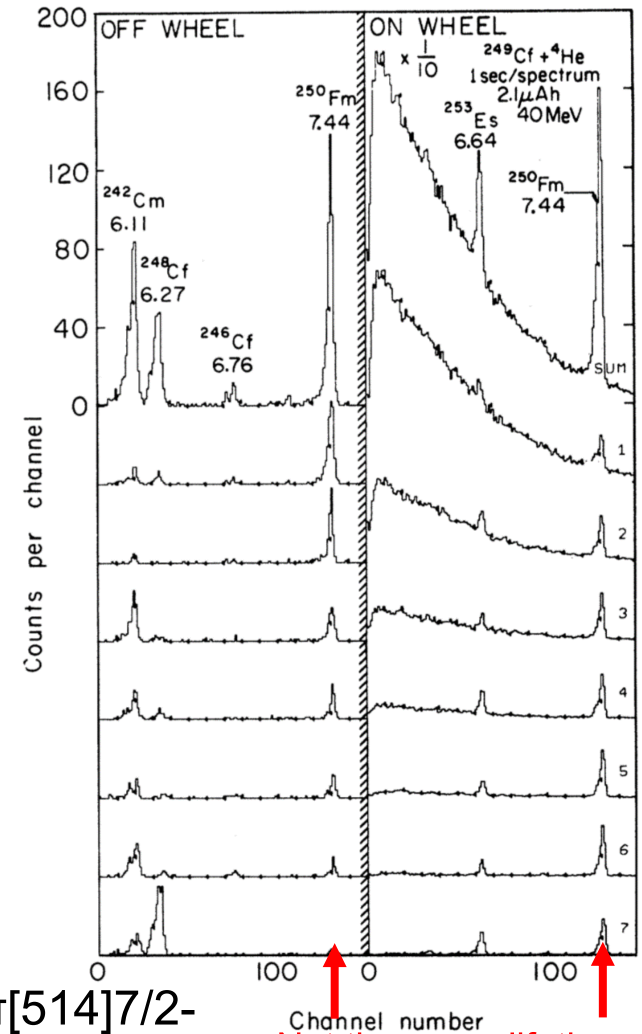
Albert Ghiorso, Kari Eskola,* Pirkko Eskola,* and Matti Nurmia
*Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720*
(Received 30 November 1972)

A preliminary report on the discovery of isomeric states in $^{250}$Fm and $^{254}$No was included in a recent article on $\alpha$-emitting isotopes of element 104. The existence and assignments of the $1.8\pm 0.1$-sec isomer to $^{250}$Fm and the $0.28\pm 0.04$-sec isomer to $^{254}$No have now been confirmed by cross-bombardment techniques. Isomeric ratios based on measurements of collection efficiency of recoil atoms from the decay of isomeric states are given. An interpretation of the even-even isomers as high-spin two-quasiparticle states is discussed.

# Transfermium high-K isomer

First observed in $^{250}$Fm, $^{254}$No by Ghiorso et al. using the Vertical Wheel Nature 229 (1971) 603, PRC 7 (1973) 2032




Interpretation ($^{250}$Fm) : K=8- isomer 1.8 s, π[633]7/2+ ⊗ π[514]7/2-

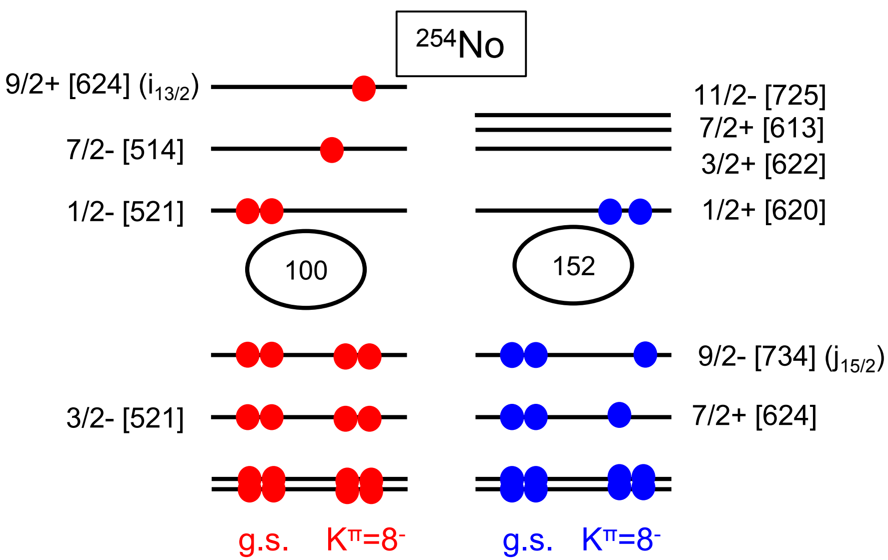
# Why are high-K isomers interesting ?

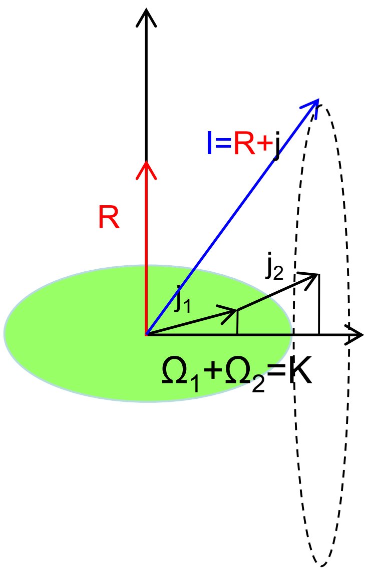
- In even-even nuclei, 0+ states are trivial. 2qp are not !
  - Pair breaking: $E_{2qp} = \sqrt{\underbrace{(E_{sp1} - \lambda)^2}_{\text{Esp vs fermi level}} + \Delta^2} + \sqrt{(E_{sp2} - \lambda)^2 + \Delta^2}$

    Esp vs fermi level — Pairing gap ($\Delta$)

  → pairing correlations

  → study of single-particle states



# Why are high-K isomers interesting ?

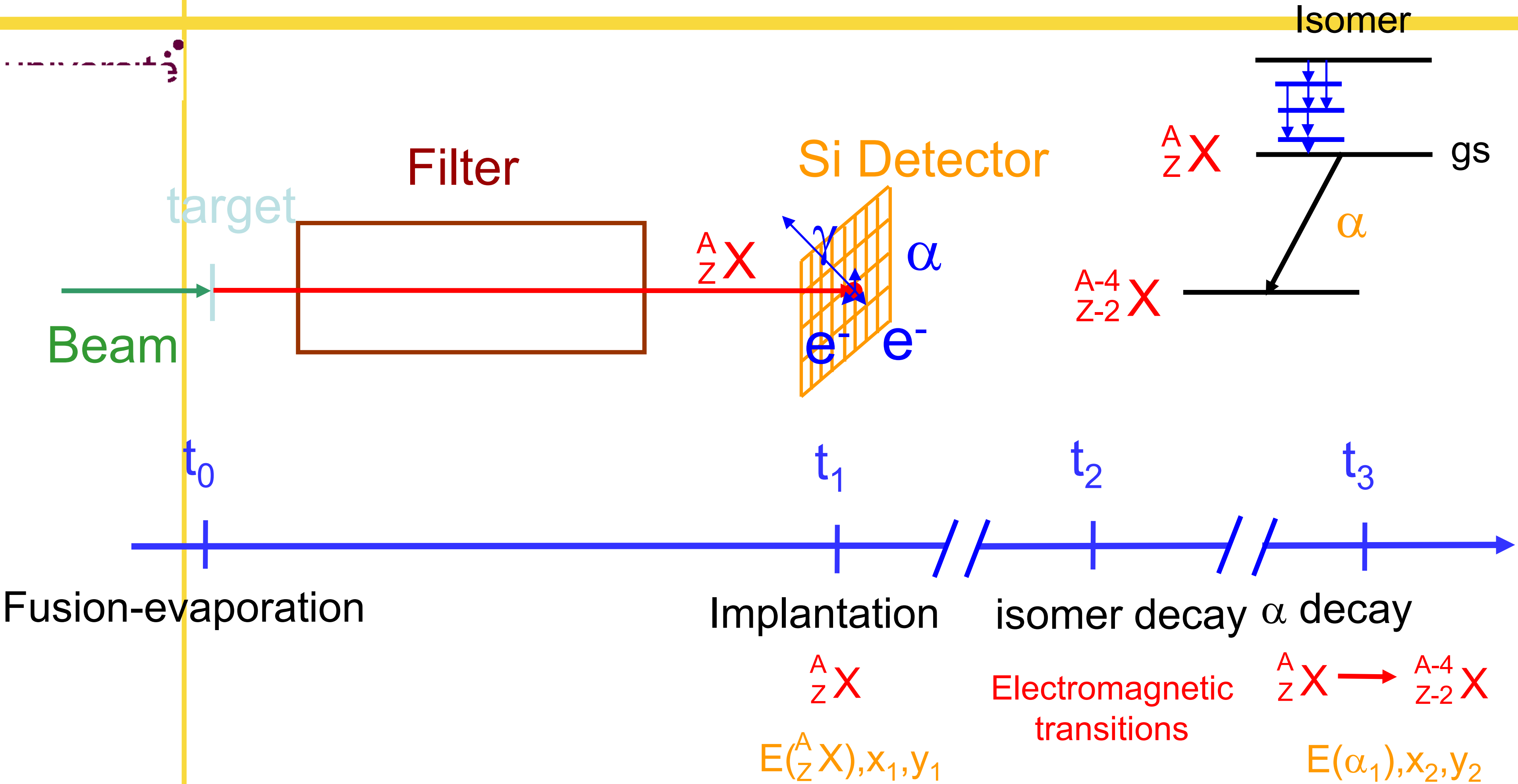
- Pick experimentally states that would not be accessible otherwise, or with too low intensity
  - Spectroscopy of states above the isomer (collectivity)
  - States along the decay path

- High-K states may enhance the stability of SHN due to larger fission barrier (anti-fission role).

  Xu et al. PRL 92 (2004) 252501

- Comparison with theory : proper calculation of 2qp state is very complicated.
  - Pairing gap
  - Recoupling
  - Possible role of vibrations and octupole correlations (→ QRPA)
  - In general agreement is poor in particular for self-consistent models which do not reproduce Z=100 and N=152 deformed shell gaps

# Modern Isomer tagging



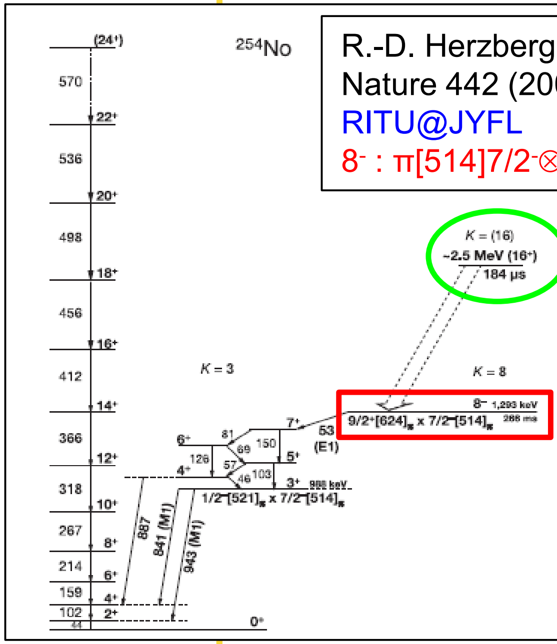

Calorimeter technique :
isomer tagging using the implantation detector
G.D. Jones, Nucl. Instr. And Meth. A 488 (2002) 471

$\Delta t = t_2 - t_1$

$\Rightarrow t_{1/2}$(isomer)

# $^{254}$No K-isomer 30 years after Ghiroso

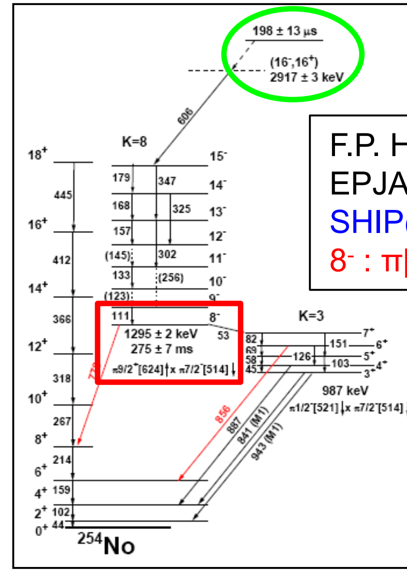
universite PARIS-SACLAY



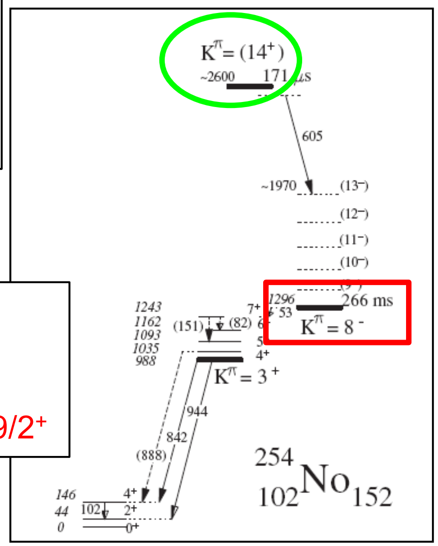

R.-D. Herzberg *et al.*
Nature 442 (2006) 896
RITU@JYFL
8$^-$ : π[514]7/2$^-$⊗ π[624]9/2$^+$

4qp

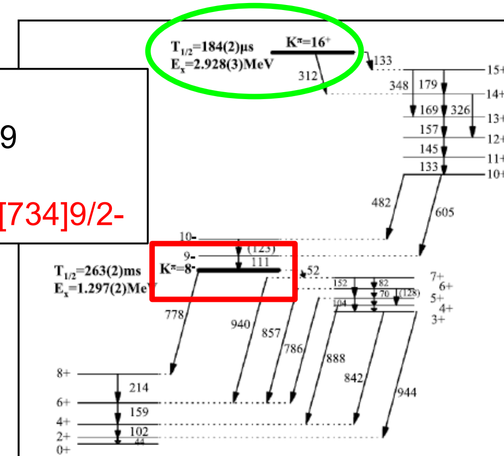
Ghiroso et al
PRC 7 (1973) 2032
$T_{1/2}$ = 0.28 ± 0.04 s
$K^\pi = 8^-$ ,2qp




F.P. Hessberger *et al.*
EPJA 43 (2010) 55
SHIP@GSI
8$^-$ : π[514]7/2-⊗ π[624]9/2+



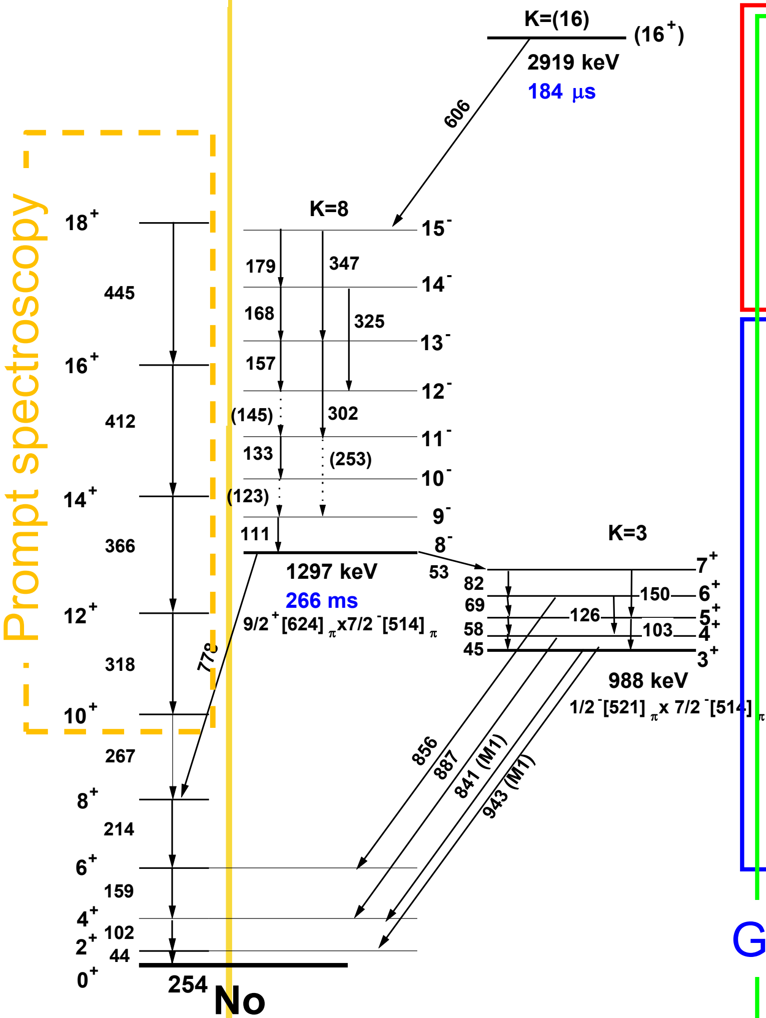

S.K. Tandel *et al.*
PLR 97 (2006) 082502
FMA@ANL
8$^-$ : π[514]7/2-⊗ π[624]9/2$^+$



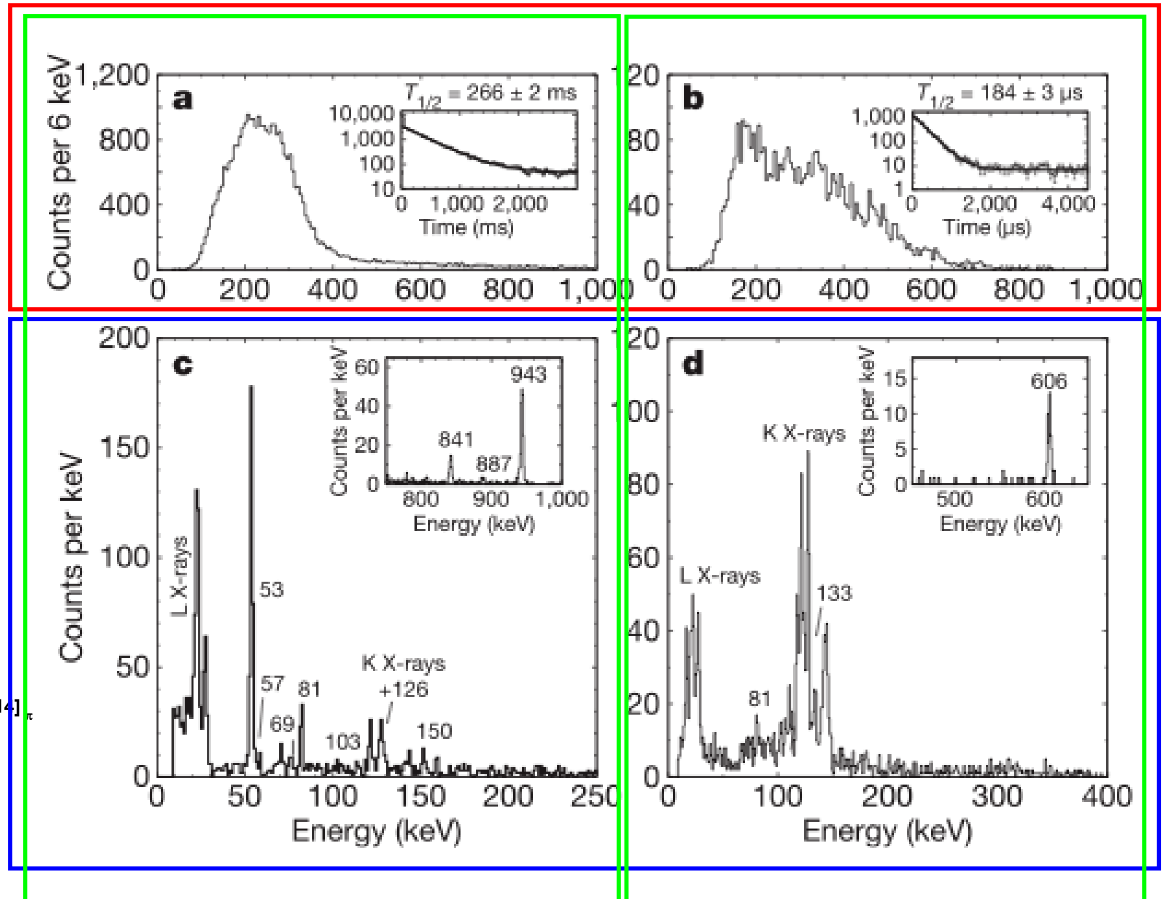

R.M. Clark *et al.*
PLB 690 (2010) 19
BGS@LBNL
8$^-$ : ν[613]7/2+⊗ ν[734]9/2-

Level scheme and single-particle configuration not (yet) clear

# $^{254}$No K-isomers




Electrons, implantation det.




Gammas, Delayed ER-gamma-electron coincidences

Long isomer

Short isomer

R.-D.Herzberg et al Nature 442 (2006) 896

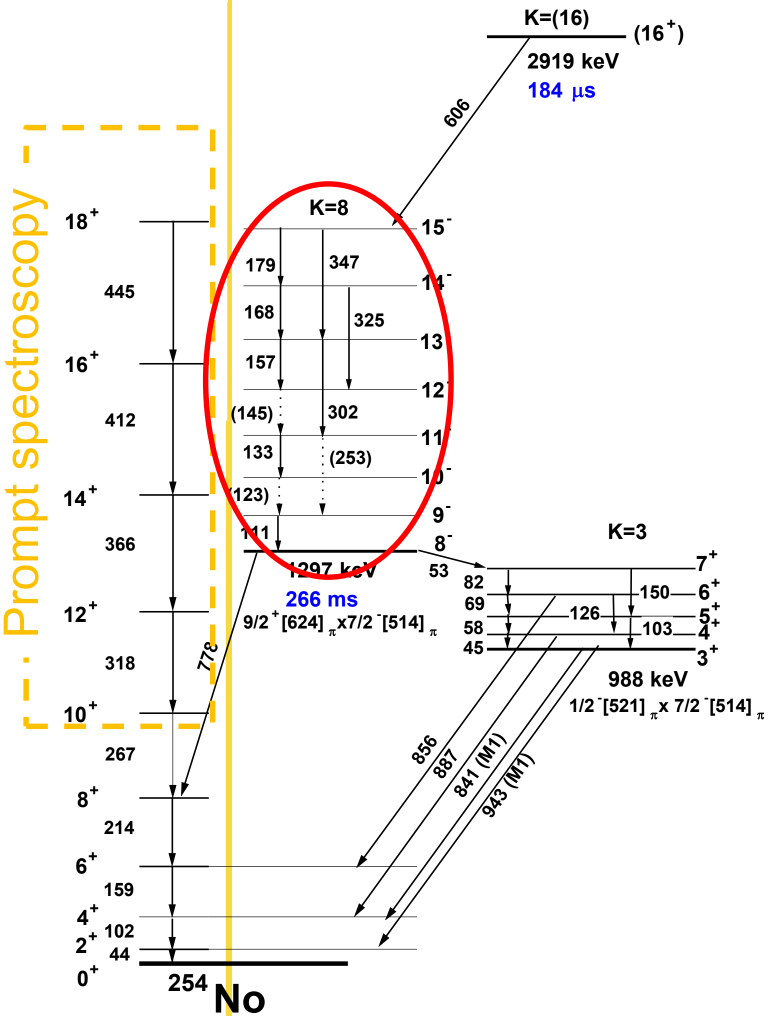
# $^{254}$No K-isomers

$$B(E2) = \frac{5}{16\pi} \langle I\ K\ 2\ 0 \mid I\text{-}2\ K \rangle^2\ Q_0^2\ (e^2\ fm^4)$$

$$B(M1) = \frac{3}{4\pi} K^2 (g_K - g_R)^2 \langle I\ K\ 1\ 0 \mid I\text{-}1\ K \rangle^2\ (\mu_n^2)$$

$$\mu = \left[ g_R I + (g_K - g_R) \frac{K^2}{I+1} \right] \mu_N \qquad g_R \sim Z/A$$

$$g_K \sim \frac{1}{K} (g_s \Sigma + g_l \Lambda)$$




$g_K$ is characteristic of the orbital(s) and helps to constrain the single-particle alignment.

For 2 qp however no so simple since the $g_K$ factors sum.
Gallagher–Moszkowski rule : coupling anti-parallel spins favoured → $g_K \sim \frac{1}{K} g_l (\Lambda_1 + \Lambda_2)$ = 1 for protons, 0 for neutrons

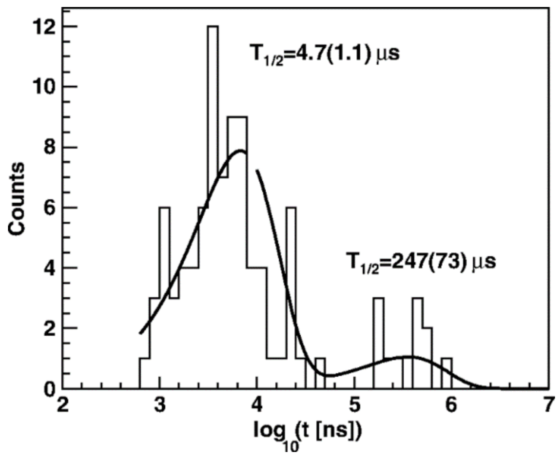
Also a good (better) case for prompt spectroscopy

# $^{254}$Rf high-K isomer

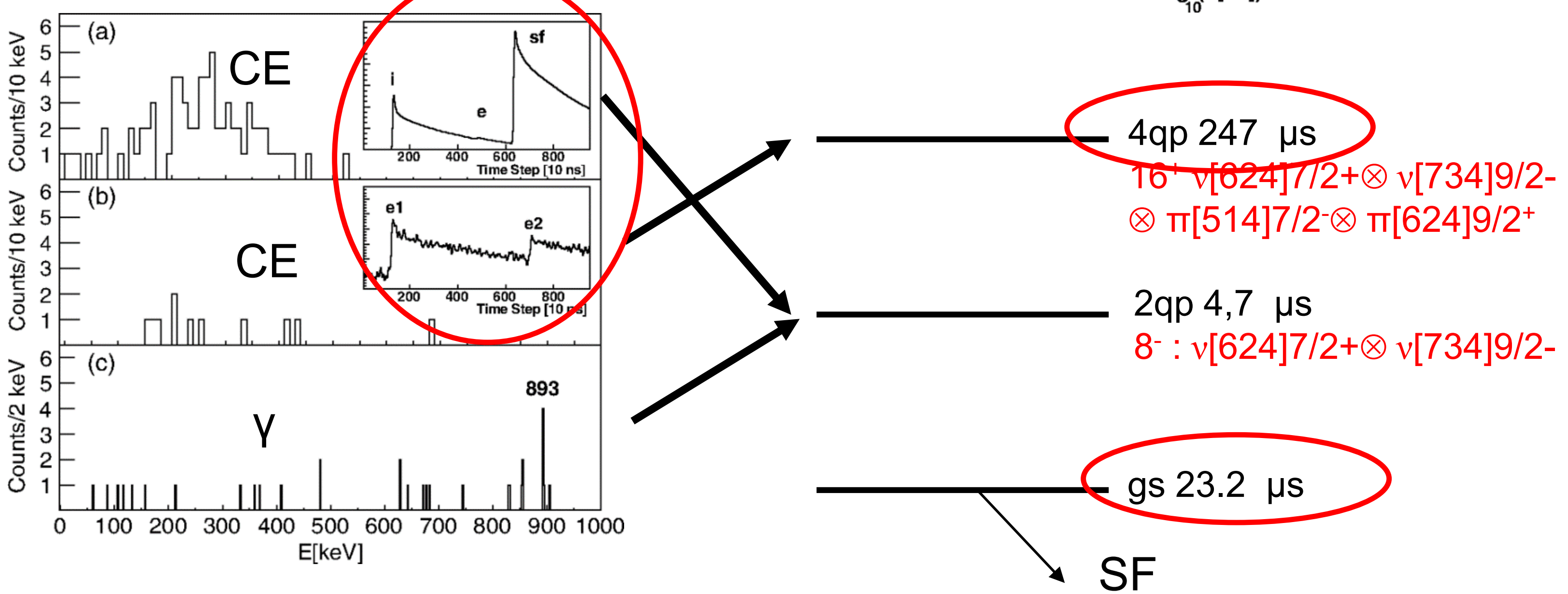
David et al PRL 115 (2015) 132502

FMQ@ANL and BGS@LBNL

$^{50}$Ti($^{206}$Pb,2n)$^{254}$Rf σ ~2.4 nb

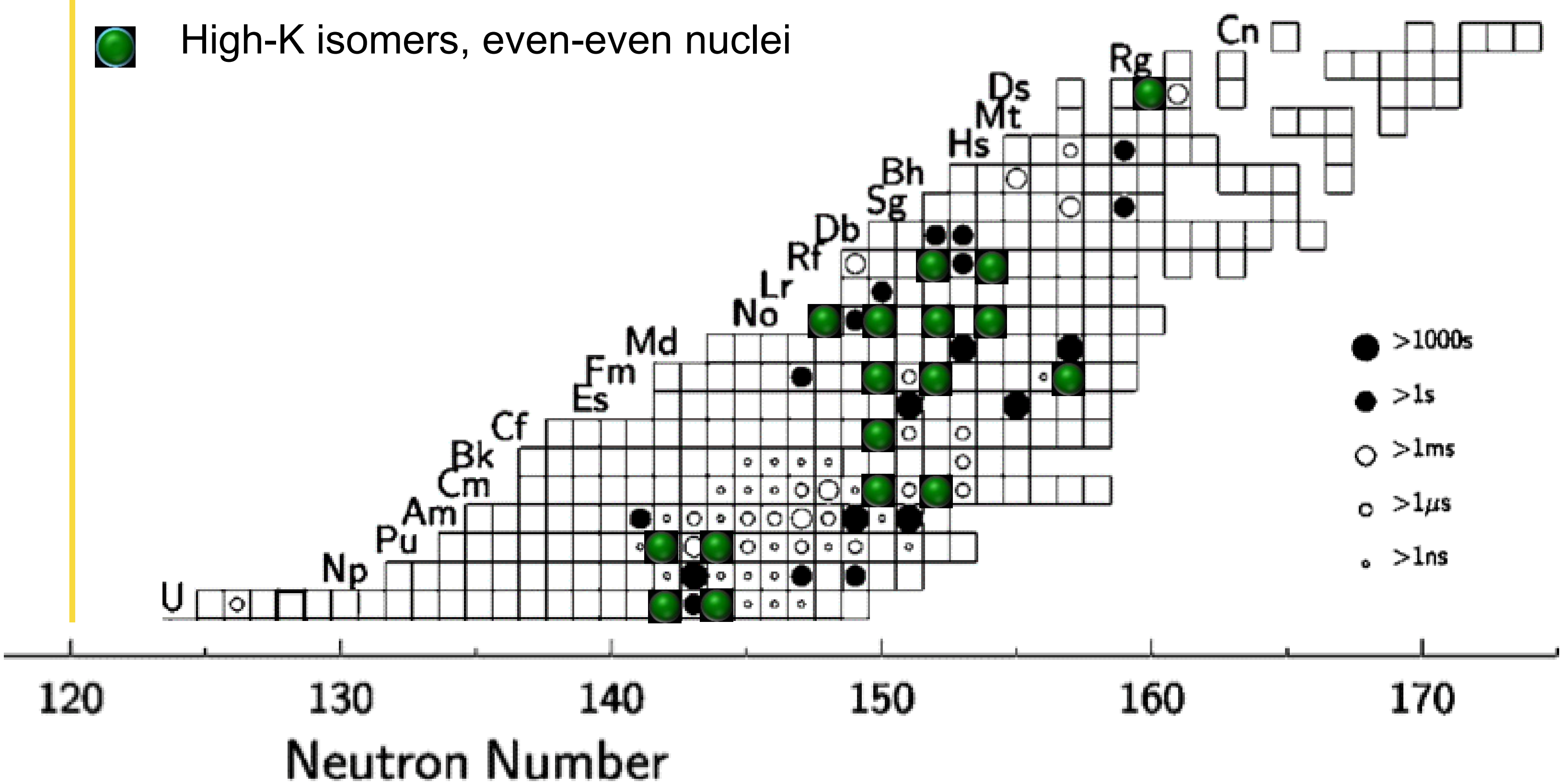



Digital electronics mandatory




Also isomeric state longer than g.s. in $^{250}$No
(Peterson D et al PRC 74 (2006) 014316, Barbara + Jinesh to be published)

# Isomers in heavy nuclei




R.-D. Herzberg* and D. M. Cox, Radiochim. Acta 99, 441–457 (2011)

Also 3qp high-K isomers in even-Z, even-N isotopes

# Ground state properties

- Mass measurement

One of the most fundamental quantity in nuclear physics and test for the models

- Laser spectroscopy

Basics = influence of the nucleus on the atomic electrons

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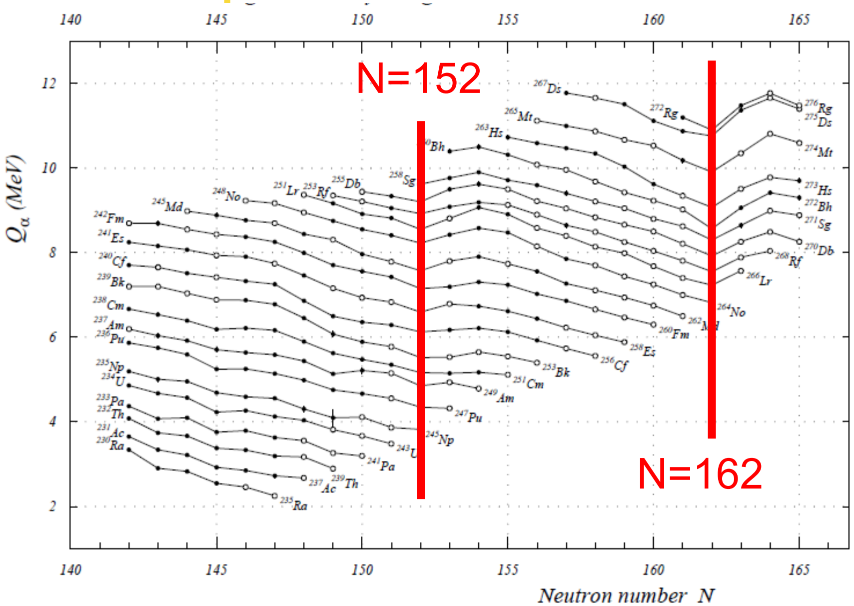
université PARIS-SACLAY

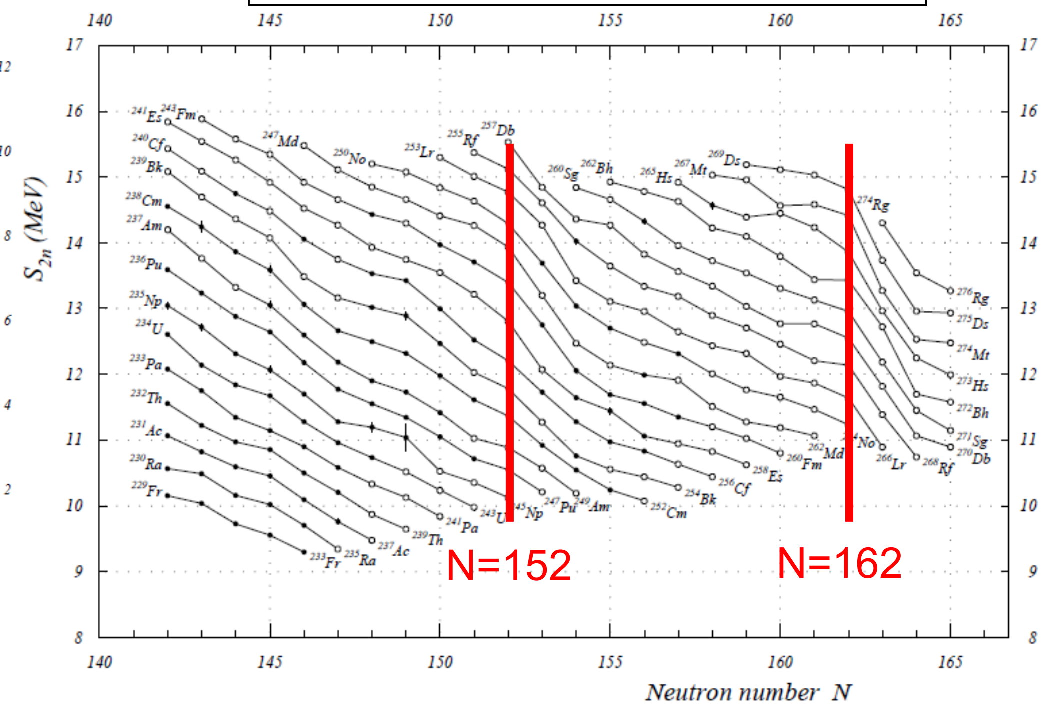
# Mass measurement

- In VHE/SHE : mass usually deduced from alpha decay. Chain anchored to lighter nucleus which mass is known.
  - In some SHE decay chain ending by fission (hot fission region)
  - Problem in odd nuclei since most intense alpha line not a gs to gs transition.

$Q_\alpha(N,Z) = M(N,Z)-M(N-4,Z-2)-M_\alpha$



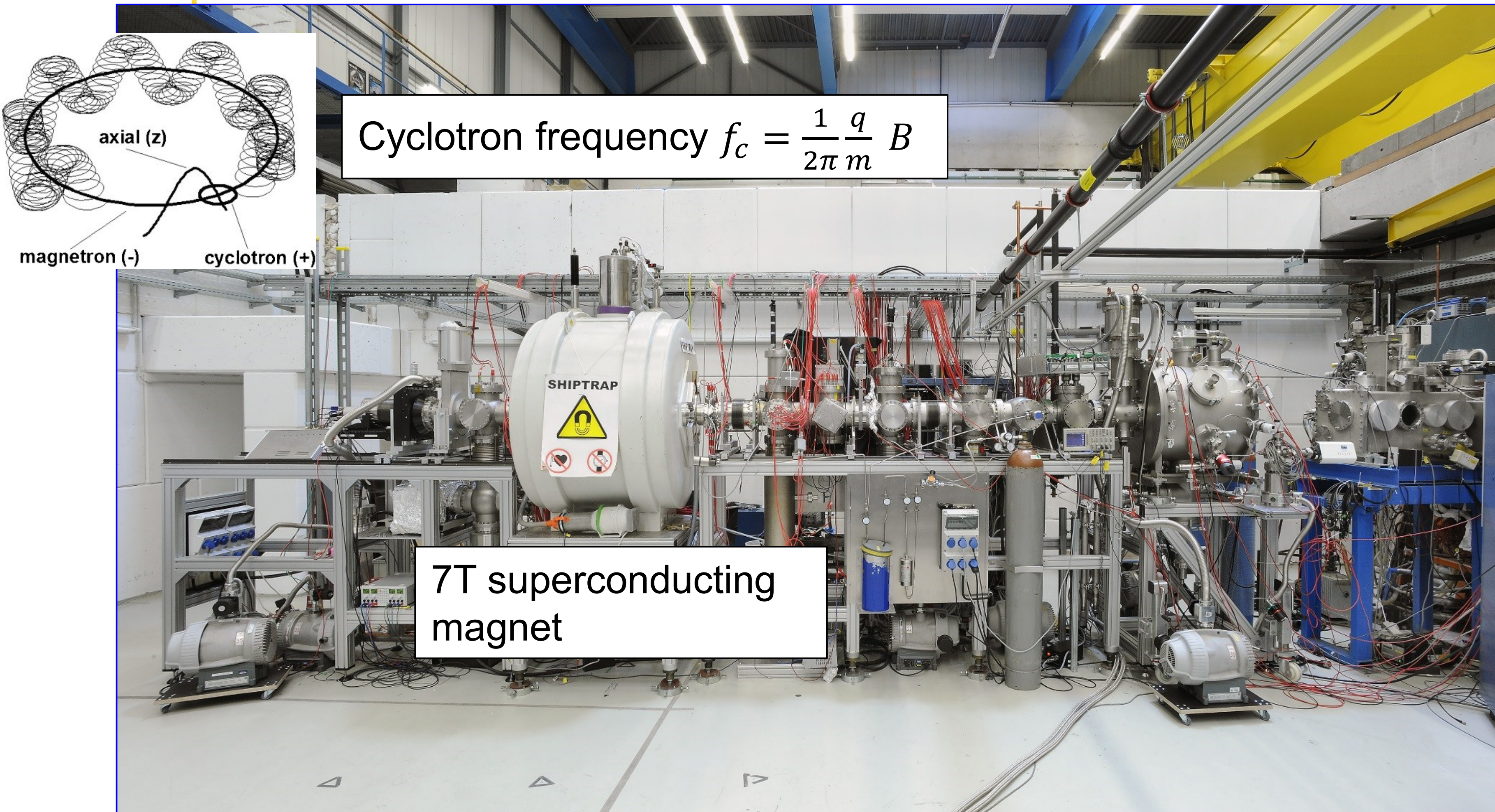

Two-neutrons separation energy
$S_{2n}(N,Z) = M(N,Z)-M(N-2,Z)+2M_n$




Atomic Mass Evaluation 2016
Chin. J. Phys. C 41 (2017) 030003

# Mass measurement

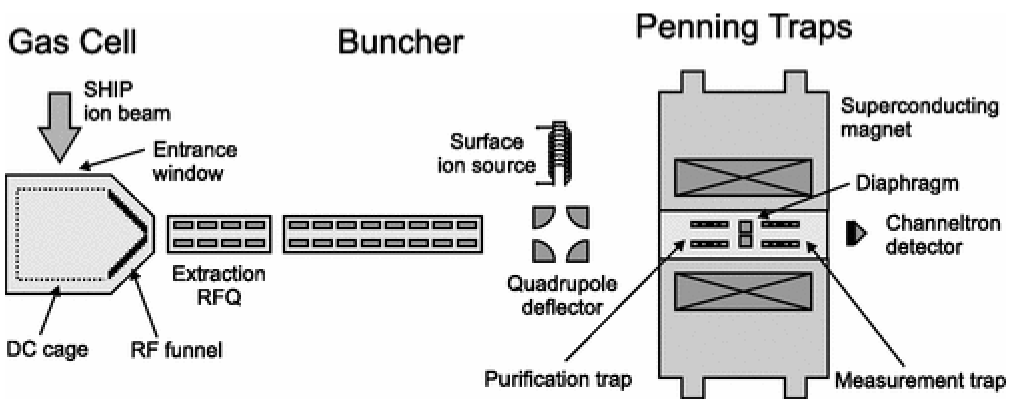
Recent breakthrough : Mass measurement in $^{252\text{-}255}$No, $^{255,256}$Lr at SHIP + SHIPTRAP (penning trap)



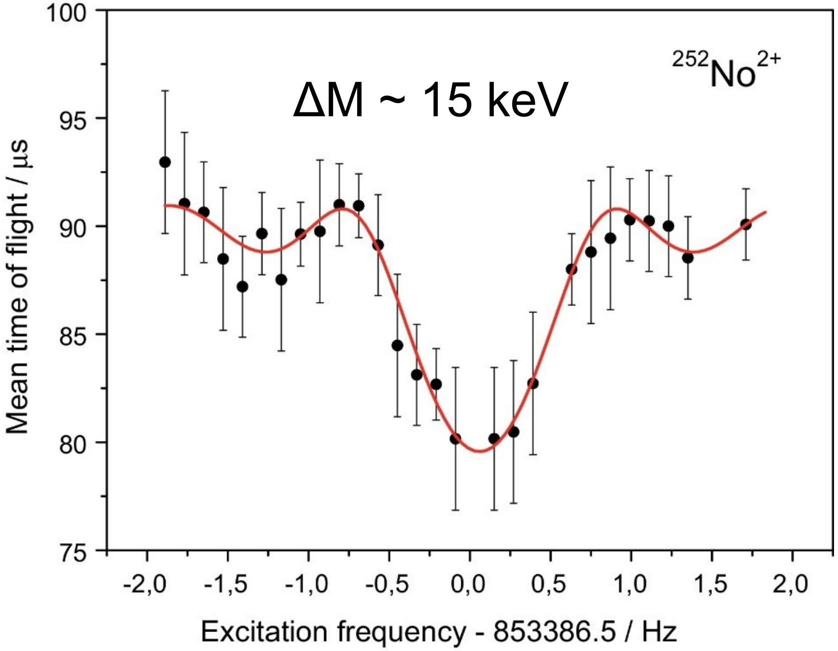

Cyclotron frequency $f_c = \frac{1}{2\pi}\frac{q}{m}B$

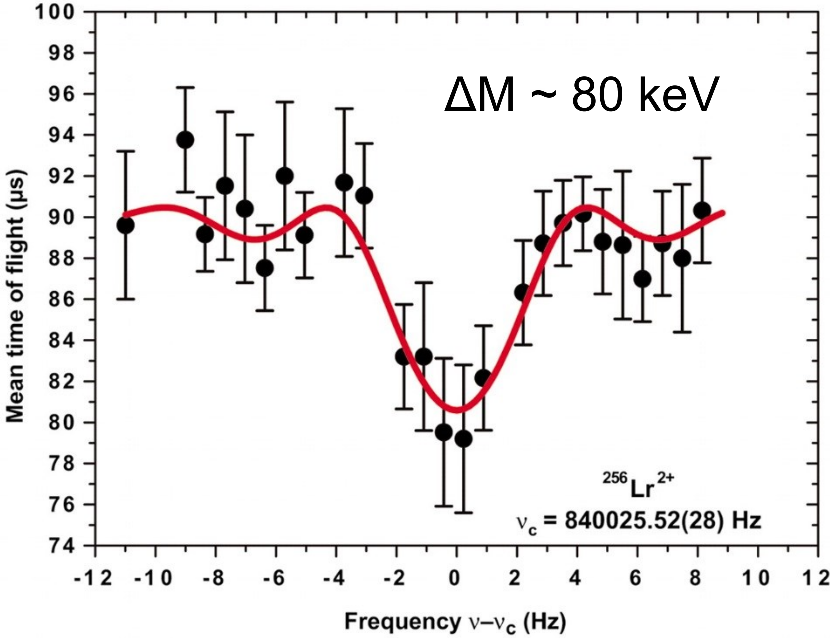
7T superconducting magnet

# Mass measurement in No-Lr




Dworschak et al.
PRC 81 (2010) 064132




M. Block. Int. J. Mass. Spec. 349 (2013) 94

E. Minaya Ramirez Science 337 (2012) 1207

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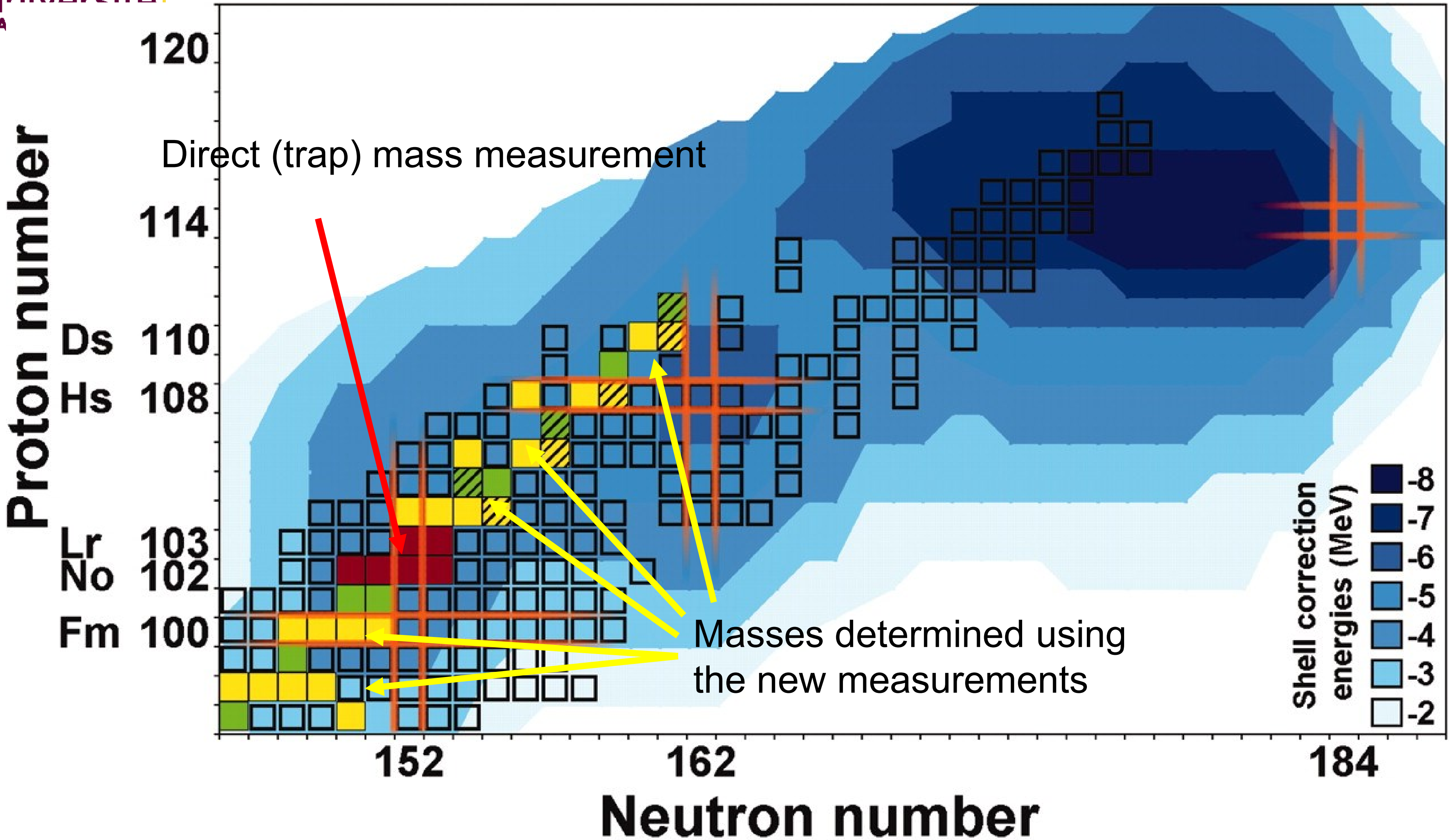
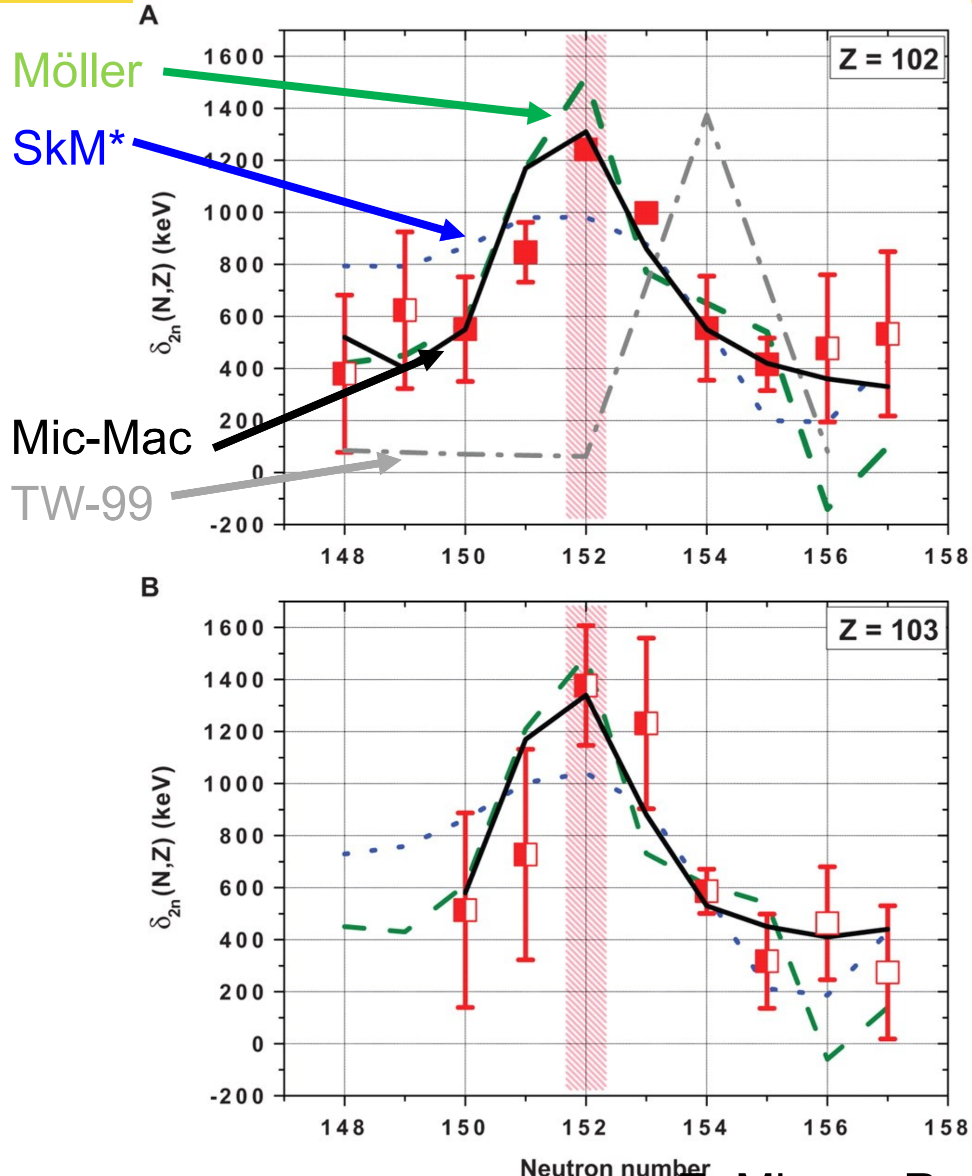



E. Minaya Ramirez Science 337 (2012) 1207

# Masses vs models




*Shell gap parameter*
$\delta_{2n}(N,Z) = S_{2n}(N,Z) - S_{2n}(N+2,Z) = -2\, M_{exc}(N,Z) + M_{exc}(N-2,Z) + M_{exc}(N+2,Z)$,

E. Minaya Ramirez Science 337 (2012) 1207

# Prospects

Mass measurement of isomeric states

Use of an ion trap for purification before spectroscopy

- trap assisted decay spectroscopy
- In-trap decay spectroscopy = detectors in the trap.

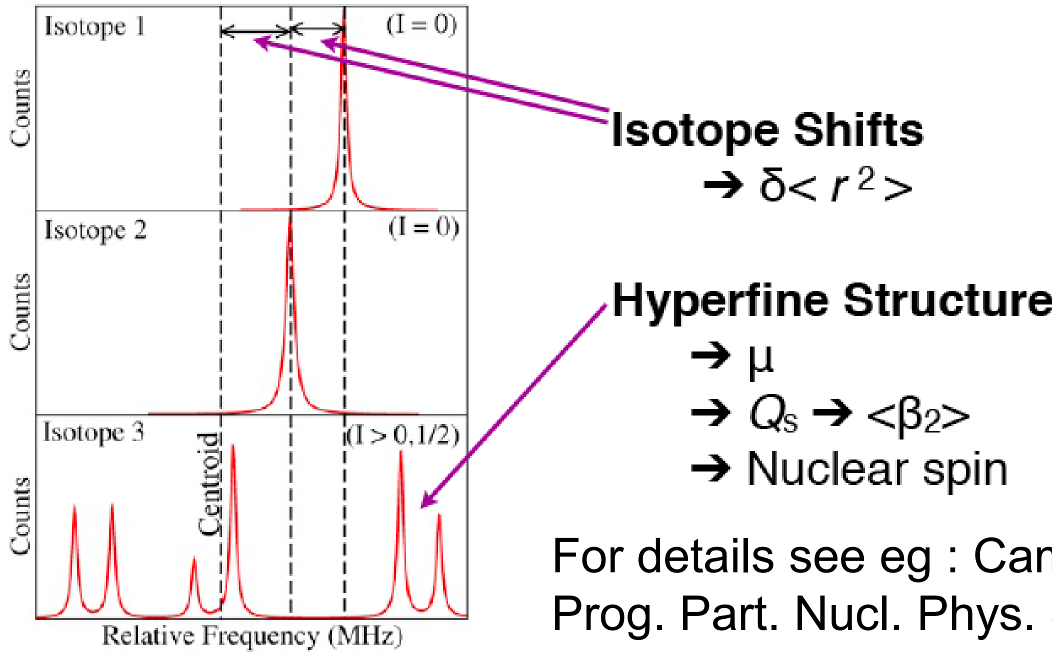
→ see eg conversion electron in-trap spectroscopy at REXTRAP (ISOLDE) Weissman et al NIM A 492 (2002) 451, MLLTRAP Weber, P. Müller, P.G. Thirolf Int. J. Mass Spec. 349 (2013) 270

# Laser spectroscopy

Basics : effect of the nuclear moments (electric quadrupole, magnetic dipole) and radius on the atomic lines. Nuclear model independent.

- Small effect therefore high precision needed.
- Atom excitation using lasers
- Scan of the laser frequency → selective ionisation

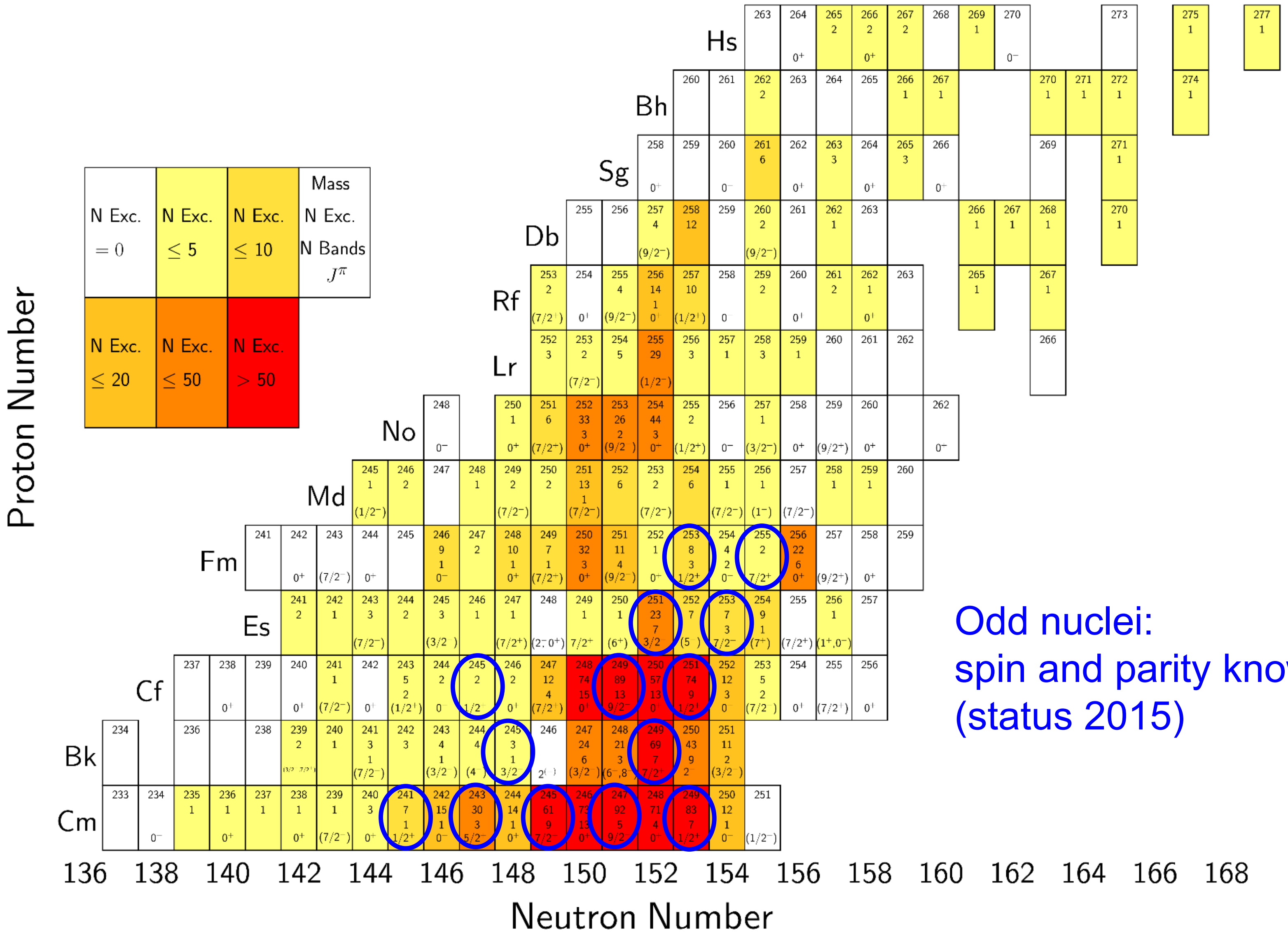
→ spectroscopy




M. Block

For details see eg : Campbell, Moore, Pearson Prog. Part. Nucl. Phys. 86 (2016) 127

# Spin and parity




Odd nuclei:
spin and parity known
(status 2015)

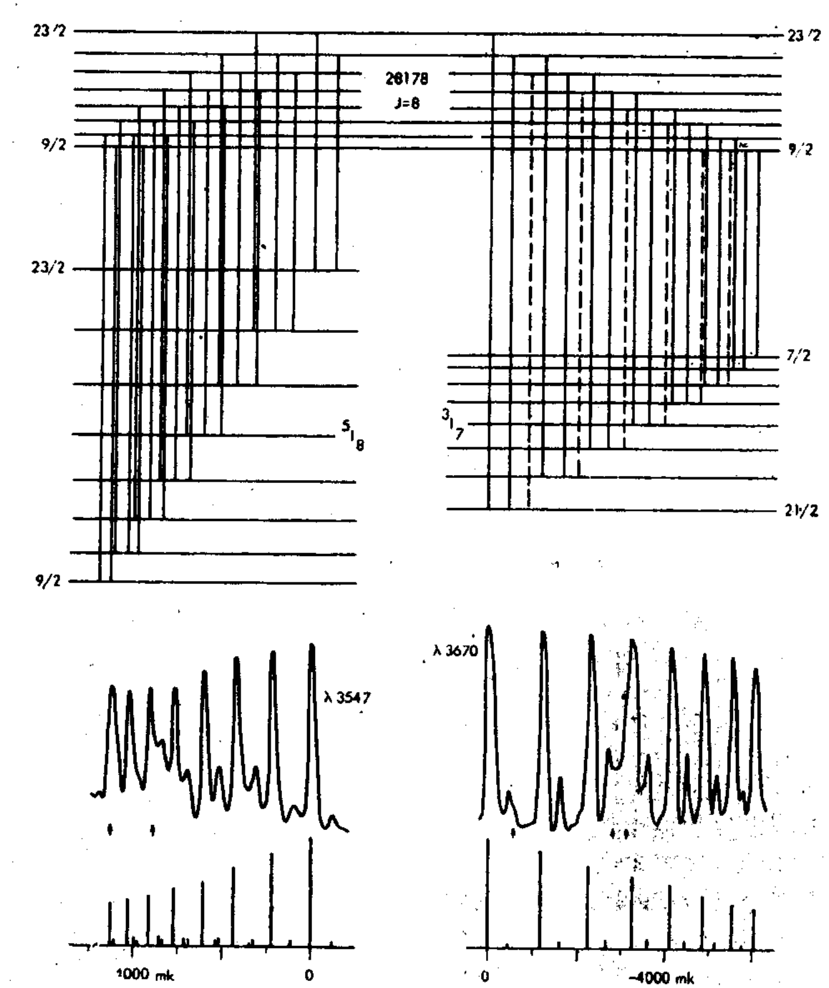
# $^{253}$Es optics spectroscopy case (no laser)

E.S. Worden et al., Jour. Opt. Soc. Am. 58 (1968) 998, 60 (1970) 1297

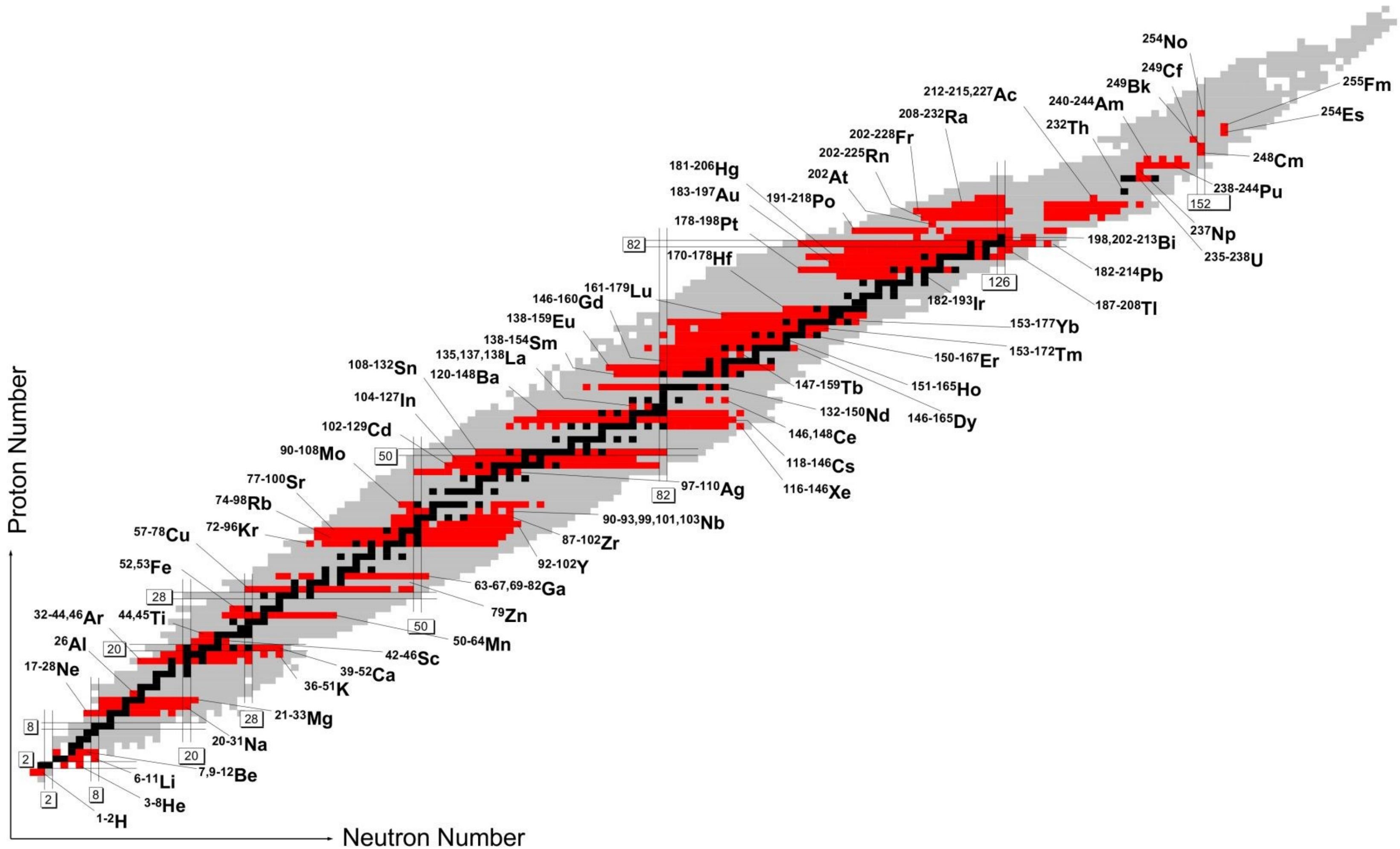
Ionisation : lamp from $^{253}$Es ($t_{1/2}$ = 20days) sample (0.8 µg)

53 lines observed;
23 with hyperfine structure

I = 7/2
$\mu$ =5.1 ± 1.3 $\mu_N$
Q ≠ 0, but not deduced



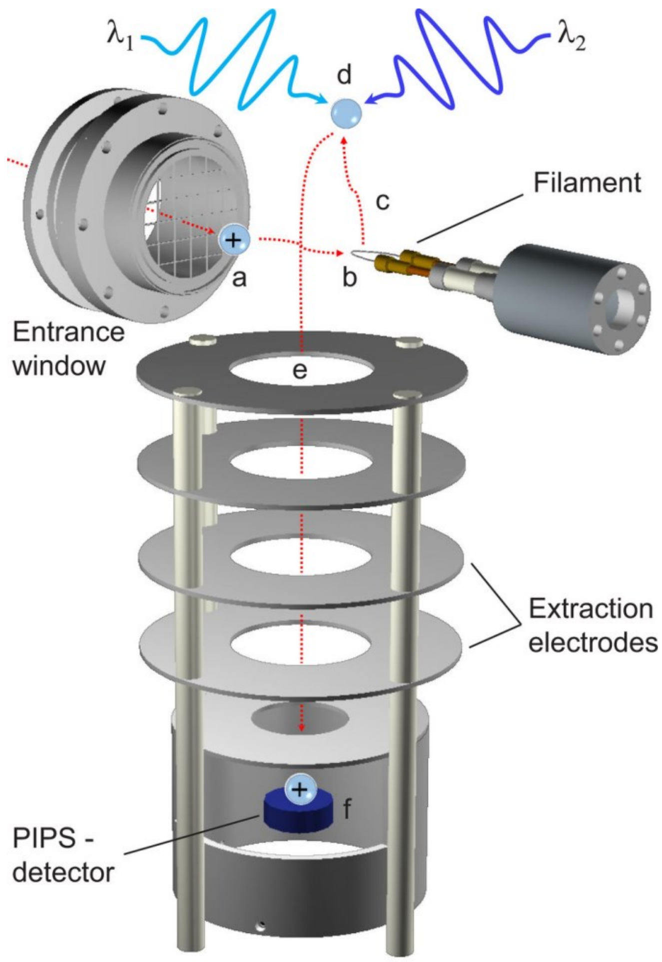
# Laser spectroscopy status (2017/03)



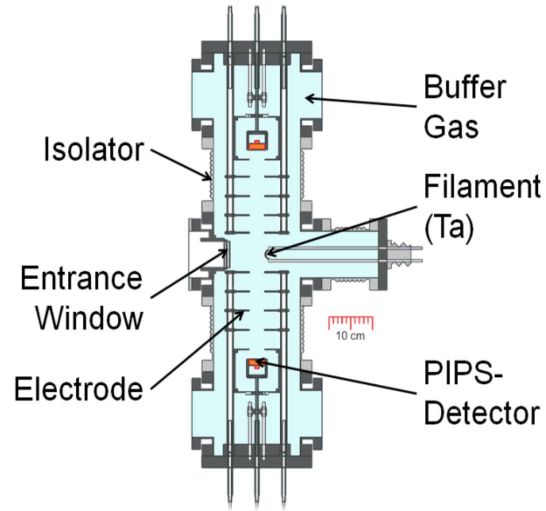

http://www.ikp.tu-darmstadt.de/gruppen_ikp/ag_noertershaeuser/research_wn/exotic_nuclei_wn/uebersicht_2/laserspectroscopy_survey.en.jsp

# The RADRIS technique at SHIP

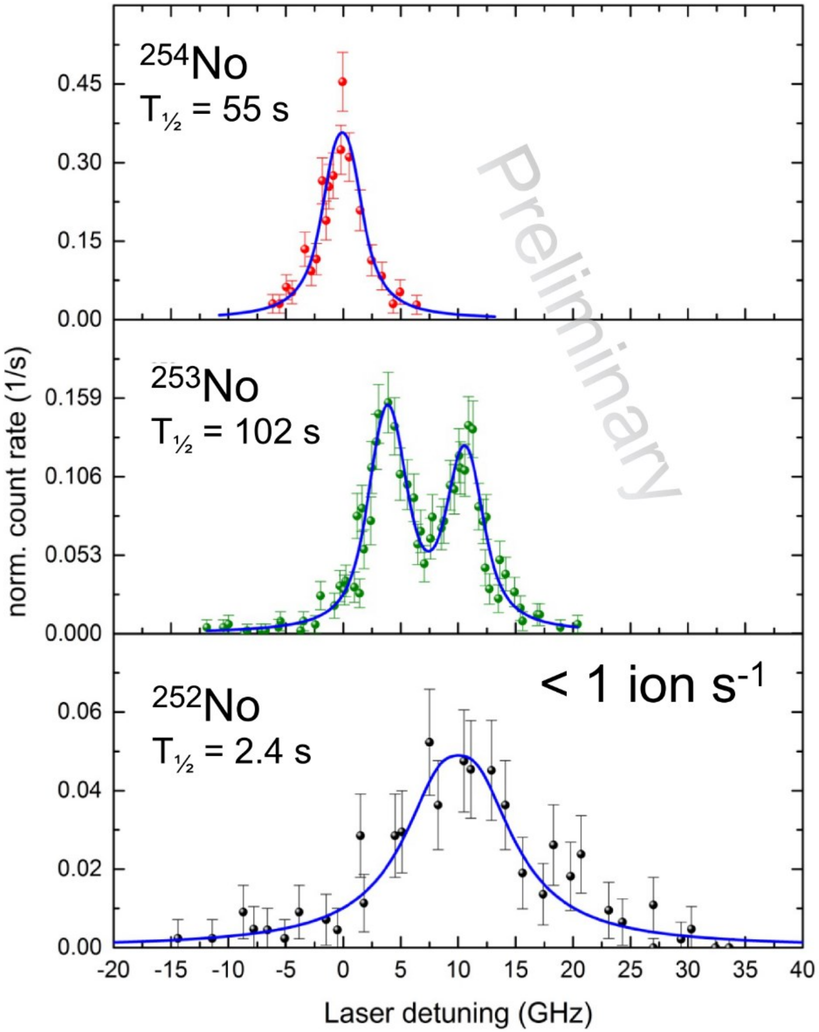
RAdioactive Decay-Detected Resonance Ionization Spectroscopy




a: thermalization in gas
b: accumulation on a filament
c: re-evaporation from the filament
d: two step ionisation (laser)
e: transport to the detector
f: decay detection



# $^{232-254}$No laser spectroscopy

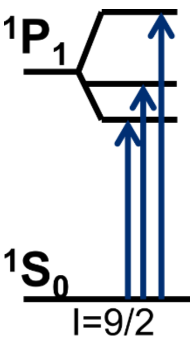



$^{252,254}$No :

M. Laatiaoui et al., Nature 538 (2016) 495

→Isotopic shift

- $^{253}$No, M. Laatiaoui et al. to be published
  - Fine structure not fully resolved
  - Compatible with I=9/2
  - μ, Qs



# Hyperfine splitting

$$\Delta E_{HFS} = \Delta E_{dipole} + \Delta E_{quadrupole}$$

$$\Delta E_{HFS} = \frac{A}{2}C + \frac{B}{4}\frac{\frac{3}{2}C(C+1) - 2IJ(I+1)(J+1)}{IJ(2I-1)(2J-1)}$$

*I* : nuclear spin; *J*: atomic spin

$$C = F(F+1) - J(J+1) - I(I+1)$$

*A, B* : hyperfine factor

$$A = \frac{\mu B_e(0)}{IJ}$$

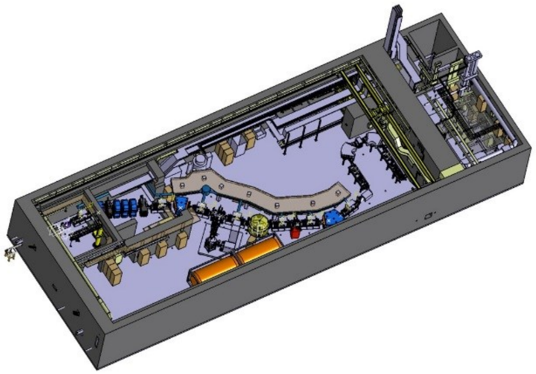
$\mu$: nuclear magnetic dipole moment

$$B = eQ_s\left\langle\frac{\partial^2 V}{\partial z^2}\right\rangle$$

$Q_s$: nuclear electric quadrupole moment

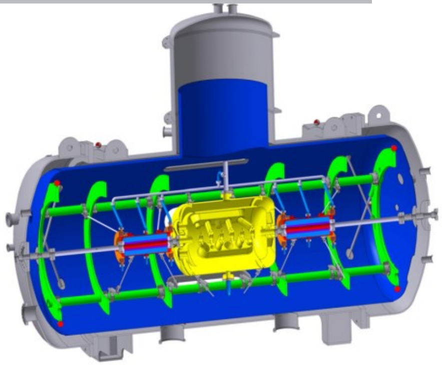
# Forthcoming facilities, upgrades

- S3 at SPIRAL2/GANIL



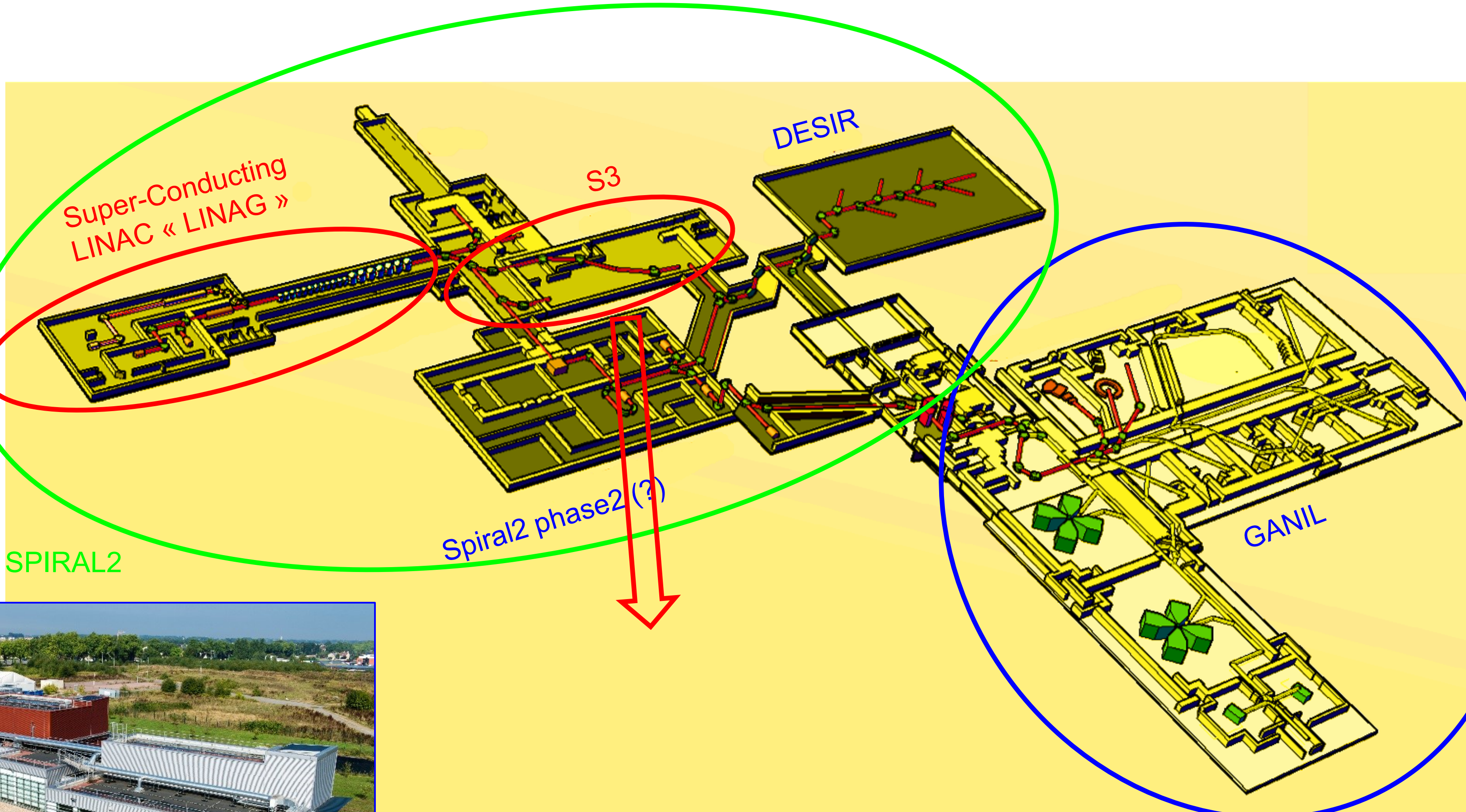
- SHE factory, Dubna

- GSI cw-linac upgrade

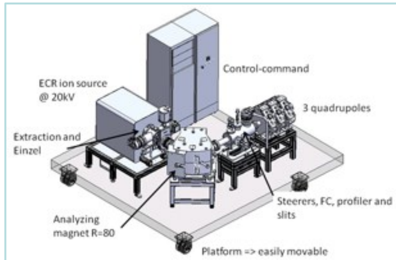


- ATLAS upgrade at ANL

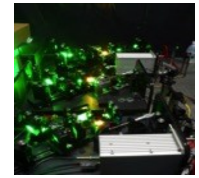
# GANIL/SPIRAL2




# S3

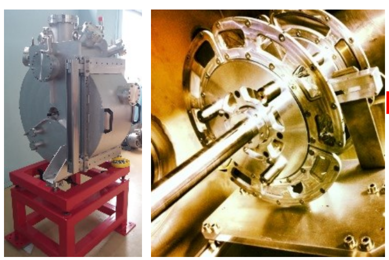



**Atomic Physics**
FISIC =
Fast Ion Slow
Ion Collisions
Electron exchange

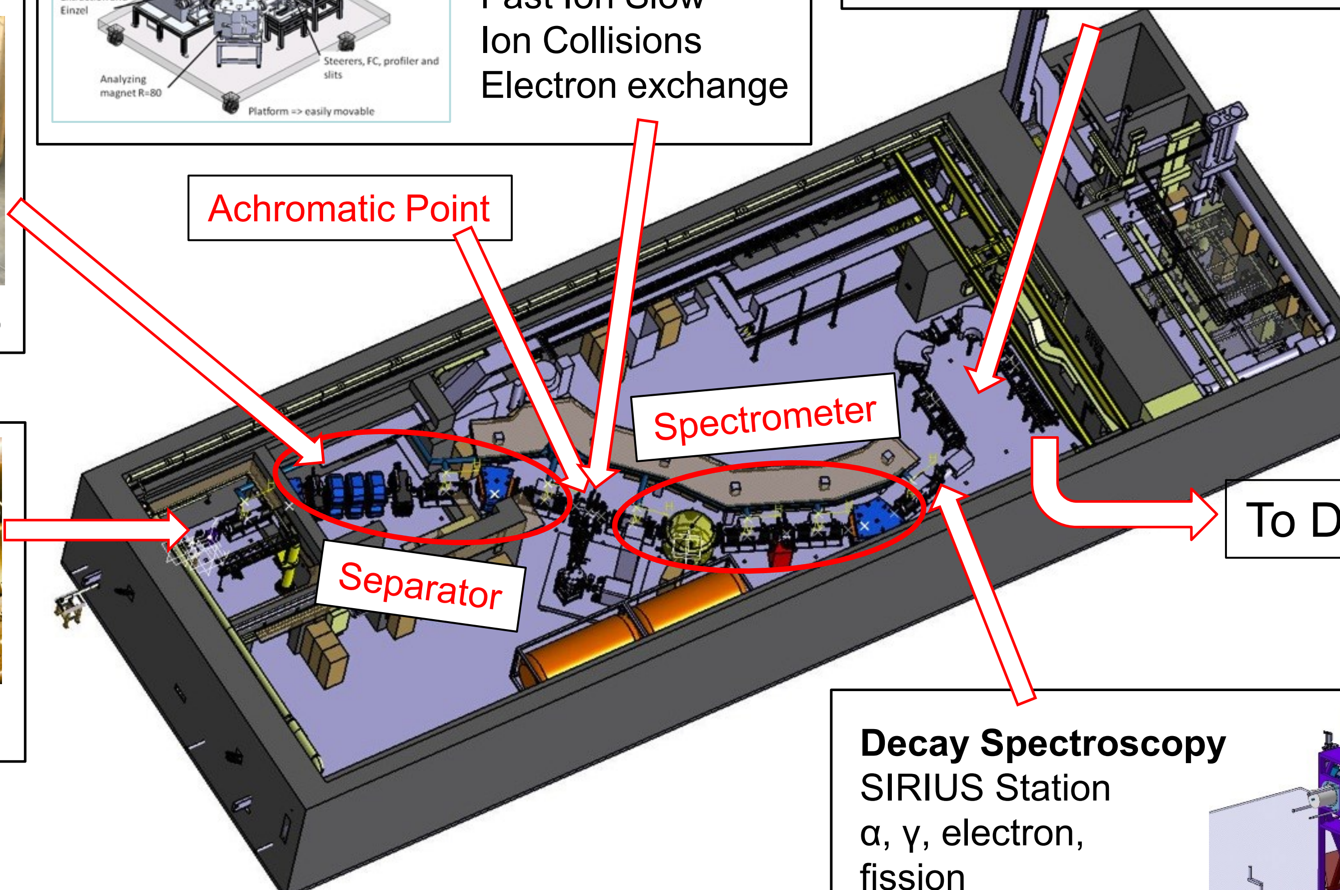


**Ground state properties**
Low energy branch
REGLIS

Primary beam dump

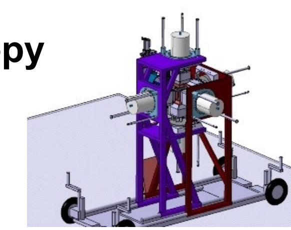


**Target cave**




F. Dechery et al., Eur. Phys. J. A (2015) 51: 66

**Decay Spectroscopy**
SIRIUS Station
α, γ, electron,
fission



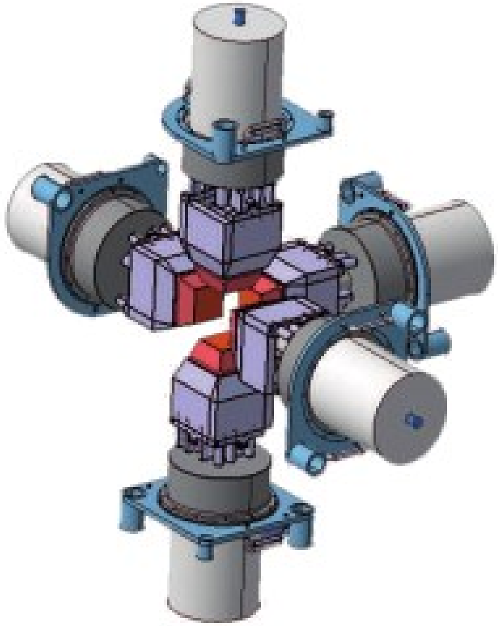
# SIRIUS



## Spectroscopy & Identification of Rare Ions Using S3

Alpha, electron, gamma decay spectroscopy

- Time of flight and tracking of (super)heavy ions
- Implantation decay correlation (10x10cm$^2$, 128x128ch DSSD)
- Tunnel 4 det. 10x10cm$^2$ 1 mm thick, electron spectroscopy
- Ge detector « CLODETTE » and EXOGAM
- Digital electronics for fast decay measurements



*J. Piot and the S$^3$ collaboration, Acta Phys. Pol. B* ***43*** *(2012) 285.*

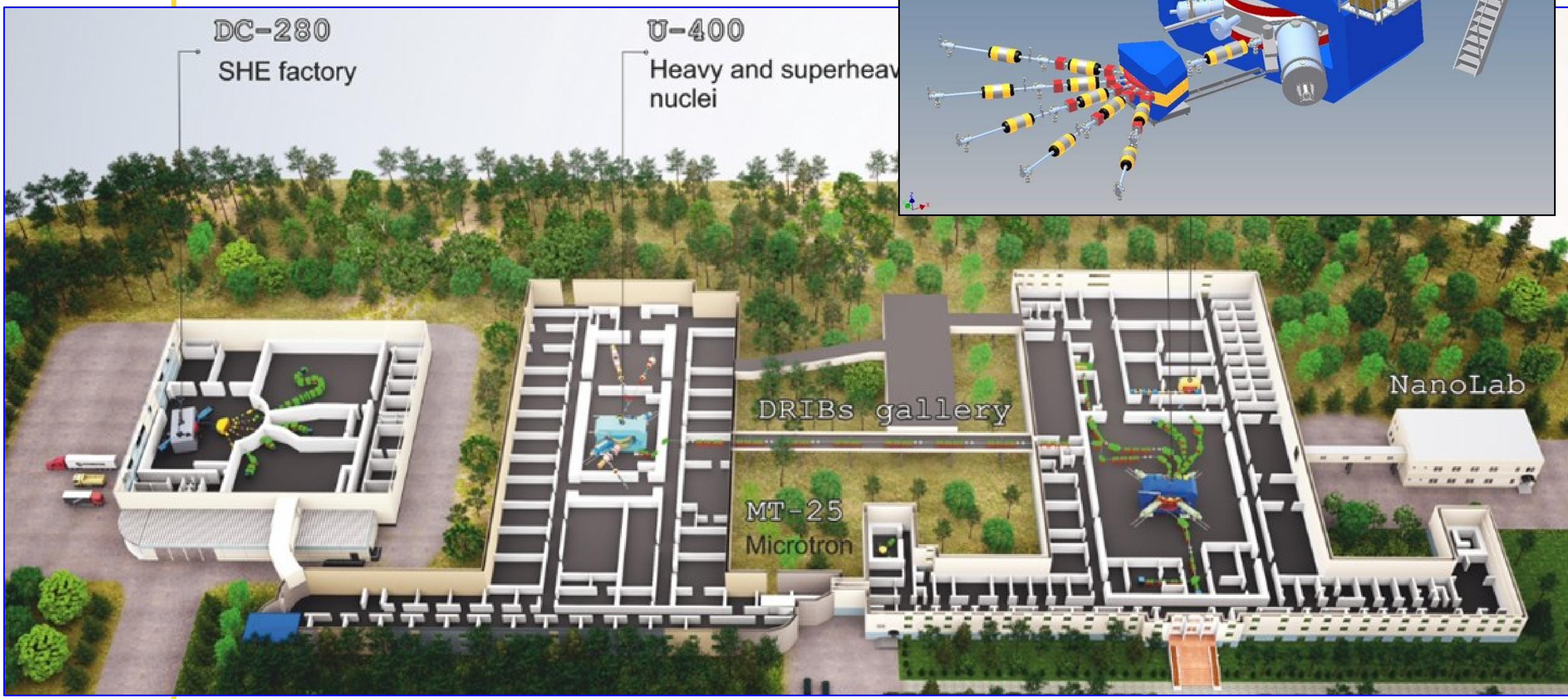
Irfu Institut de recherche sur les lois fondamentales de l'Univers

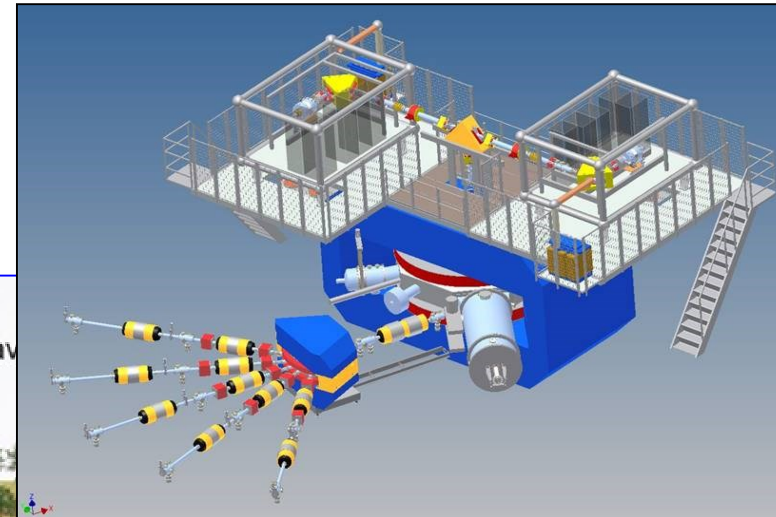
CSNSM

IPHC Institut Pluridisciplinaire Hubert CURIEN STRASBOURG

GANIL Spiral2

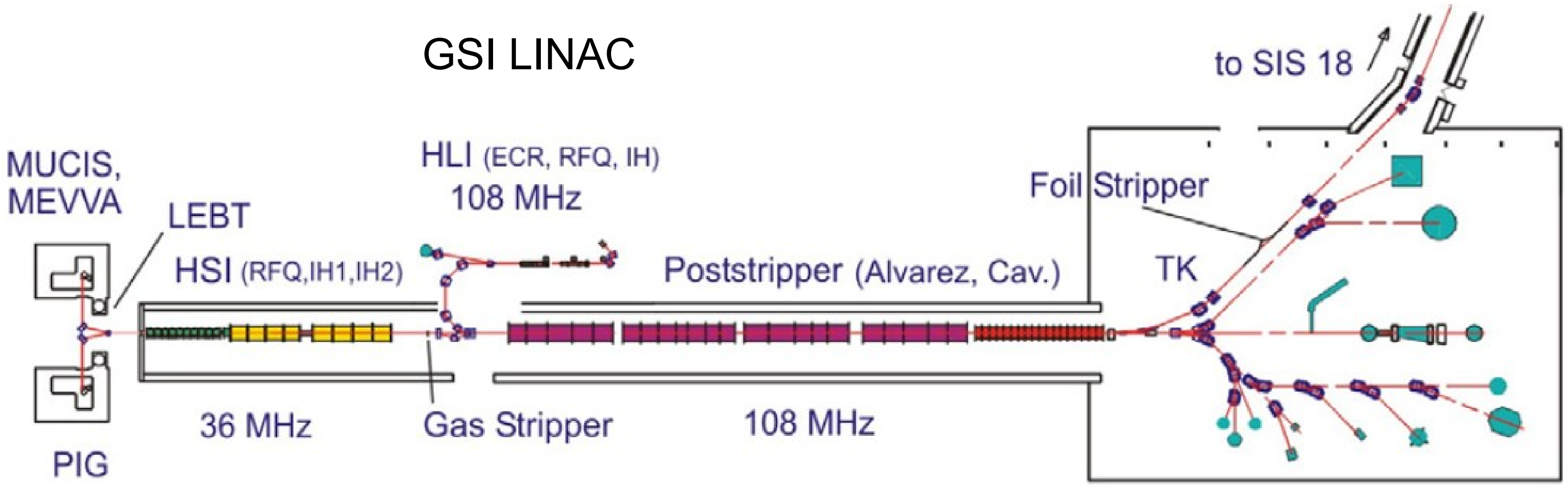
# SHE factory, Dubna

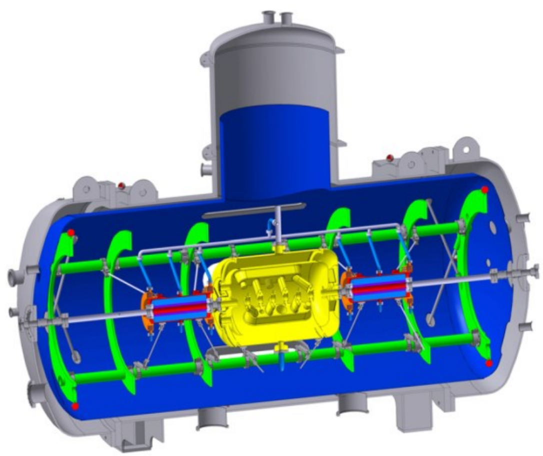


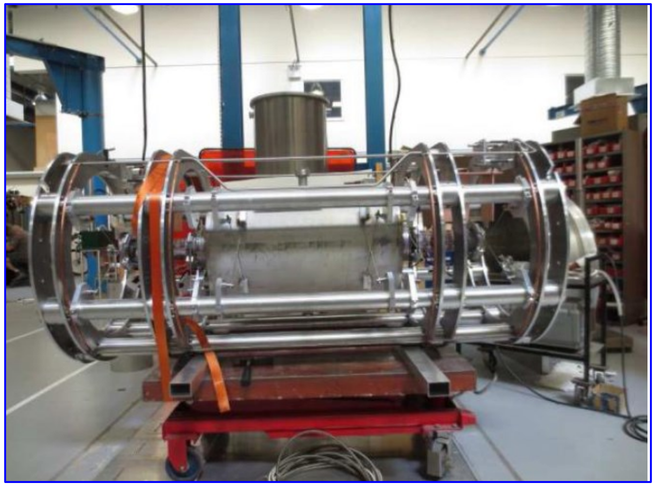



http://flerovlab.jinr.ru/flnr/she_factory_no.html

# GSI LINAC upgrade





Overall gain × 40 compared to present facility.

Bath et al. EPJ Web of conferences 138 (2017) 01026

cw-LINAC demonstrator

# Curent trends, …

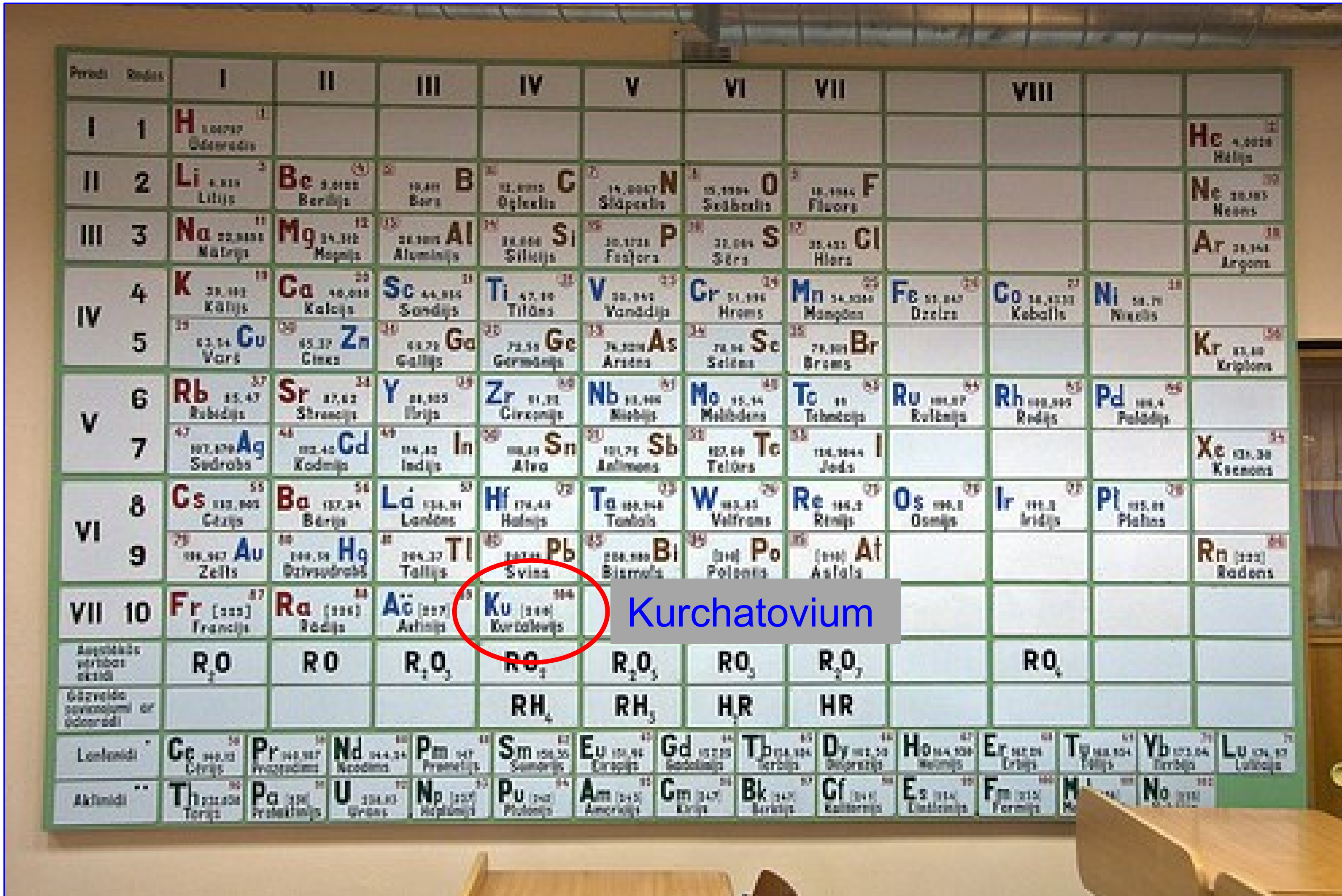
- Synthesis of new nuclei/elements
  - Heavier and heavier
  - More neutron rich (MNT reactions, etc.)
- Spectroscopy
  - Heavier elements, more details
  - Decay spectroscopy
    - Conversion electrons
    - Trap-assisted, In-trap
  - Prompt spectroscopy
    - Conversion electrons
    - Beyond $^{256}$Rf
  - High-K isomers, 2qp, 3qp, 4qp
  - Elements in the U-Es region
- Ground states properties
  - Mass measurements
  - Laser spectroscopy
- Theory
  - the Z=100, N=152 puzzle
  - Beyond mean field
- …

# Naming of the elements


Naming ceremony conducted at the GSI on 7 September 1992 for the namings of elements 107, 108, and 109 as nielsbohrium, hassium, and meitnerium

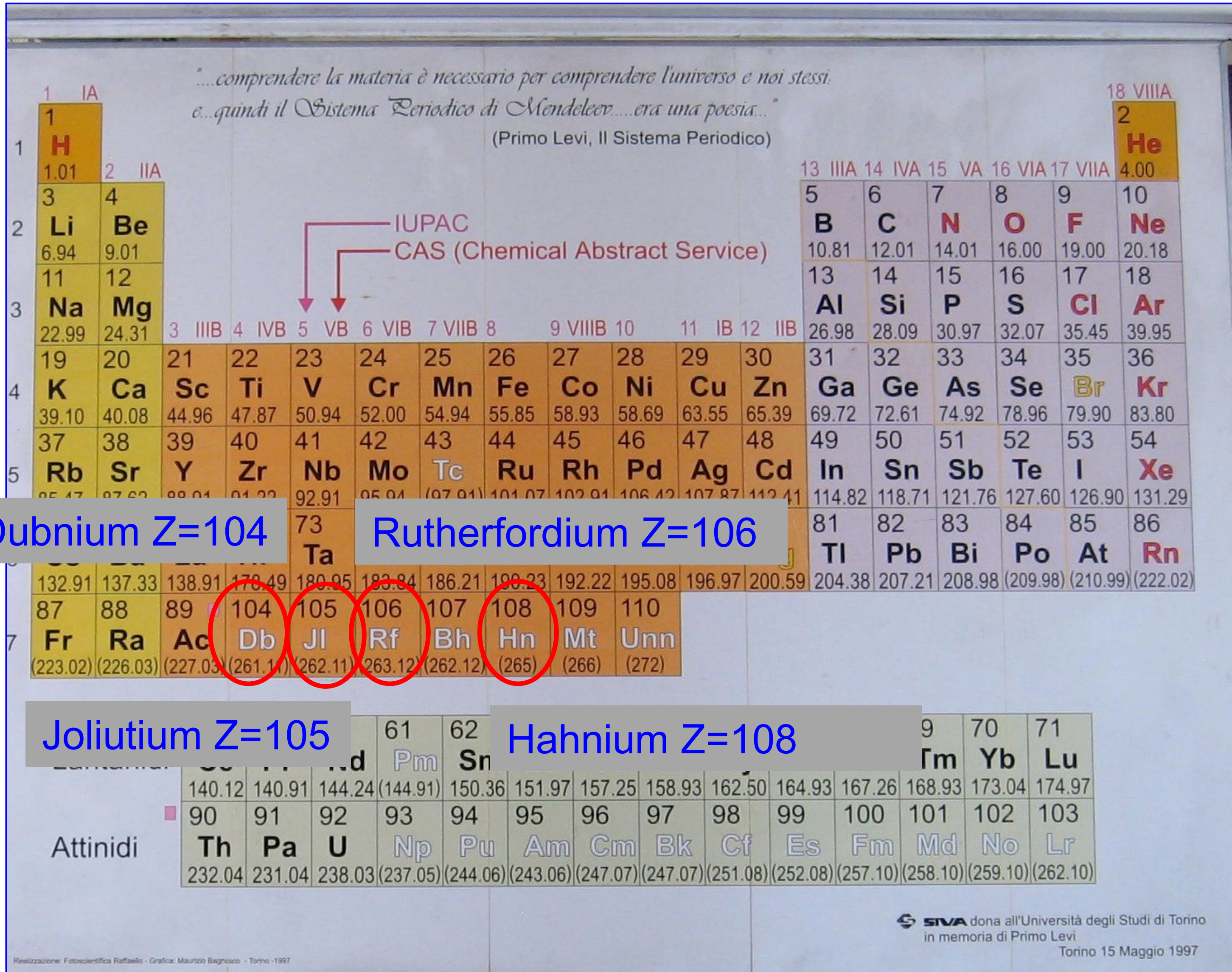
# Naming of the elements





# Naming of the elements





# Naming of the elements

Discovery of elements 104-106 was controversial. Groups who claimed the discovery named these elements.

The situation was clarified in 1997 only by the IUPAC (International Union of Pure and Applied Chemistry).

Procedure :

- Discovery approved by a joint IUPAC–IUPAP Working Group
- Discoverers suggest a name to the IUPAC Inorganic Chemistry Division
- The division examine the proposed name and symbol for suitability
- Public review
- Formal naming

# Naming of the elements

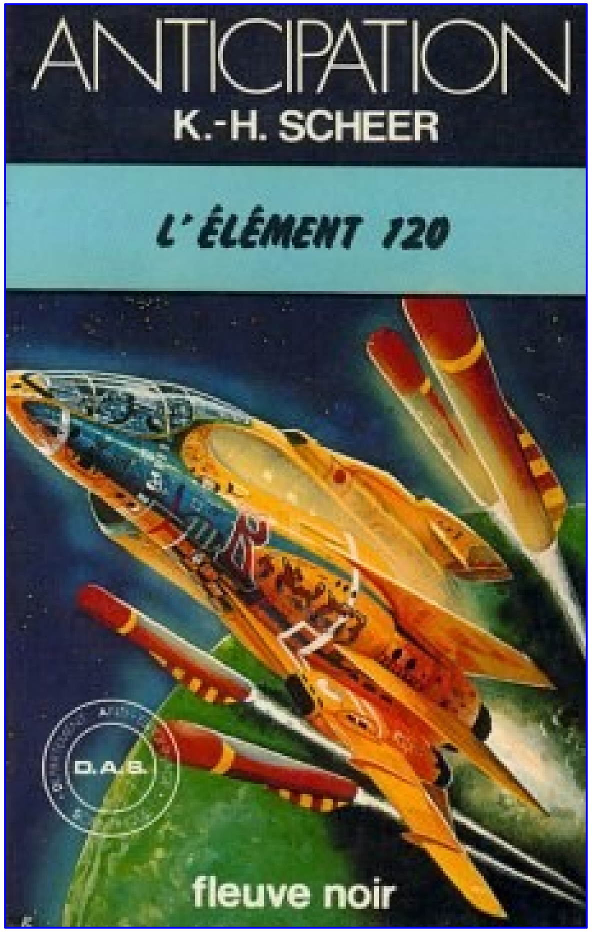
Latest elements approved and named :

- 2003 Z=110 Ds, darmstadtium (GSI)
- 2004 Z=111 Rg, roentgenium (GSI)
- 2010 Z=112 Cn, copernicium (GSI)
- 2012 Z=114 Fl, flerovium (Dubna and Livermore)
  Z=116 Lv, livermorium (Dubna and Livermore)
- 2016 Z=113 Nh, nihonium (RIKEN)
  Z=115 Mc, moscovium (Dubna, Livermore, and Oak Ridge)
  Z=117 Ts, tennessine (Dubna, Livermore, and Oak Ridge)
  Z=118 Og, oganesson (Dubna and Livermore)

Elements are universal.
Should we name the heaviest elements ?

# Further reading

# Holwynium element 120



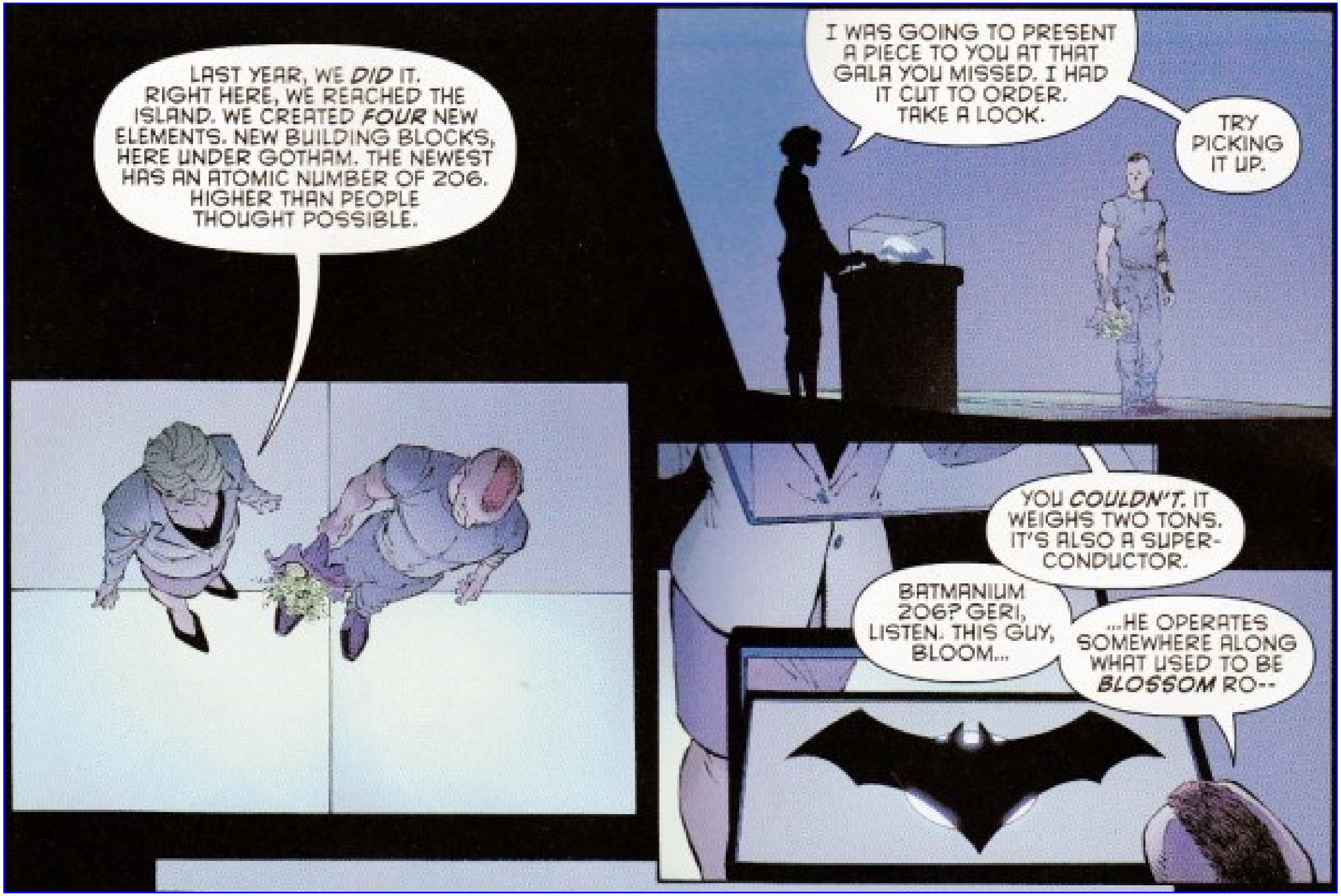

Original book in German «Ordnungszahl 120 »

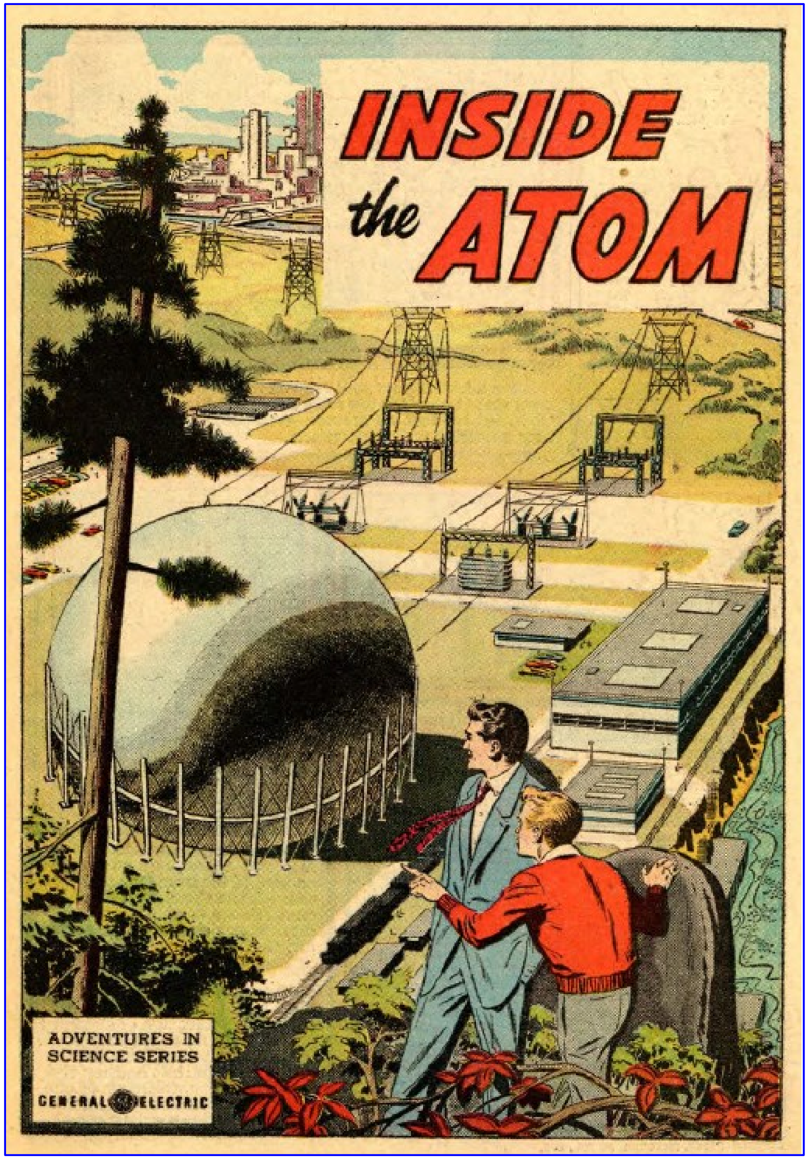
In 2002, element 120 « holwynium » was synthesized by Pr. Holwyn in a US secret atomic base (working on the cobalt bomb) located on the dark side of the moon. This element seems to be useless, but 3400 grams were stolen by Asian enemies. Holwynium has half-life of 2.6 y and is obtained bombarding C on halmanium 112, itself made using a superbevatron.
An official from DAS « Département antiespionnage scientifique » is sent to the moon to fix the problem.
It turns out that decay of element 120 produces a kind of stable mesons which can be used to produce mesonic atoms of deuterium. Since the radius of these atoms is smaller, controlled fusion is highly favoured. This provides an inexhaustible source of energy. The enemy base on the moon is destroyed using an H bomb.


Batman DC #45


In French : Tome 8 « La relève »
1ere partie.

# Z=206


LAST YEAR, WE DID IT. RIGHT HERE, WE REACHED THE ISLAND. WE CREATED FOUR NEW ELEMENTS. NEW BUILDING BLOCKS, HERE UNDER GOTHAM. THE NEWEST HAS AN ATOMIC NUMBER OF 206. HIGHER THAN PEOPLE THOUGHT POSSIBLE.
I WAS GOING TO PRESENT A PIECE TO YOU AT THAT GALA YOU MISSED. I HAD IT CUT TO ORDER. TAKE A LOOK.
TRY PICKING IT UP.
YOU COULDN'T. IT WEIGHS TWO TONS. IT'S ALSO A SUPER-CONDUCTOR.
BATMANIUM 206? GERI, LISTEN. THIS GUY, BLOOM...
...HE OPERATES SOMEWHERE ALONG WHAT USED TO BE BLOSSOM RO--

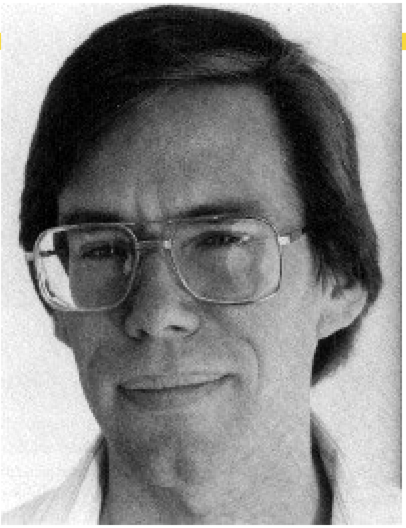


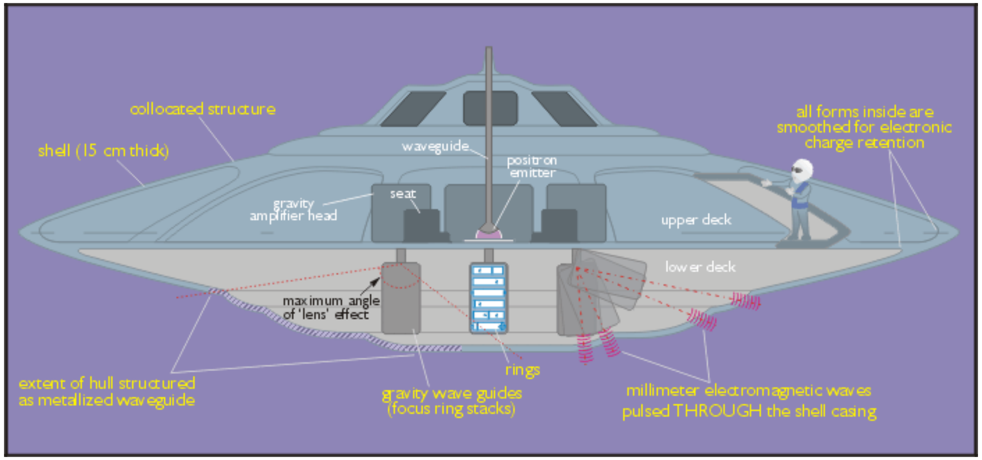

General Electrics, 1948

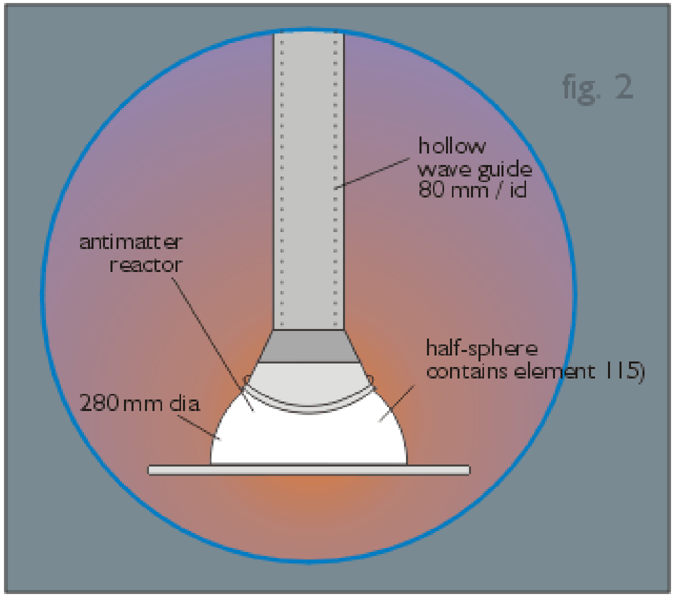

--IF YOU COULD DESTROY A TINY BIT OF MASS--SAY, A POUND--YOU'D GET THE SAME ENERGY AS THE BURNING OF ABOUT 2 MILLION TONS OF COAL!
RIDICULOUS!--AND ENOUGH OF ALBERT'S DAY-DREAMING... WE'VE GOT WORK TO DO!
"IN THE YEARS THAT FOLLOWED, THE SCIENTISTS' ATOMIC-CANNONS CONTINUED TO FIRE AWAY AT THE ELEMENTS, IN THE ATTEMPT TO CHANGE - TO CREATE NEW ELEMENTS. URANIUM--THE HEAVIEST, THE LAST ELEMENT IN THE TABLE--OFFERED THE BIGGEST CHALLENGE...
THEN CAME THE TURNING-POINT IN THE QUEST FOR ATOMIC ENERGY--1939: WHILE GERMAN PHYSICISTS, OTTO HAHN AND FRITZ STRASSMAN, WERE SHOOTING NEUTRONS AT URANIUM..."
WELL, DOCTOR, ALTHOUGH WE'VE FAILED TO CREATE A NEW ELEMENT, WE HAVE SUCCEEDED SOMEHOW IN PRODUCING ONE OF THE OLD ONES--BARIUM!
--A MUCH LIGHTER ELEMENT, AT THAT! HMMM... I WISH DR. MEITNER WERE STILL HERE WORKING WITH US...
"IN DENMARK, DR. LISE MEITNER HEARD OF THE EXPERIMENTS--DISCUSSED THEM WITH HER ASSOCIATE, DR. BOHR..."
THE BARIUM--AND THE KRYPTON--COULD ONLY HAVE BEEN PRODUCED BY THE URANIUM'S "FISSIONING"--SPLITTING IN TWO--WHEN IT WAS STRUCK BY THE NEUTRON!
BUT THOSE TWO HALVES WEIGH LESS THAN THE ORIGINAL URANIUM MASS! WHAT ABOUT THE DIFFERENCE--THE MASS THAT'S MISSING? COULD IT MEAN--
KRYPTON (90)
URANIUM WEIGHS 235
? 2 UNITS OF WEIGHT ?
BARIUM (143)
"YES, PROFESSOR BOHR--THAT IT MUST HAVE BEEN RELEASED IN THE FORM OF ENERGY!"
8

# Bob Lazar

From Wikipedia : «Robert Scott Lazar (born January 26, 1959) claims to have worked on reverse engineering extraterrestrial technology at a site called S-4, near the Area 51 test facility, and that the UFOs use gravity wave propulsion. This is powered by the, at the time, undiscovered element 115 »





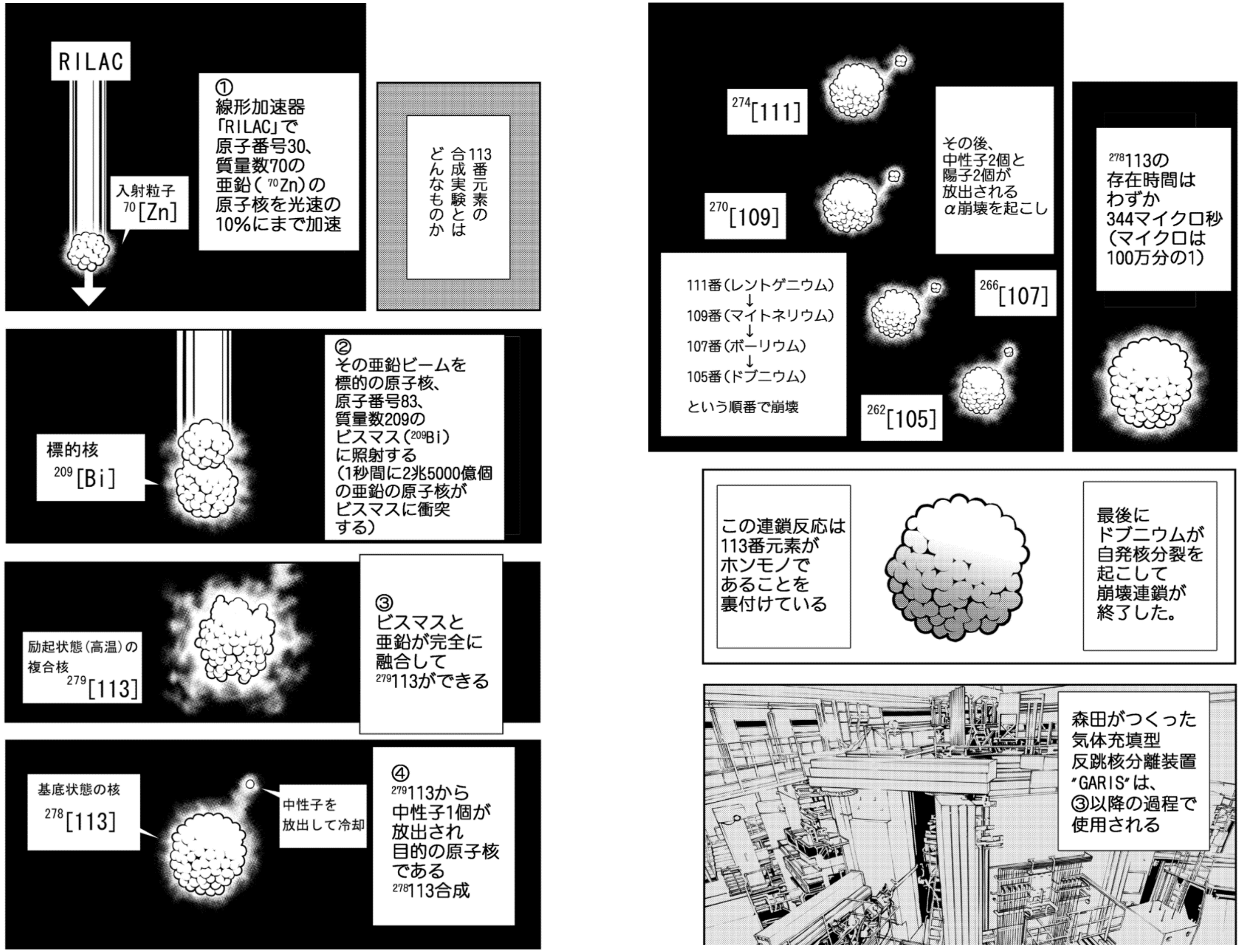

Element 115 + p → 116
116 decay → 2 antiprotons
Antimatter → antigravity waves
+ antigravity amplifiers

http://www.boblazar.com/

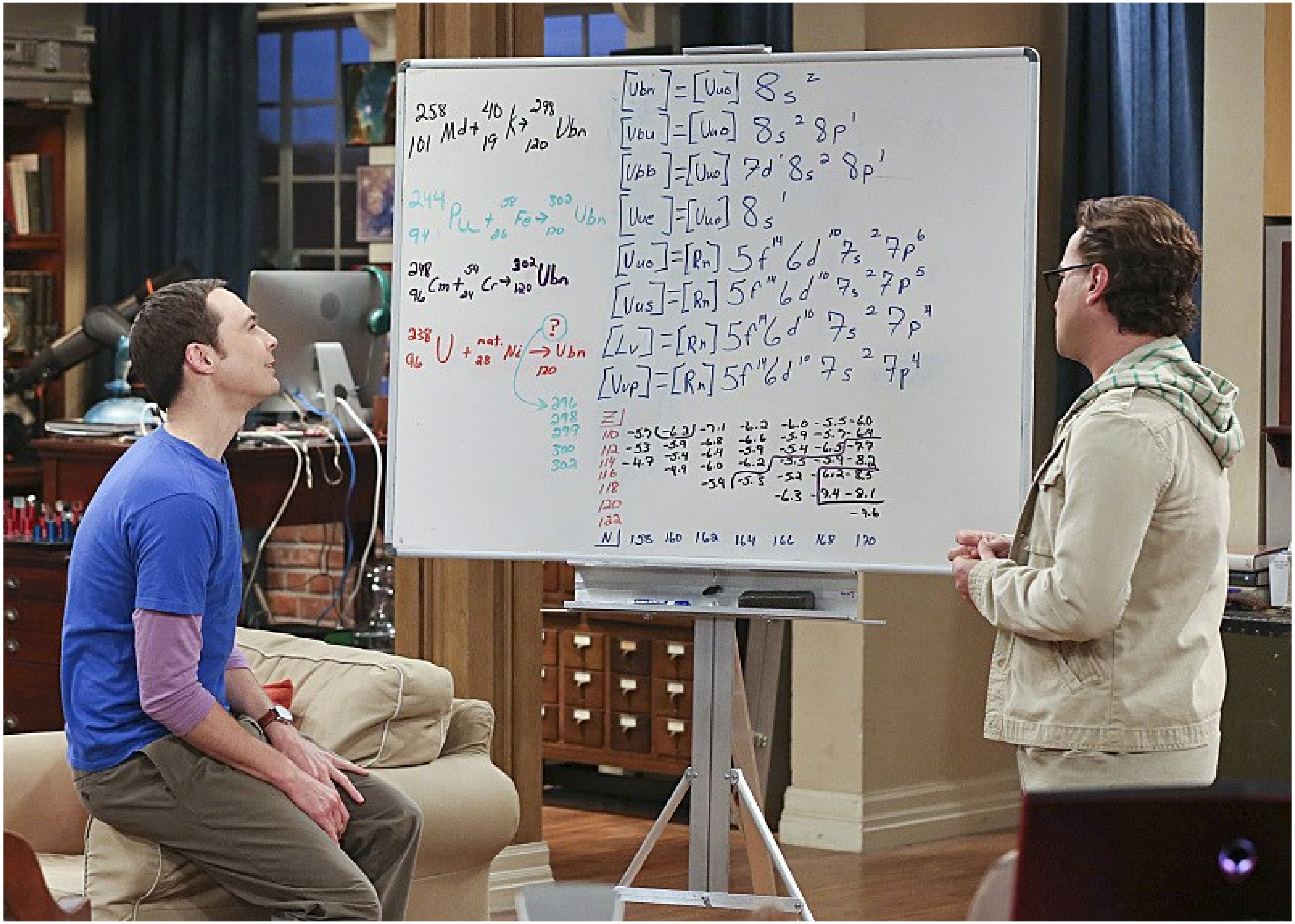

113
新元素発見に至る20年の戦い
作　画：千田灰司
制　作：株式会社スポマ
発行人：独立行政法人 理化学研究所
RIKEN


気体充填型反跳分離装置(GARIS)
ビーム
差動排気システム
一次ビーム
Heガス導入口
マイラー箔
ビームストッパー (Ta)
回転ターゲット
検出器チェンバー
D1
Q1
Q2
D2
0
1
2(m)
おい森田…この設計図…


その後森田らは112番の追試に成功
そして2004年7月――
9月の予定だった実験期間が急遽割り当てられることになった
113番元素の合成実験再開
しかし今回も結果はすぐにはでなかった――


113番元素の
合成実験とは
どんなものか
RILAC
①
線形加速器
「RILAC」で
原子番号30、
質量数70の
亜鉛($^{70}$Zn)の
原子核を光速の
10%にまで加速
入射粒子
$^{70}$[Zn]
②
その亜鉛ビームを
標的の原子核、
原子番号83、
質量数209の
ビスマス($^{209}$Bi)
に照射する
(1秒間に2兆5000億個
の亜鉛の原子核が
ビスマスに衝突
する)
標的核
$^{209}$[Bi]
③
ビスマスと
亜鉛が完全に
融合して
$^{279}$113ができる
励起状態(高温)の
複合核
$^{279}$[113]
④
$^{279}$113から
中性子1個が
放出され
目的の原子核
である
$^{278}$113合成
基底状態の核
$^{278}$[113]
中性子を
放出して冷却
$^{278}$113の
存在時間は
わずか
344マイクロ秒
(マイクロは
100万分の1)
その後、
中性子2個と
陽子2個が
放出される
α崩壊を起こし
$^{274}$[111]
$^{270}$[109]
111番(レントゲニウム)
↓
109番(マイトネリウム)
↓
107番(ボーリウム)
↓
105番(ドブニウム)
という順番で崩壊
$^{266}$[107]
$^{262}$[105]
最後に
ドブニウムが
自発核分裂を
起こして
崩壊連鎖が
終了した。
この連鎖反応は
113番元素が
ホンモノで
あることを
裏付けている
森田がつくった
気体充填型
反跳核分離装置
“GARIS”は、
③以降の過程で
使用される

# Element 120




*The Big Bang Theory* season 7, episode 6

# Further reading (II)

- Nuclear physics special issue on SHE, Vol, 944 (2015)
- Proc. of the Nobel symposium NS 160 chemistry and physics of heavy and SHEs. EPJ Web of Conf. 131 (2016)
- D. Ackermann and Ch. Theisen. Phys. Scr. 92 (2017) 083002
- P. Armbruster. Ann. Rev. Nucl. Part. Sci. 35 (1985) 135.
- P. Armbruster. Ann. Rev. Nucl. Part. Sci. 50 (2000) 411.
- G.N. Flerov and G.M. Ter-Akopian. SHEs in Treatise on Heavy-Ion Science vol 4 (1985) 331 (New York: Plenum Press)
- V.I. Gol'danskii and S.M. Polikanov. The Transuranium Elements, 1995 (New York: Consultant Bureau)
- G. Herrmann. Angew. Chem. Int. Ed. 29 (1990) 481
- R.-D. Herzberg, P.T. Greenlees. Prog. Part. Nucl. Phys., in press
- R.-D. Herzberg. J. Phys. G: Nucl. Part. Phys. 30 (2004) R123.
- S. Hofmann, Rep. Prog. Phys. 61 (1998) 639
- S. Hofmann, G. Münzenberg, Rev. Mod. Phys. 72 (2000) 733
- S. Hofmann. On Beyond Uranium: Journey to the End of the Periodic Table, 2002 (CRC Press)
- S. Hofmann. The Euroschool Lectures on Physics with Exotic Beams, vol III, 2009 203 (Berlin: Springer
- S. Hofmann. J. Phys. G: 42 (2015) 114001
- D.C. Hoffman, A. Ghiorso, G.T. Seaborg. The transuranium people; the inside story.
- M. Leino, F.-P. Hessberger, Ann. Rev. Nucl. Part. Sci. 54 (2004) 175.
- G. Münzenberg 1988 Rep. Prog. Phys. 51 (1988) 57
- Y. Oganessian 2007 J. Phys. G 34 (2007) R165
- Y. Oganessian, A. Sobiczewski, G.M. Ter-Akopian. Phys. Scr. 92 (2017) 023003
- G.T. Seaborg and W.D. Loveland Transuranium nuclei In Treatise on Heavy-Ion Science vol 4 (1985) 253 (New York: Plenum)
- Ch. Theisen, Cours Ecole Joliot-Curie 2002 (in french)