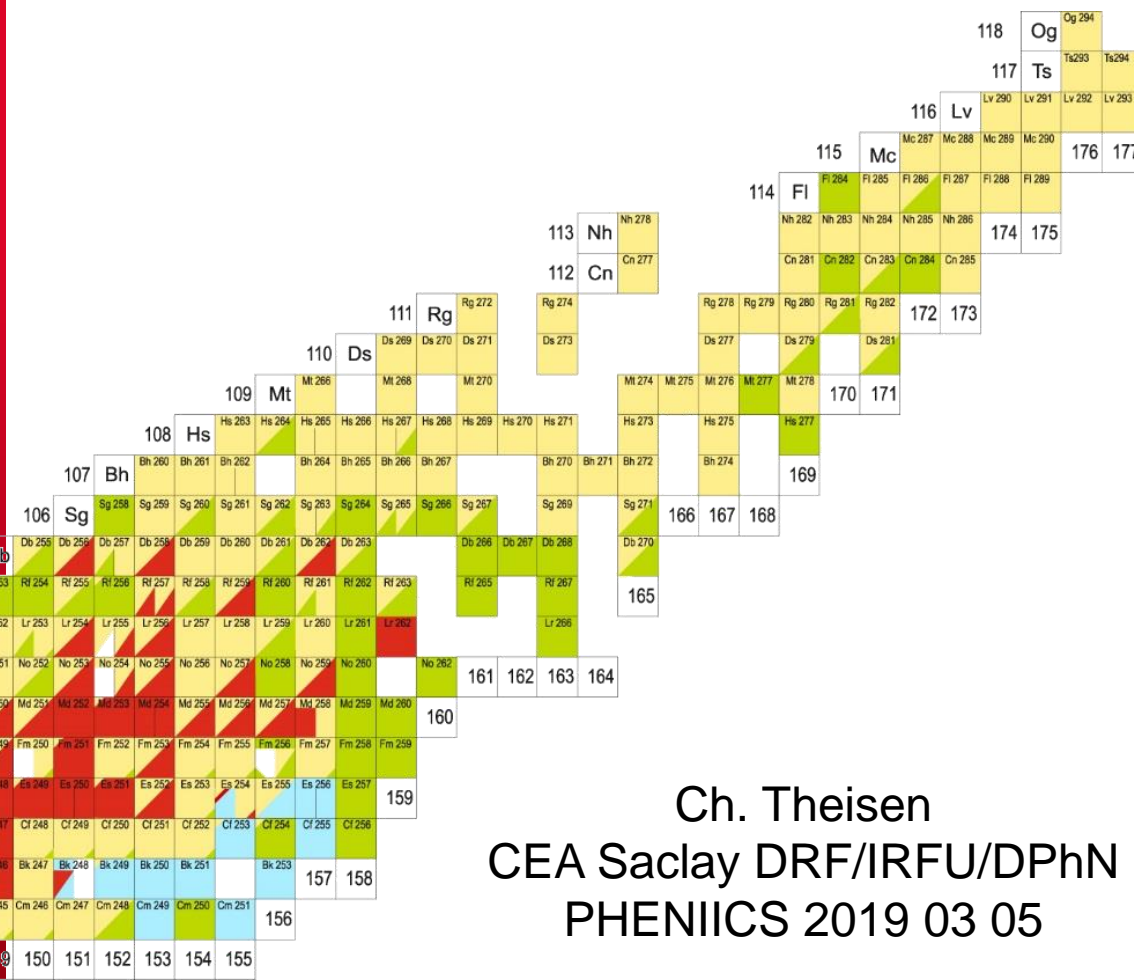
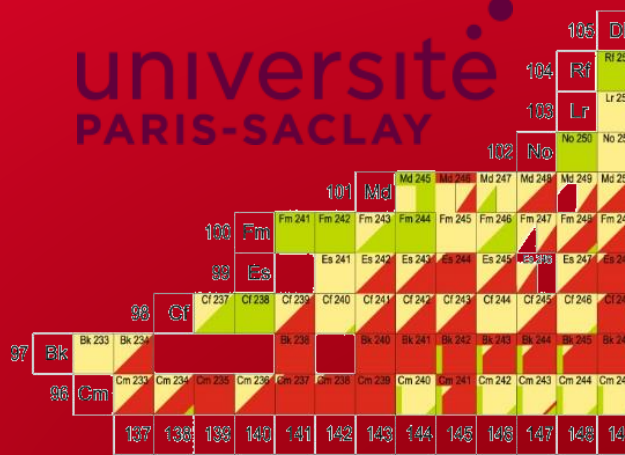


DE LA RECHERCHE À L'INDUSTRIE



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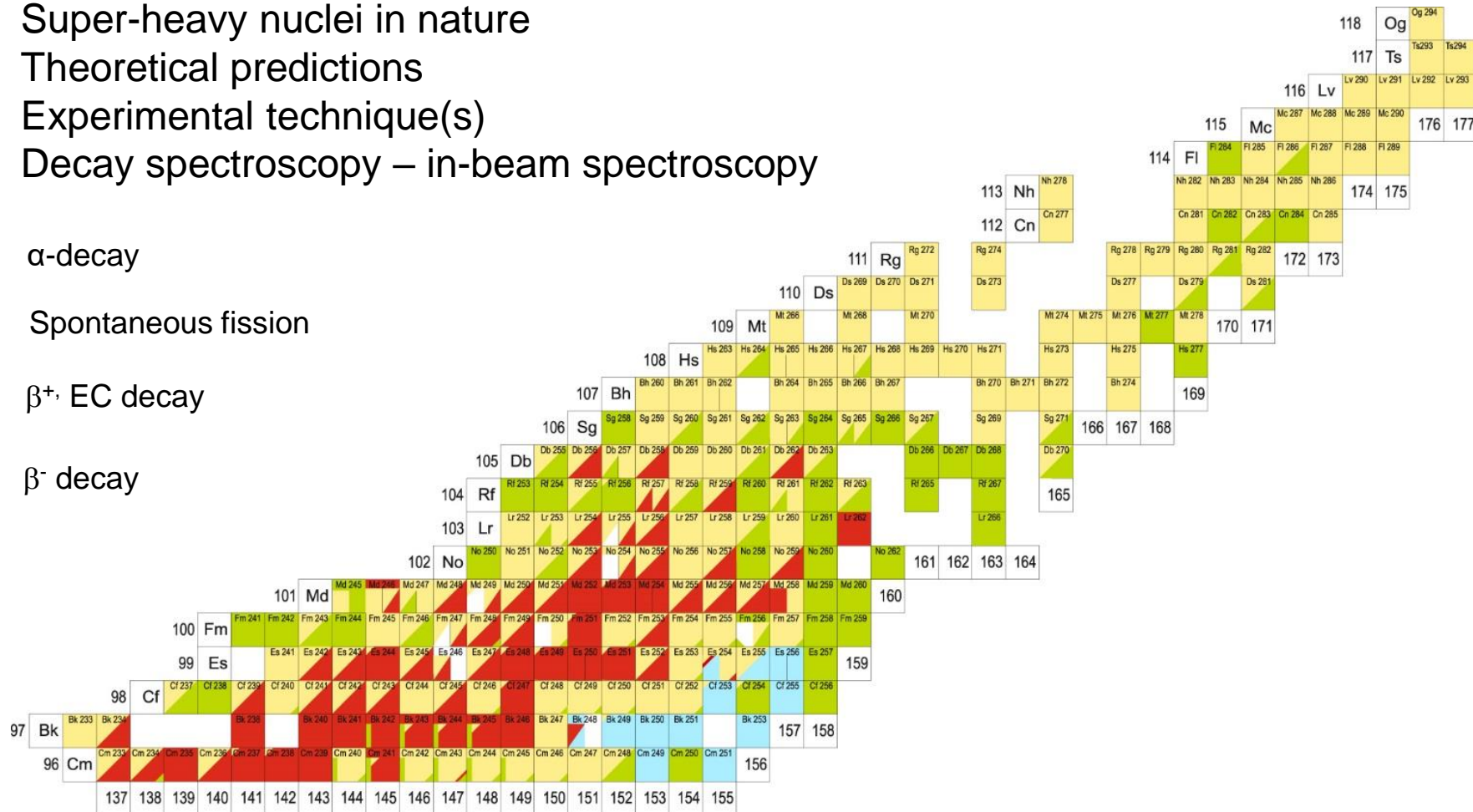
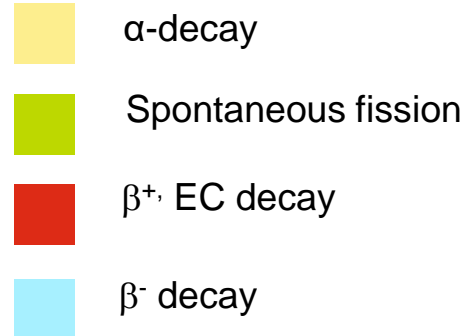


Ch. Theisen
CEA Saclay DRF/IRFU/DPhN
PHENIICS 2019 03 05



SUPERHEAVY NUCLEI

- Historical notes : fission, first transuranium elements
- Limits of stability : macroscopic / microscopic effects
- Super-heavy nuclei in nature
- Theoretical predictions
- Experimental technique(s)
- Decay spectroscopy – in-beam spectroscopy



100 % SCIENCE

C'est du lourd!
Des physiciens viennent de fabriquer les atomes les plus gros jamais créés. Une prouesse d'autant plus remarquable qu'à peine formés, ces monstres disparaissent quasi instantanément!

Fabrice Nicol

Vers les Atomes supe

Ce sont des monstres! Et ils portent des noms que l'on oserait à peine invoquer dans le noir, de peur de réveiller quelque démon... Ununtrium (symbole Uut), ununpentium (Uup), ununseptium (Uus) et ununoctium (Uuo) sont parmi les quatre

plus gros atomes jamais produits sur Terre, plus lourds même que tous ceux observés dans l'Univers jusqu'ici. Le fer et le plomb? Des minis, en comparaison de ces atomes superlourds. Songez que pour former l'ununtrium, le plus petit des quatre, il a fallu rassembler 113 > protons < et 165 > neutrons <. Soit 278 > nucléons <!

Alors que le plomb, l'un des plus gros noyaux connus, n'en compte que 208... Ces quatre atomes poids lourds ont été fabriqués par deux > accélérateurs de particules <, au Japon et en Russie. Une sacrée prouesse, car marier protons et neutrons n'est pas une mince affaire. En effet, les protons sont des particules

SVJ 321 • JUIN 2015

Science et vie junior Juin 2016

Science & découvertes > chimie

Science Aout 2014

Tableau de Mendeleïev

L'élément 117 met fin au mythe

En réussissant à synthétiser l'ultime élément qui manquait au célèbre tableau, les physiciens l'ont vraiment achevé! Car avec les noyaux lourds, il devient faillible.

Par Mathieu Grousseau

Son numéro: 117. Son nom (provisoire): ununseptium. Découvert une première fois en 2010, il vient de voir son existence confirmée par une seconde observation. Les experts de l'Union internationale de chimie pure et appliquée n'ont plus qu'à le reconnaître officiellement. Simple formalité. En attendant, la science a pris acte: ces deux

découvertes indépendantes signifient qu'il existe.

Il? Le dernier élément qui manquait au tableau proposé en 1869 par Dmitri Mendeleïev. L'ultime case vide – l'avant-dernière – ne l'est plus. Le fameux tableau accroché dans toutes les classes de science est complet pour la première fois.

Moment de grâce scientifique qui, à 145 années de distance, voit l'intuition du chimiste russe confirmée de manière éclatante. Lui qui avait laissé vacantes plusieurs cases de sa classification pour des éléments inconnus à son époque.

Car le tableau de Mendeleïev est plus qu'une simple liste de constituants de la matière, classés du plus léger au plus lourd, à laquelle s'ajouteraient

chaque nouvel atome découvert. Il permet de prédire les propriétés physiques et chimiques des éléments.

C'est l'idée toute simple d'un génie: au milieu du XIX^e siècle, alors qu'il recense les 63 éléments connus à l'époque, Dmitri Mendeleïev décide de les classer par masse atomique croissante. Il observe alors une périodicité dans leurs propriétés: à mesure que l'on avance vers les grandes masses, la couleur, l'aspect et la réactivité chimique des éléments redevennent similaires à intervalles réguliers.

UNE GÉNIALE CLASSIFICATION

Ainsi, le fluor, de masse 19, réagit fortement avec les métaux, comme le chlore (masse 35) et le brome (masse 80); le calcium, de masse 40, reste solide à haute température, comme le baryum (masse 137)...

Mendeleïev en tire une loi générale, appelée principe périodique, qu'il applique en dressant un tableau dans lequel il fait figurer dans une même colonne les éléments aux propriétés similaires.

AOUT 2014 | SVJ | 69

Repère

Le tableau périodique, ou tableau de Mendeleïev en hommage au chimiste russe qui l'inventa au XIX^e siècle, recense tous les éléments de la matière, du plus léger, l'hydrogène, aux plus lourds, tel le plutonium. Constitué de 7 lignes et 18 colonnes, il présentait des cases vides qui se sont remplies avec la découverte de nouveaux éléments. Il n'en restait plus qu'une à combler: la 117.

ILLUSTRATION

La recherche, June 2017

3

À la recherche des éléments superlourds

**Antoine Drouart, CEA, université Paris-Saclay,
et Michael Bender, CNRS, Institut de physique nucléaire de Lyon**

Avec l'oganesson et ses 118 protons, élément le plus lourd synthétisé sur Terre, les physiciens créent des éléments toujours plus riches en protons et en neutrons avec leurs accélérateurs. Ils espèrent trouver un « îlot des noyaux superlourds », où les effets quantiques autoriseraient des durées de vie de plusieurs années.

L'installation Spiral2/S³ au Ganil, à Caen, doit y contribuer.



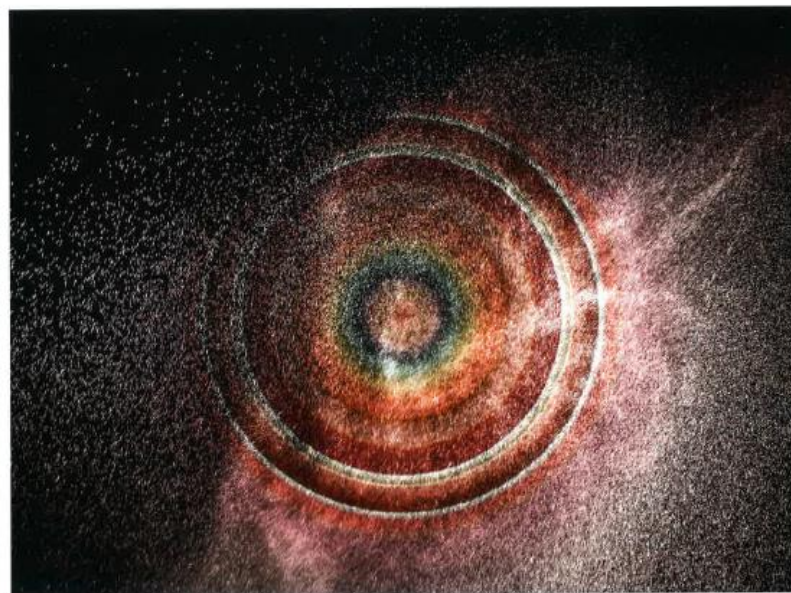
PHYSICIENS

Antoine Drouart (1), responsable du laboratoire d'étude du noyau de l'atome, à l'Ifnu, est impliqué dans le projet S³ à l'accélérateur Ganil, à Caen. Le directeur de recherche Michael Bender (2) développe des outils numériques pour la modélisation microscopique des noyaux atomiques.

Les noyaux des atomes les plus légers (hydrogène, hélium, lithium) ont été fabriqués au moment du Big Bang. Les noyaux plus lourds ont été synthétisés plus tard, tout au long de la vie des étoiles, ou lors des explosions des étoiles massives ou encore au cours d'autres phénomènes violents, comme les collisions d'étoiles à neutrons. Sur Terre, on retrouve les noyaux stables (jusqu'au plomb 208, qui contient 82 protons), ainsi que ceux qui ont une durée de vie suffisante pour avoir perduré depuis leur synthèse jusqu'à nos jours, comme l'uranium 238 (92 protons), qui a une demi-vie ^(*) de 4,5 milliards d'années. Il existe pourtant des éléments plus lourds encore, dont la durée de vie est très brève. Ces éléments, dont les plus massifs sont dits « superlourds », ont été progressivement fabriqués dans les laboratoires. En 2016, nous avons complété la dernière ligne du tableau de Mendeleïev avec la nomination de quatre éléments récemment découverts : le nihonium (113 protons), le moscovium (115 protons), le tennesseine (117 protons) et l'oganesson (118 protons), l'élément le plus lourd synthétisé sur Terre. Cela ne signi-

fie pas qu'il n'existe pas d'autres éléments plus lourds encore, qui entameraient une nouvelle ligne du tableau périodique, mais la synthèse de ces noyaux se heurte à de nouveaux défis. Par ailleurs, des effets quantiques déterminent les propriétés de ces noyaux, et les recherches théoriques et expérimentales se penchent en particulier sur l'existence d'un « îlot de stabilité » où les éléments superlourds perdureraient sans se désintégrer rapidement ⁽¹⁾. Au cours du XX^e siècle, des noyaux de plus en plus lourds ont été créés, d'abord par bombardement de neutrons, dans des réacteurs nucléaires. Lorsqu'un noyau capture un neutron, il se trans-

Contexte. Dans les années 1960, la théorie a prédit la possibilité de noyaux superlourds qui n'existeraient pas naturellement sur Terre, dont certains à la demi-vie très longue. Une demi-douzaine d'installations nucléaires dans le monde permettent de produire ces objets qui aident à mieux comprendre la structure du noyau atomique.



forme en un autre isotope qui peut être sensible à la désintégration bêta : un de ses neutrons se transforme en proton, en émettant un électron (et un antineutrino). La désintégration bêta transmute un élément en un autre d'un numéro atomique plus élevé. On a même découvert des traces de fermium (100 protons) sur le site d'une explosion nucléaire !

Projet S³ à l'accélérateur Ganil

Au-delà du fermium, la méthode la plus efficace connue pour fabriquer des éléments lourds est la fusion de deux noyaux plus légers. Le noyau formé contient un nombre de protons qui est simplement la somme de celui des partenaires de fusion. Le nombre de neutrons n'est pas conservé car quelques-uns sont émis durant la réaction. Pour réussir la fusion, il faut rapprocher suffisamment les deux noyaux, qui, chargés positivement, se repoussent. Pour cela, un faisceau de noyaux est envoyé sur une cible. Si les noyaux sont suffi-

samment proches, les forces nucléaires, attractives mais de courte portée, peuvent agir pour fusionner les deux partenaires. Néanmoins, la fusion de deux noyaux est un processus extrêmement minoritaire : le noyau étant très petit au milieu de l'atome, le projectile traverse souvent la cible sans aucune interaction nucléaire. Et même lorsque les deux se rapprochent suffisamment, le projectile est dans la majorité des cas simplement dévié par le noyau cible, ou n'échange que quelques nucléons avec lui. Lorsque la fusion survient, le noyau résultant est formé avec une énergie d'excitation interne élevée. La plupart du temps, il fissionne très rapidement en deux noyaux plus légers. Mais il peut également émettre un ou plusieurs neutrons. Ce processus, appelé « évaporation », diminue l'énergie interne du noyau. Une fois « refroidi », le noyau voit son cortège électronique se réorganiser pour former enfin un élément. Dans des conditions expérimentales favorables, il aura fallu un milliard ...

« Vue d'artiste. Les noyaux superlourds sont des systèmes quantiques complexes, qui ne peuvent être modélisés que grâce à des approximations/simplifications.

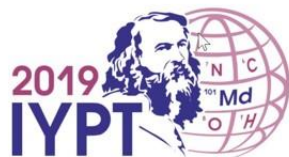
^(*) La demi-vie est la durée au bout de laquelle la moitié des noyaux d'un échantillon radioactif se sont désintégrés.



2019, INTERNATIONAL YEAR OF THE PERIODIC TABLE



United Nations
Educational, Scientific and
Cultural Organization



2019
International Year
of the Periodic Table
of Chemical Elements

Opening Ceremony 2019 02 01, Paris





Celebrate with us!

2019 International Year of Periodic Table

 Springer © welcomia / Getty Images / iStock

Tableau périodique des éléments chimiques

Tableau périodique des éléments chimiques

← nom de l'élément (gaz, liquide ou solide à 0°C et 101,3 kPa)
← numéro atomique
← symbole chimique
← masse atomique relative [ou celle de l'isotope le plus stable]
[CIAAW "Atomic Weights 2013" + rev. 2015]

2016 Z=118 oganesson

2016 Z=113 nihonium

2016 Z=117 tennesseine

2012 Z=114 flerovium

2004 Z=111 roentgenium

2003 Z=110 darmstadtium

2010 Z=112 copernicium

2012 Z=116 livermorium

2016 Z=115 moscovium

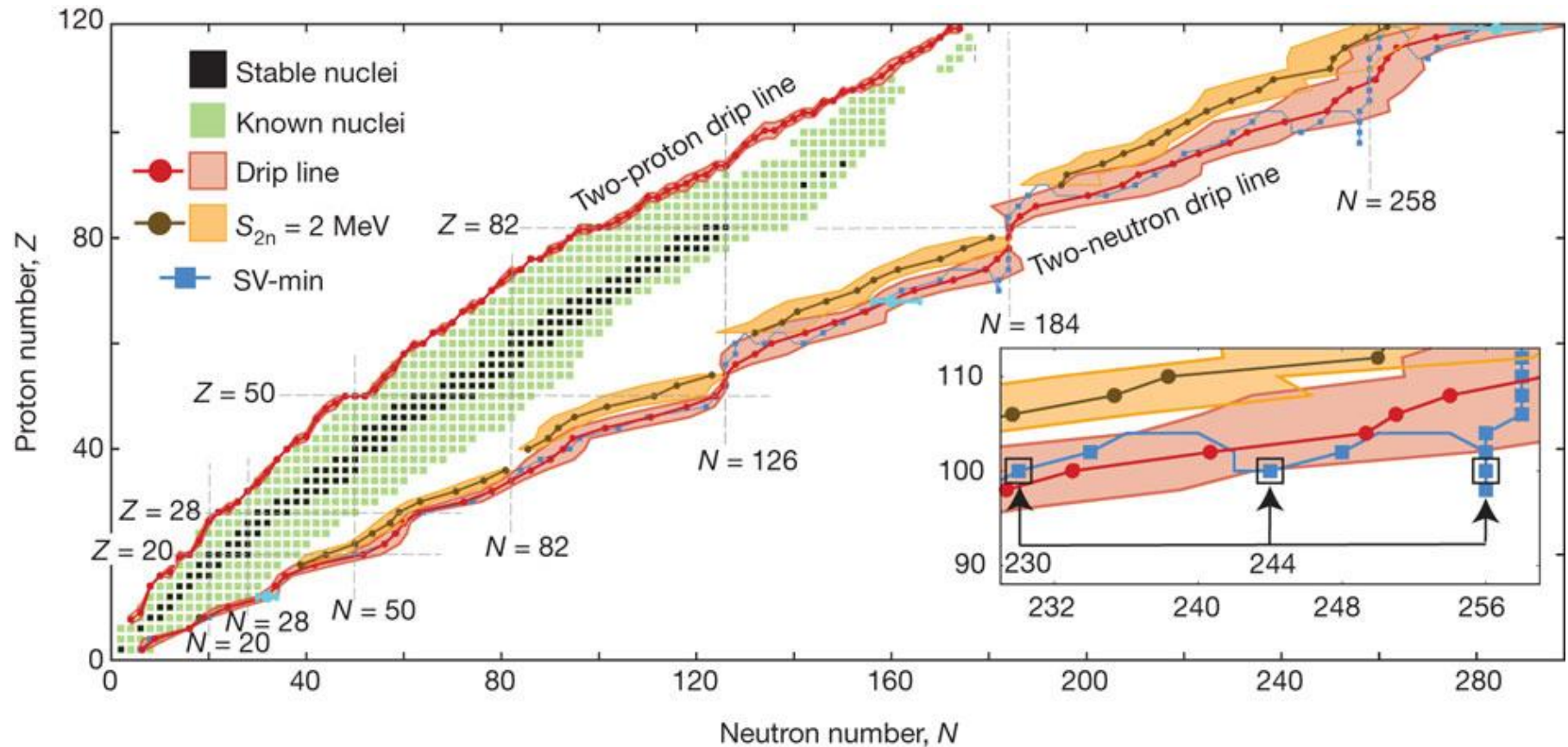
Métaux

Alcalins Alcalino-terreux Lanthanides Actinides Métaux de transition Métaux pauvres Métalloïdes Autres non-métaux Halogènes Gaz nobles

primordial désintégration d'autres éléments synthétique

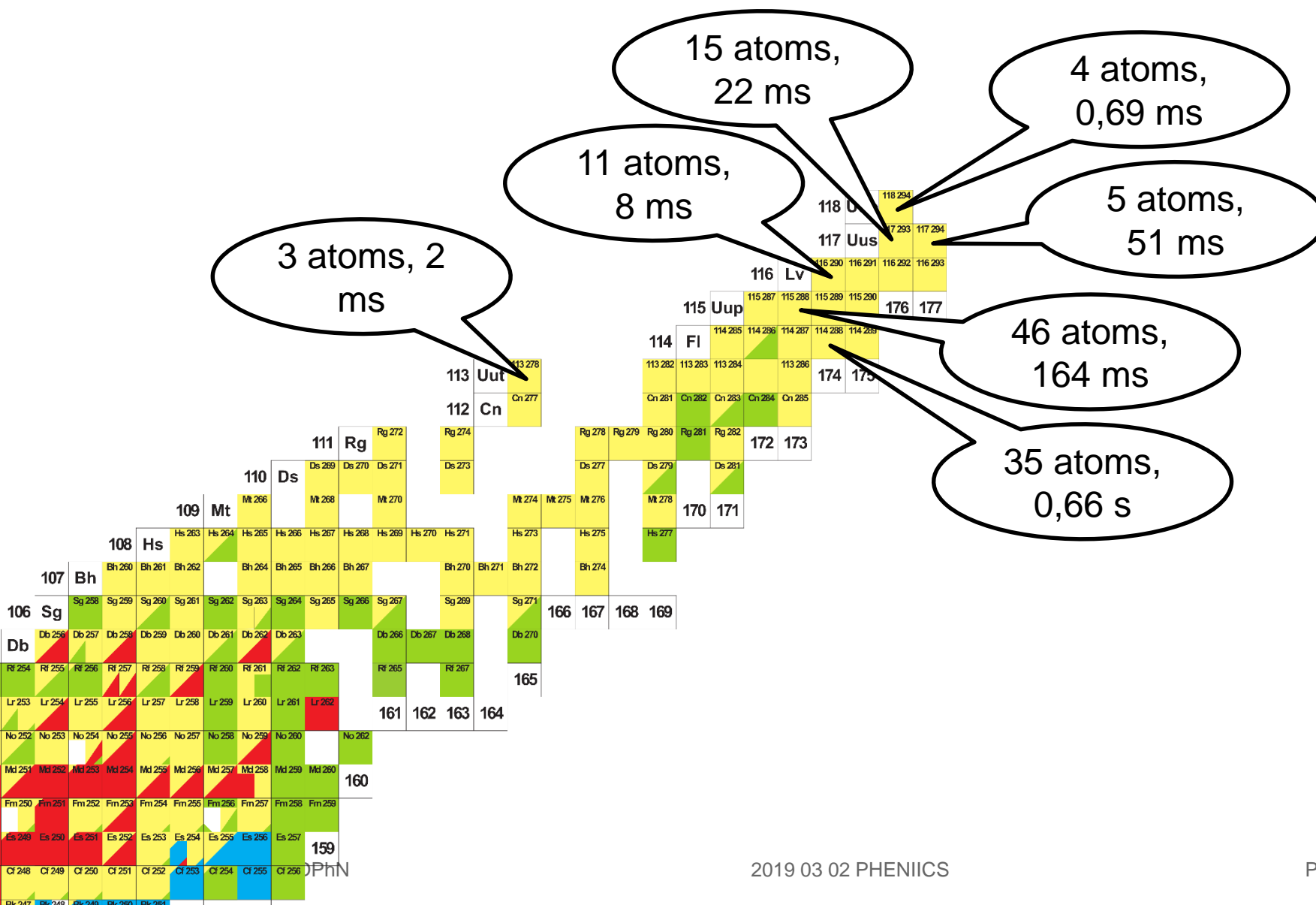
A LOT OF ROOM FOR NEW ISOTOPES !

~3200 known isotopes
~7000 predicted isotopes

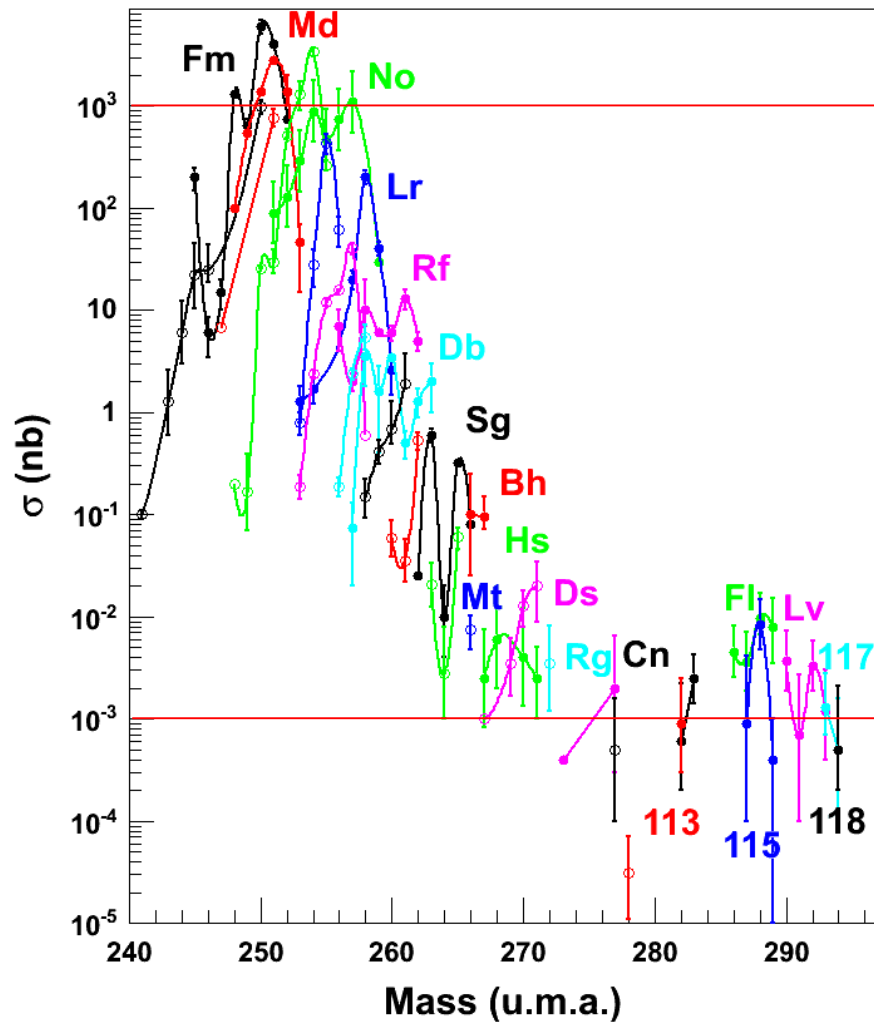


[J Erler et al. Nature 486 \(2012\) 509](#)

FROM Z=113 TO Z=118



Fusion-evaporation reactions

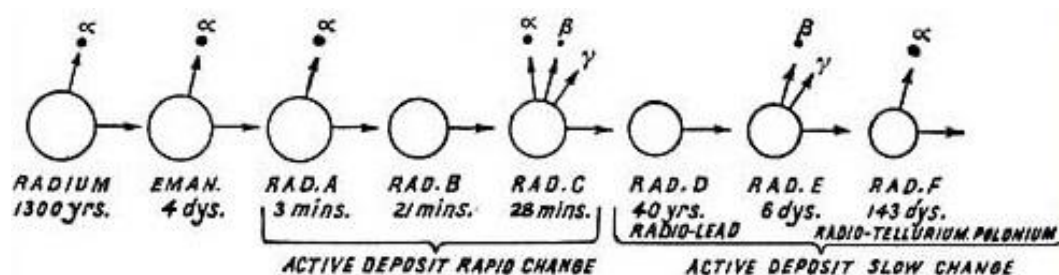


μb : production few/s/ μA

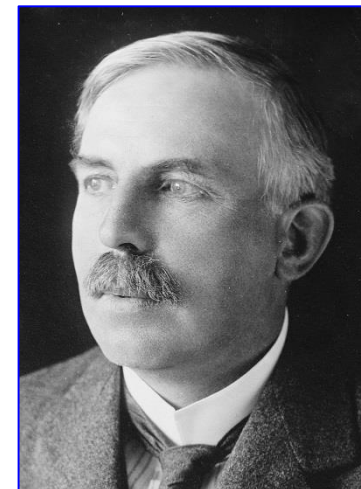
pbarn : production $\sim 20/\text{month}/\mu\text{A}$

1899 Rutherford isolates α and β radioactivities from uranium

1902 Rutherford and Soddy.
Emission of $\alpha \rightarrow$ transmutation



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



Ernest Rutherford



Frederick Soddy 12

TABLE IV.—PERIODIC ARRANGEMENT OF THE RADIO-ELEMENTS.

THE FIRST NUCLEAR REACTIONS



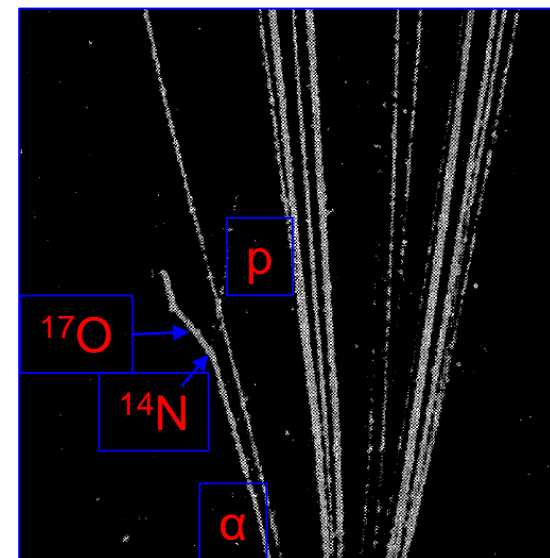
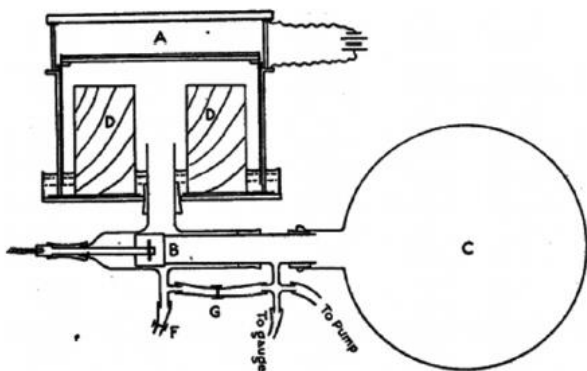
1919 Rutherford Transmutation using α « beam ». α + Nitrogen.

First nuclear reaction ! Interpreted as α + Nitrogen \rightarrow p + something

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

1924 Blackett. Visualization of the reaction using a cloud chamber

[Proc. Roy. Soc. A 107 \(1925\) 349](#)



[C.T.R. Wilson, Proc. Roy. Soc. A 87, 277 \(1912\)](#)

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

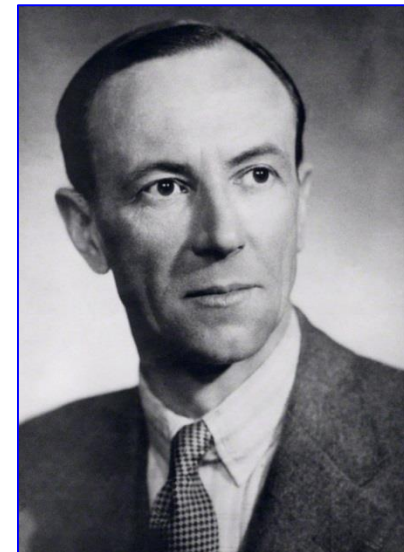
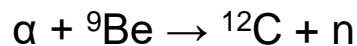
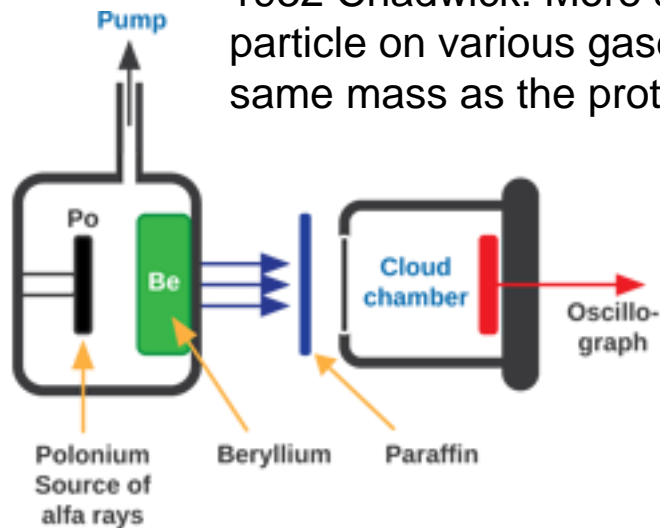
THE NEUTRON DISCOVERY



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

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

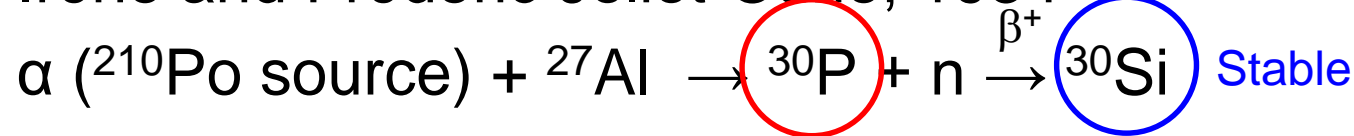
1932 Chadwick. More sensitive device. Range of protons and impact of the unknown particle on various gases. → Existence of a neutral particle « neutron » having the same mass as the proton



James Chadwick



Irène and Frédéric Joliot-Curie, 1934



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 $Z \sim 15$ due to coulomb repulsion... Not possible to go beyond. Also rather low yield.

- 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 ${}^A_ZX + n \rightarrow {}^{A+1}_ZX \xrightarrow{\beta \text{ decay}} {}^{A+1}_{Z+1}Y$

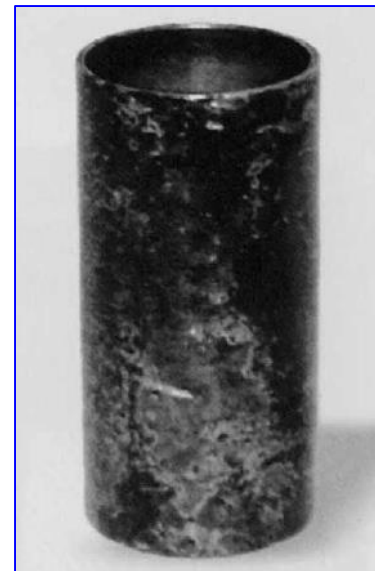
– (chemical separation)

– Detection of radioactivity (β -)

Using a Geiger-Müller counter

→ lifetime and eventually β -
energy using absorbers

Neutron source inside



About 30 new isotopes discovered !

Possible Production of Elements of Atomic Number Higher than 92

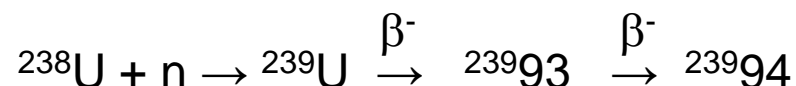
By PROF. E. FERMI, Royal University of Rome

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).

[Nature 133 \(1934\) 898](#)

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)



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)

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



Footnote in Fermi's lecture :

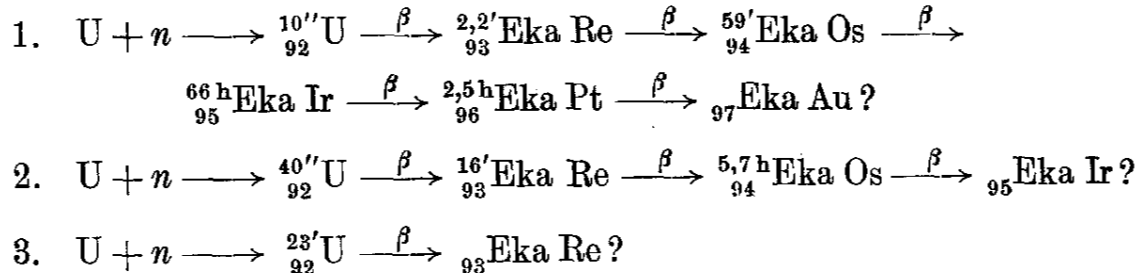
“The discovery by Hahn and Strassmann of barium among the disintegration products of bombarded uranium, as a consequence of a process in which uranium splits into two approximately equal parts, makes it necessary to reexamine all the problems of the transuranic elements, as many of them might be found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

ELEMENT 93 CONFIRMED IN BERLIN... AND MUCH MORE !

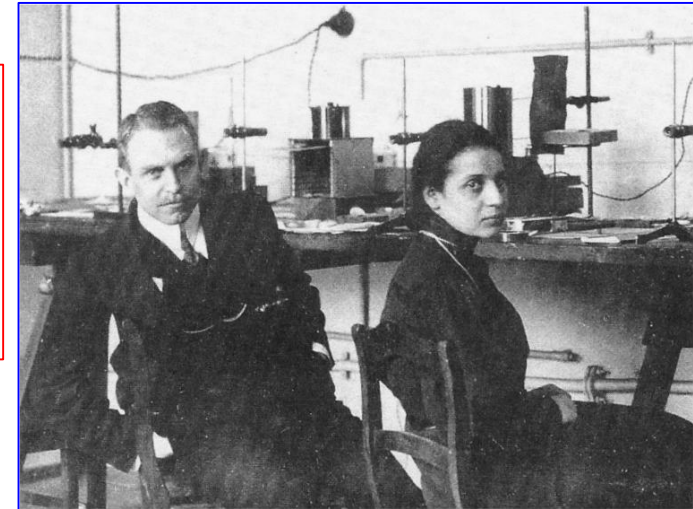


1935 : neutron induced reaction repeated by chemists Hahn, Meitner and Strassmann at Kaiser Wilhelm-Institut für Chemie, Berlin (and in other places)

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

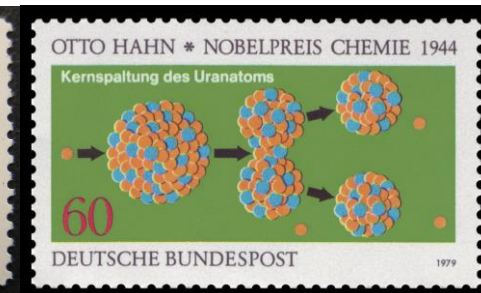
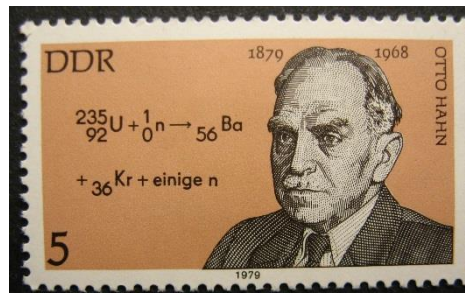


[Meitner, Hahn, Strassmann. ZP 106 \(1937\) 249](#)



Otto Hahn, Lise Meitner

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



1938 Hahn and Strassmann.

→ identification of one product as Ba

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

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



Fritz Strassmann



Niels Bohr

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*](#)

Spring 1939 : Theory of fission by Bohr and Wheeler

([PR 56 \(1939\) 426](#)), Frenkel ([PR 55 \(1939\) 987](#))

using the liquid drop model

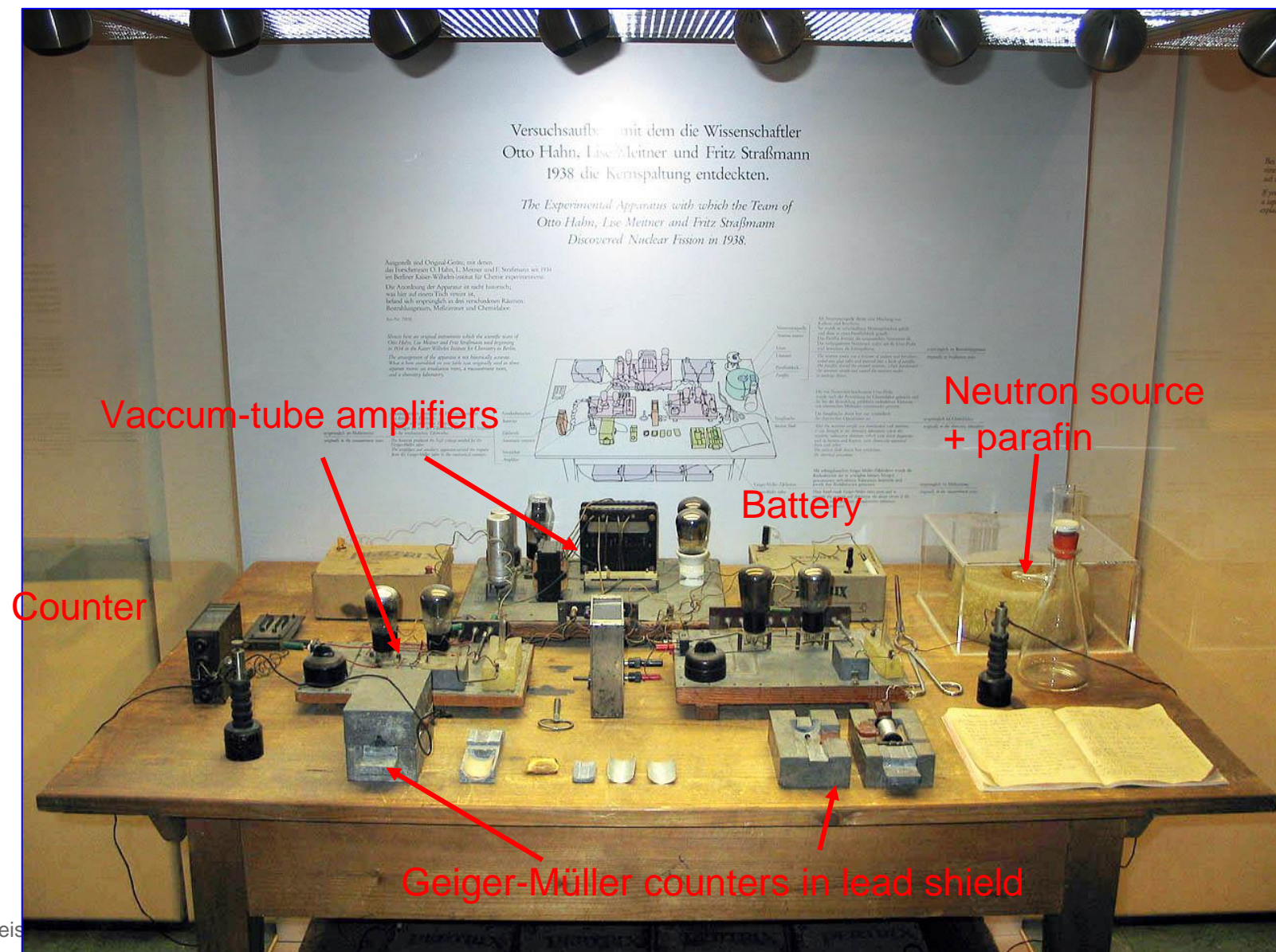


John Archibald
Wheeler (selfie !)



Yakov Frenkel

Dec. 1939 : about 100 papers on fission published !



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

Energy of a deformed liquid drop :

$$E_C(a) = E_C(0) \left(1 - \frac{1}{5}a^2 - \frac{4}{105}a^3 + \dots \right), \quad a = \sqrt{\frac{5}{4\pi}} \beta_2.$$

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

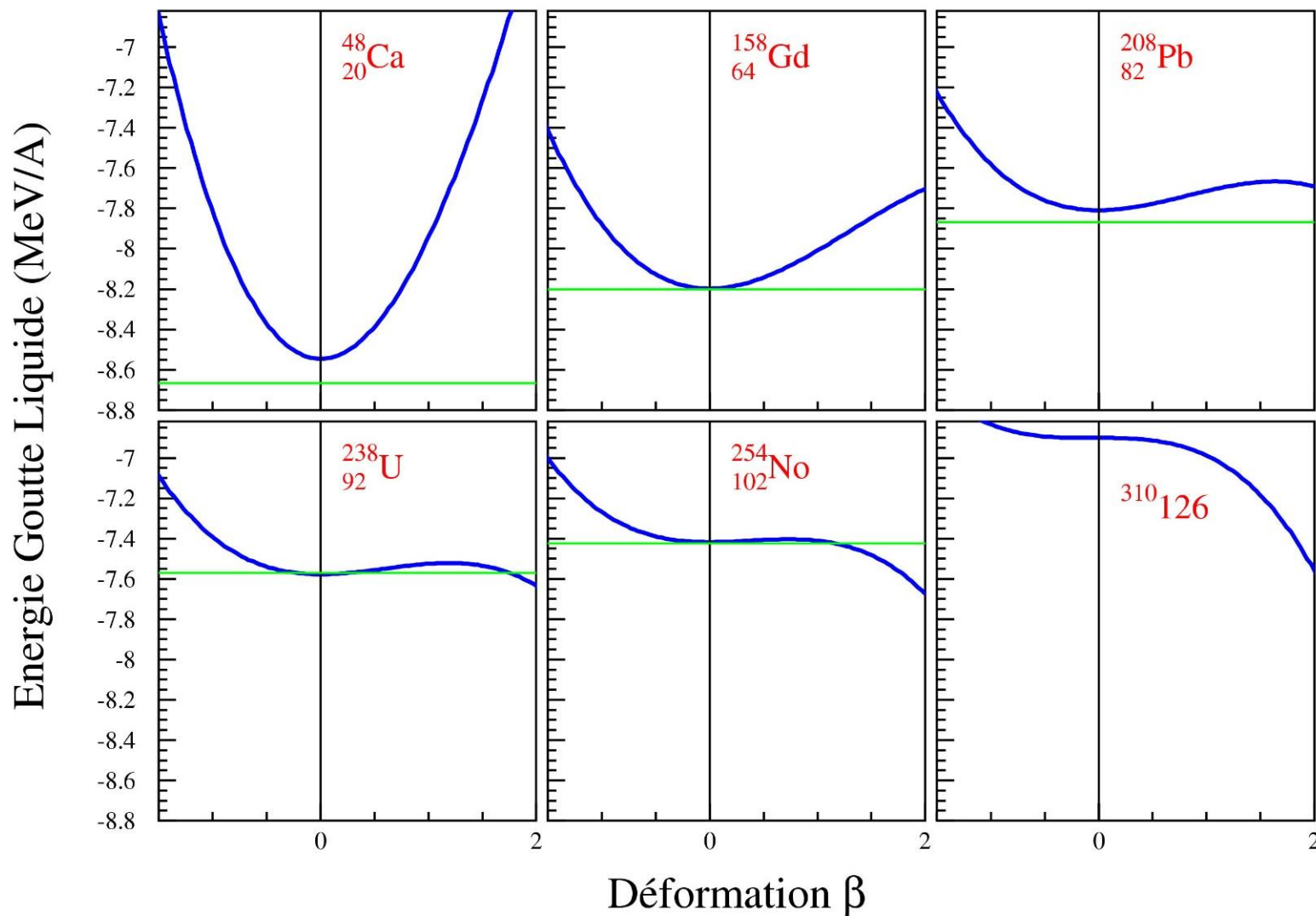
Change of energy as a function of deformation :

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

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

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

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



Paramétrisation : Myers - Swiatecki NPA 81 (1966)

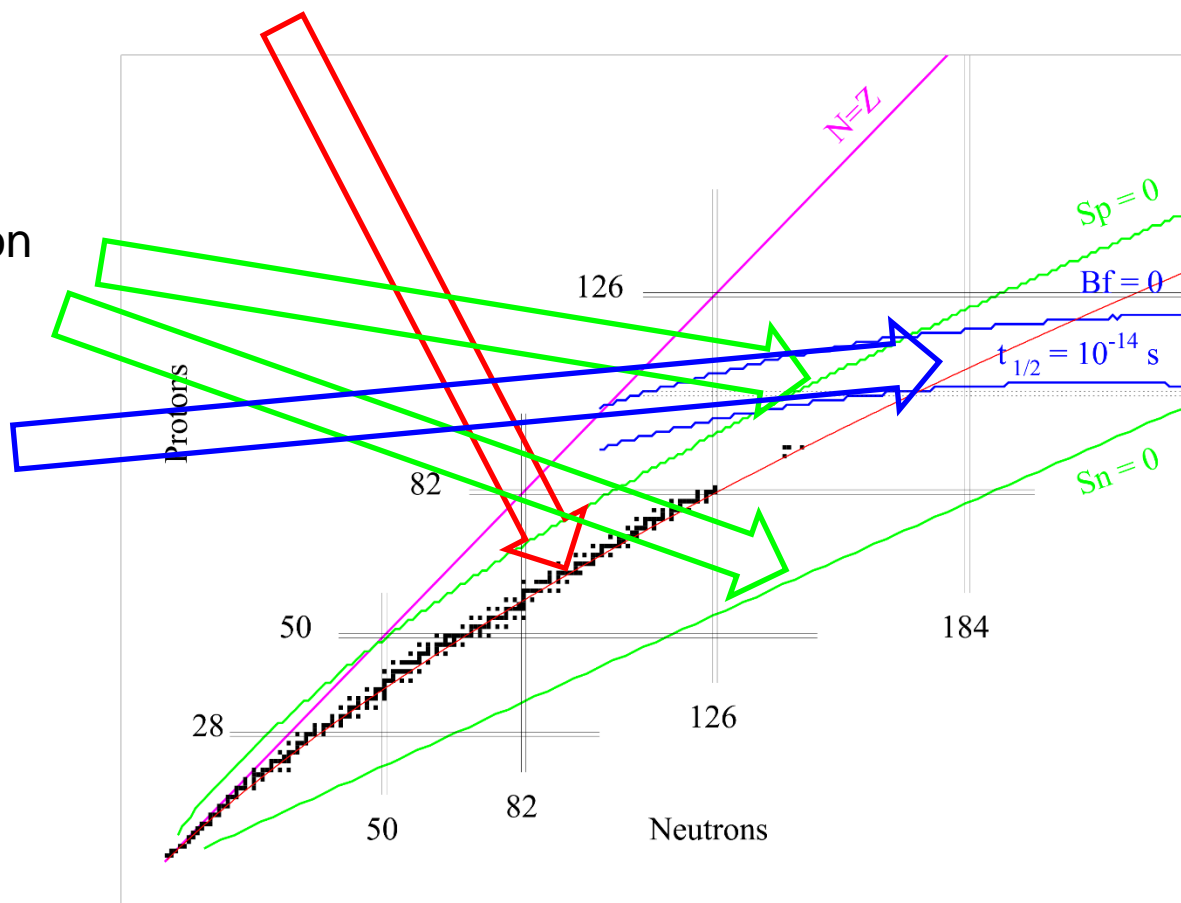
CONSEQUENCES OF THE LIQUID DROP MODEL



- 1 : heavy nuclei can fission spontaneously
- 2 : fission releases energy
- 3 : one can estimate the Q_{β^-} , Q_{β^+} , Q_{α} 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



SHE : chemist concept.

SHN : nuclear physicist concept.

SHE : usually equivalent to transactinide: $Z > 103$.

SHN: no scholar definition, but a generally accepted definition is that of elements that would not exist without shell or quantum effects \rightarrow above $Z \sim 104$.

NEPTUNIUM (93) AND PLUTONIUM (94)



- 1940 : **McMillan and Albersen**

Neutron from the reaction $d(8\text{MeV}) + {}^8\text{Be}$.

$n + {}^{238}\text{U} \rightarrow$ 2.3 days activity corresponds to ${}^{239}\text{93}$

but not a rare-earth, not homolog to Re. Chemical properties similar to U !

Second « rare-earth » group starting from U ?

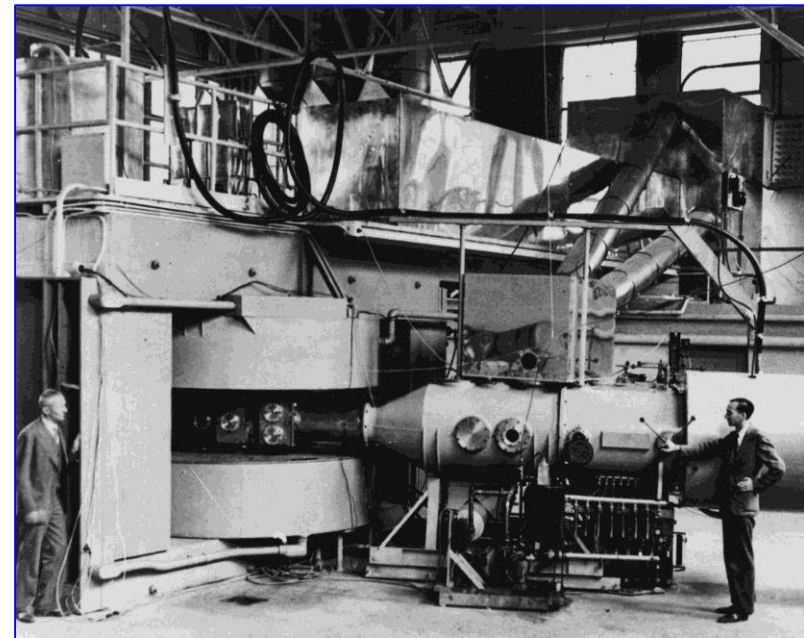
- 1940, 1941 : **G. Seaborg's team**

$d(16\text{ MeV}) + {}^{238}\text{U} \rightarrow {}^{238}\text{93} \rightarrow {}^{238}\text{94} \rightarrow {}^{234}\text{U}$

$d(16\text{ MeV}) + {}^{238}\text{U} \rightarrow {}^{239}\text{93} \rightarrow {}^{239}\text{94}$

Voluntary restrictions to publish papers on fission and transuranium elements: potential application for energy production.

Berkeley, 60 inch cyclotron in 1939



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 report¹ 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.

PR 70 (1946) 555

I A	II A	III B	IV B	V B	VI B	VII B	VIII					IB	II B	III A	IV A	V A	VIA	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 ~1930 : Z=93 same column as Mn, Tc, Re

THE ACTINIDE SERIE

1 H 1.008																				
3 Li 6.940	4 Be 9.02															5 B 10.82	6 C 12.010	7 N 14.008	8 O 16.000	
11 Na 22.997	12 Mg 24.32	13 Al 26.97															13 Al 26.97	14 Si 28.06	15 P 30.98	16 S 32.06
19 K 39.096	20 Ca 40.08	21 Sc 45.10	22 Ti 47.90	23 V 50.95	24 Cr 52.01	25 Mn 54.93	26 Fe 55.85	27 Co 58.94	28 Ni 58.69	29 Cu 63.57	30 Zn 65.38	31 Ga 69.72	32 Ge 72.60	33 As 74.91	34 Se 78.96					
37 Rb 85.48	38 Sr 87.63	39 Y 88.92	40 Zr 91.22	41 Nb 92.91	42 Mo 95.95	43 Tc [101.1]	44 Ru 101.1	45 Rh 102.91	46 Pd 106.7	47 Ag 107.880	48 Cd 112.41	49 In 114.76	50 Sn 118.70	51 Sb 121.76	52 Te 127.61					
55 Cs 132.91	56 Ba 137.36	57 La 138.92	58-71 SEE L6 SERIES	72 Hf 178.5	73 Ta 180.86	74 W 183.92	75 Re 186.31	76 Os 190.2	77 Ir 193.1	78 Pt 195.23	79 Au 197.2	80 Hg 200.51	81 Tl 204.39	82 Pb 207.21	83 Bi 209.00	84 Po				
87	88 Ra	89 Ac	SEE A6 SERIES	90 Th	91 Pa	92 U	93 Np	94 Pu	95	96										







Glen Seaborg

LANTHANIDE SERIES	57 La 138.92	58 Ce 140.13	59 Pr 140.92	60 Nd 144.27	61 Pm	62 Sm 150.43	63 Eu 152.0	64 Gd 156.9	65 Tb 159.2	66 Dy 162.45	67 Ho 163.5	68 Er 167.2	69 Tm 169.4	70 Yb 173.04	71 Lu 174.98
ACTINIDE SERIES	89 Ac	90 Th 232.04	91 Pa 231	92 U 238.07	93 Np 237	94 Pu	95	96							






Actinide concept : Glen Seaborg ~ 1944

Table from G. Seaborg, [Science 104 \(1946\) 379](#)

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

Wrong placement in the periodic table

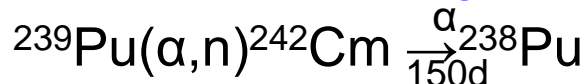
TABLE IV.—PERIODIC ARRANGEMENT OF THE RADIO-ELEMENTS.

GROUP IN PERIODIC SYSTEM	VI A	V A	IV A	III A	II A	I A	0	I B	II B	III B	IV B	V B	VI B
ELEMENT OF HIGHEST ATOMIC WEIGHT	U	Ta	Th	La	Ra	Cs	Xe	Au	Hg	Tl	Pb	Bi	Te
	Ur 1 $\xrightarrow{\alpha}$ Ur X ₁ $\xleftarrow{\beta}$ Ur X ₂ $\xleftarrow{\beta}$ Ur 2 $\xleftarrow{\alpha}$	Pa $\xrightarrow{\alpha}$ Ur X ₁ $\xleftarrow{\beta}$ Ur X ₂ $\xleftarrow{\alpha}$ Io $\xrightarrow{\alpha}$ Th $\xrightarrow{\alpha}$ Meso Th 1 $\xleftarrow{\beta}$ Meso Th 2 $\xleftarrow{\beta}$ Ra Th $\xrightarrow{\alpha}$ Th X $\xrightarrow{\alpha}$ Th Em $\xrightarrow{\alpha}$ Th A $\xrightarrow{\alpha}$ Th B $\xrightarrow{\beta}$ Th C $\xleftarrow{\alpha+\beta}$ Th D	Ac $\xrightarrow{\alpha}$ Ra $\xrightarrow{\alpha}$ Ra Em $\xrightarrow{\alpha}$ Ra A $\xrightarrow{\alpha}$ Ra B $\xrightarrow{\beta}$ Ra C $\xleftarrow{\alpha+\beta}$ Ra D $\xrightarrow{\beta}$ Ra E $\xrightarrow{\beta}$ Ra F $\xleftarrow{\alpha}$ Ra G (LEAD) $\xrightarrow{\beta}$ Th B $\xrightarrow{\beta}$ Th C $\xleftarrow{\alpha+\beta}$ Th D			Fr $\xrightarrow{\alpha}$ Rn							
			Act $\xrightarrow{\alpha}$ Ra Act 1 $\xleftarrow{\beta(2)}$ Ra Act 2 $\xrightarrow{\alpha+\beta}$ Act X $\xrightarrow{\alpha}$ Act Em $\xrightarrow{\alpha}$ Act A $\xrightarrow{\alpha}$ Act B $\xrightarrow{\beta}$ Act C $\xleftarrow{\alpha+\beta}$ Act D										

CHEMICAL NEWS, Jan. 31, 1913. Periodic System and the Radio-elements. 51

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

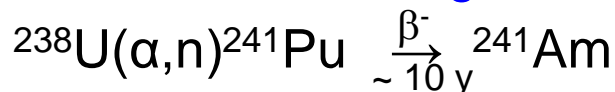
Z=96 Cm : Seaborg 1944 (60'' cyclotron)



AECD-2182 report, [Chem. Eng. News 23 \(1945\) 2190](#)



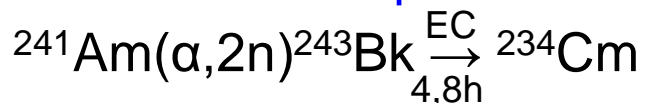
Z=95 Am : Seaborg 1944 (60'' cyclotron)



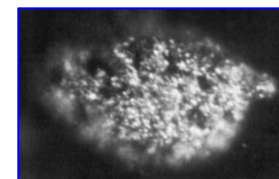
[AECD-2185 report](#), Chem. Eng. News 23 (1945) 2190



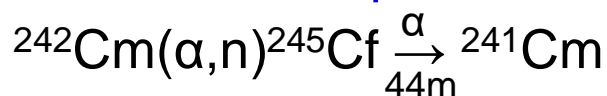
Z=97 Bk : Thompson 1949 (60'' cyclotron)



[UCRL-669 report](#), [PR 77 \(1950\) 838](#)

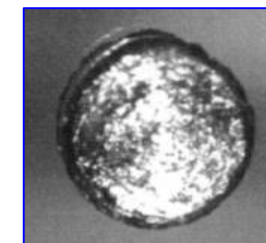


Z=98 Cf: Thompson 1950 (60'' cyclotron)



UCRL-790 report [PR 78 \(1950\) 298](#), [102 \(1956\) 747](#)

(mass assignment was wrong in the 1950 paper)





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

Explosion debris
collected by a plane transferred
to Los Alamos.

Results obviously classified.

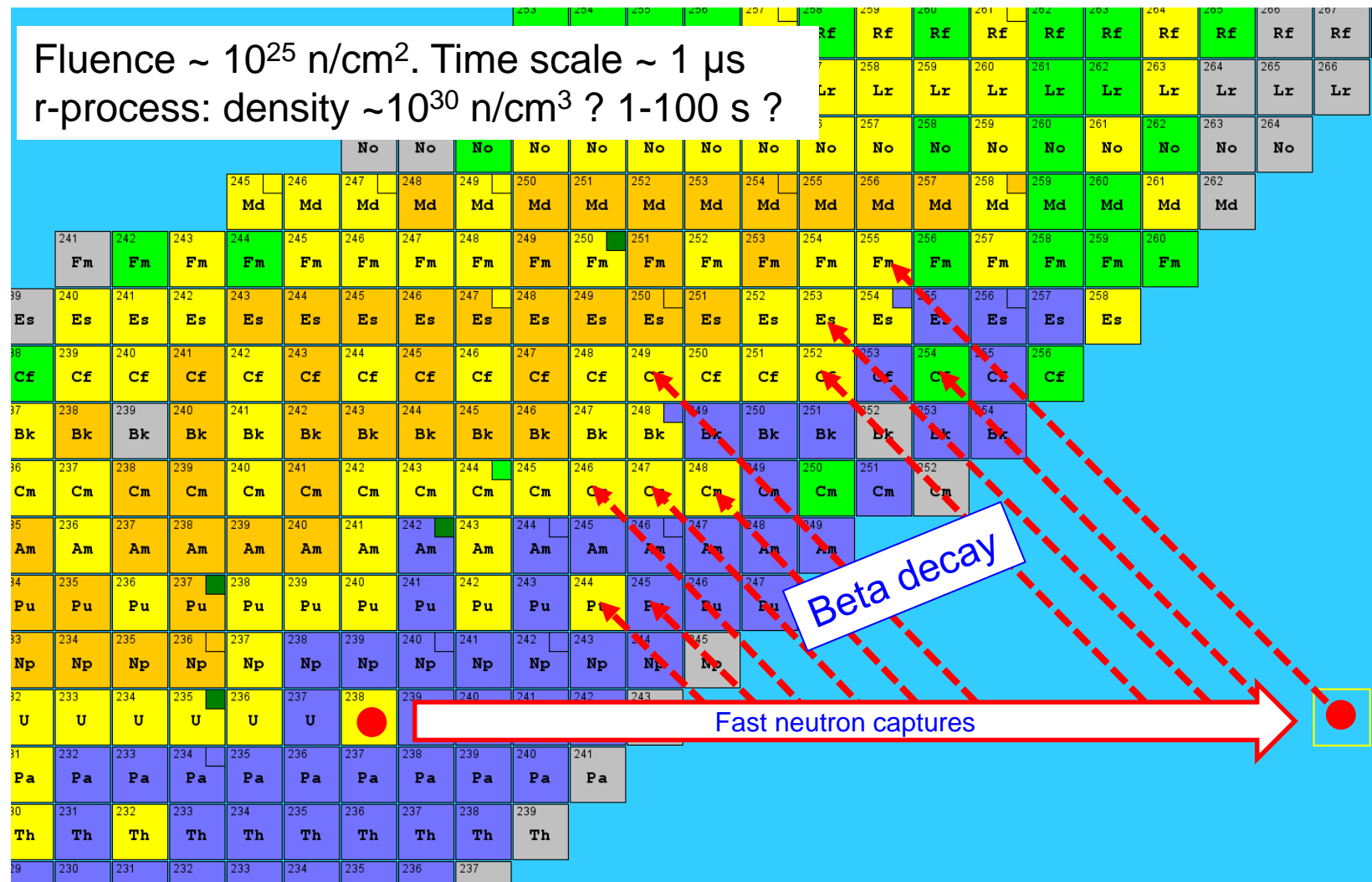
Some new alpha-rays.

Albert Ghiorso, Berkeley obtains some samples.

→ Discovery ^{253}Es and ^{255}Fm

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

Fluence $\sim 10^{25}$ n/cm². Time scale ~ 1 μ s
r-process: density $\sim 10^{30}$ n/cm³ ? 1-100 s ?



HEAVY ELEMENTS AND THE R-PROCESS

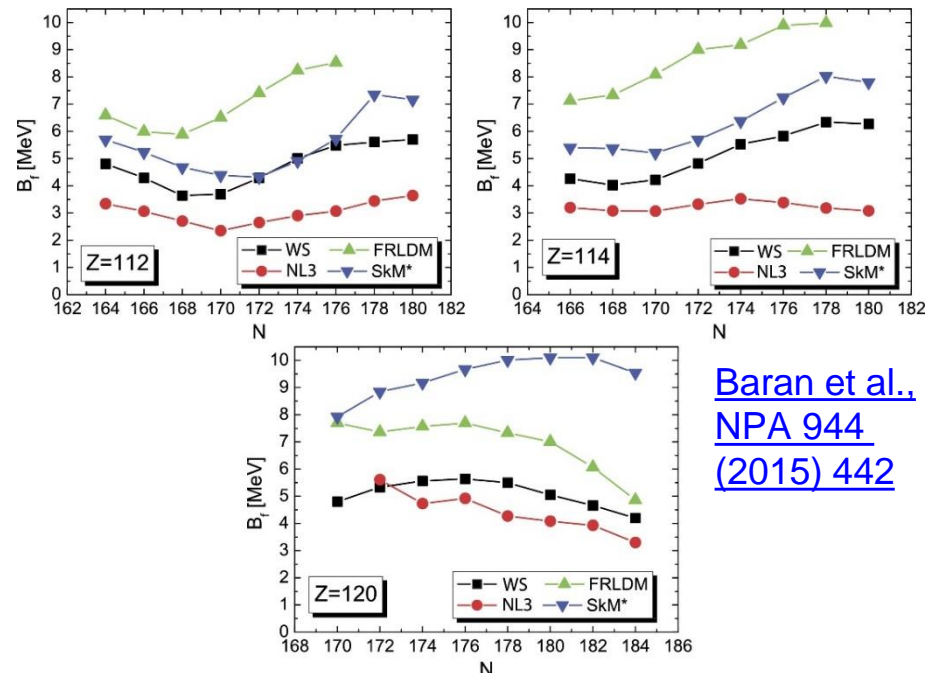
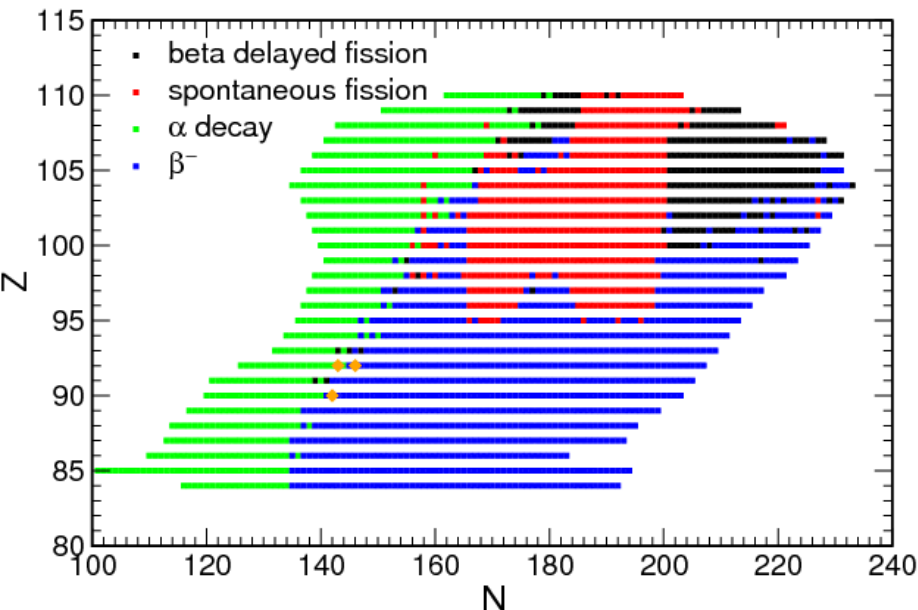


Related questions

- **Production of super-heavy in nature; r-process** : Supernovae explosions have been considered as a possible site of r-process
- Ingredients: capture cross-sections, decay mode, lifetime.
- Key ingredient calculations = fission barriers. But huge prediction spread and no data above ^{254}No

Petermann et al

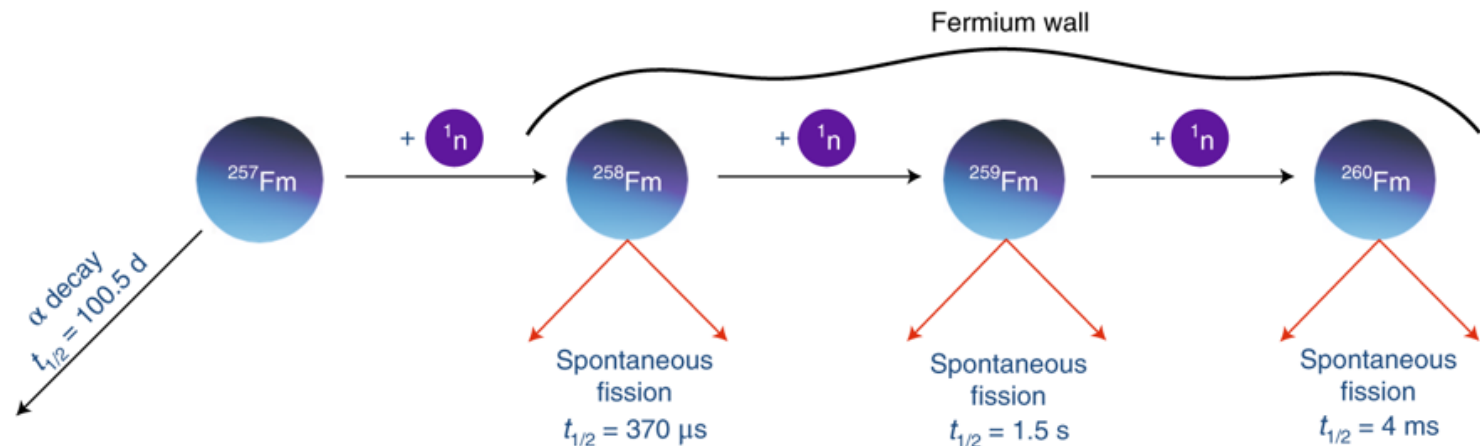
« Have superheavy elements been produced in nature? » [EPJA 48 \(2012\) 122](#)



[Baran et al.,
NPA 944
\(2015\) 442](#)

- Why nothing heavier than ^{257}Fm in thermonuclear Explosions ?

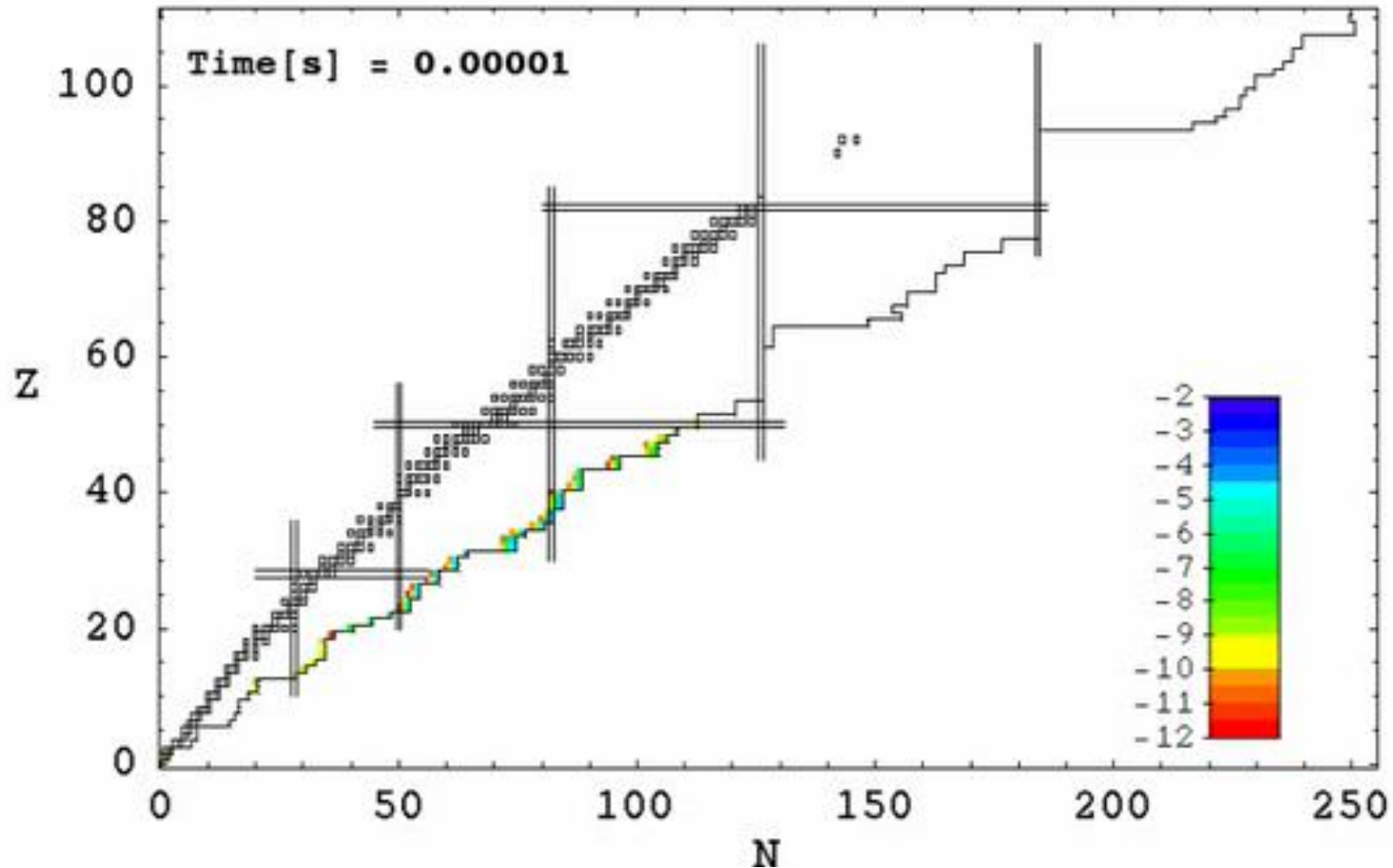
Need very neutron rich Fm nuclei to reach Beta-decaying nuclei (because $Z=100$ deformed magic shell gap). But $^{258-260}\text{Fm}$ predicted too short lived and/or fissioning spontaneously



R-PROCESS AND NEUTRON STAR MERGER



Production of super-heavy in nature; r-process : Neutron star Merger



Stephane Goriely, Andreas Bauswein, Hans-Thomas Janka

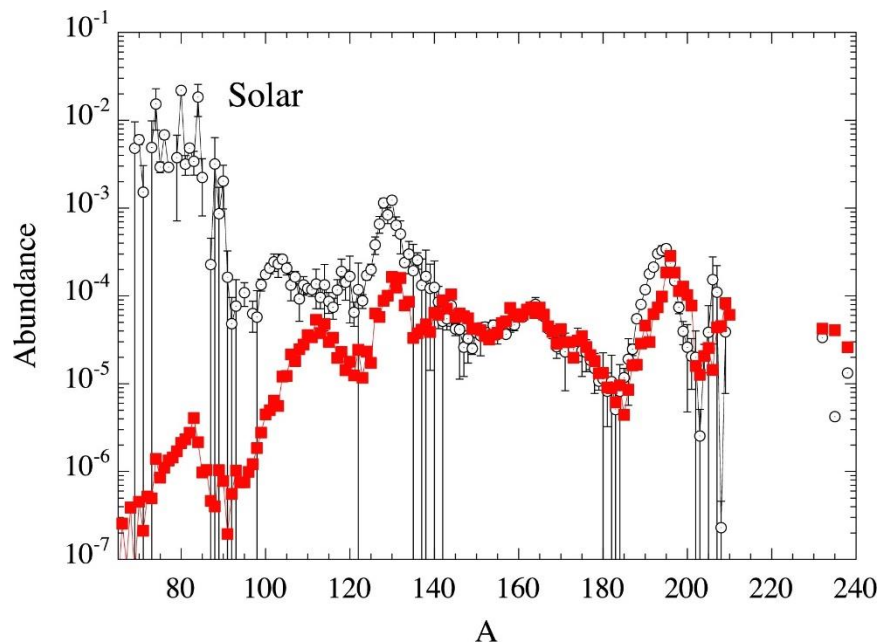
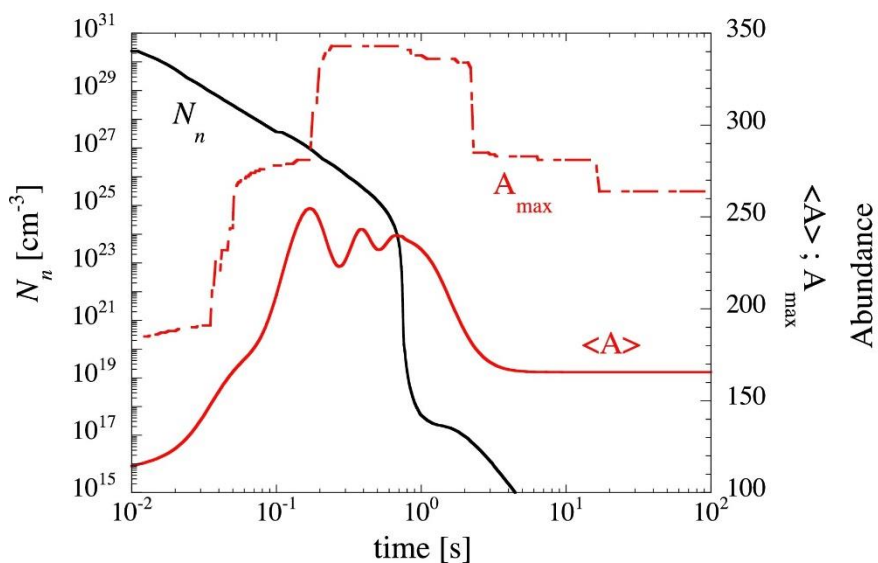
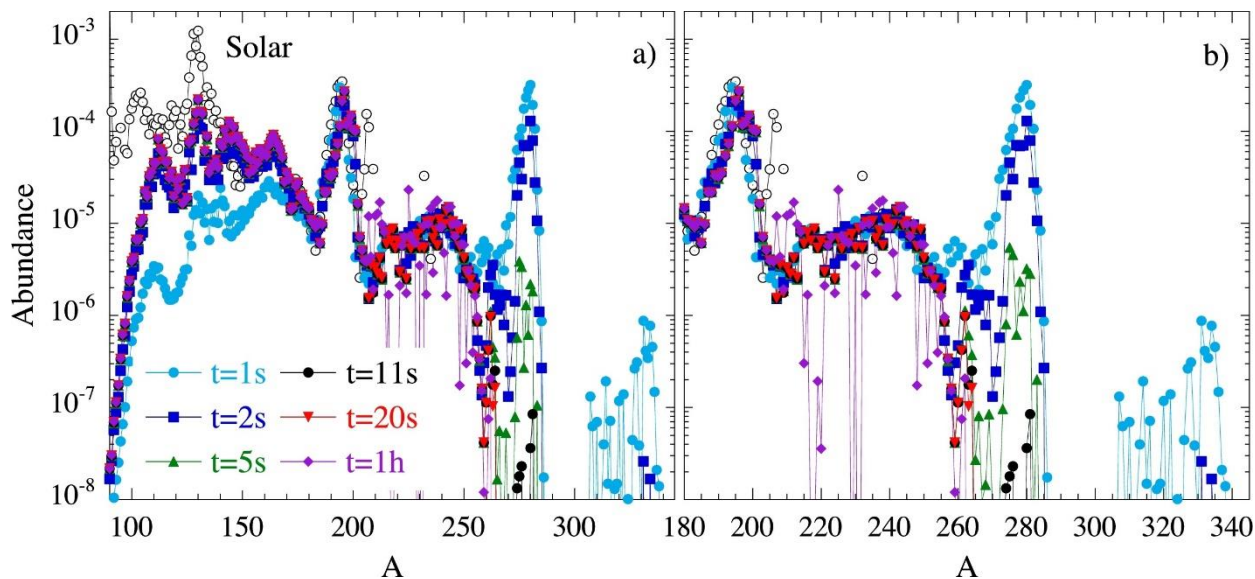
<https://www.youtube.com/watch?v=zouvhsFvKiM>

Ch.Theis See also [S.Goriely, G.Martínez-Pinedo NPA 944 \(2015\) 158](#)

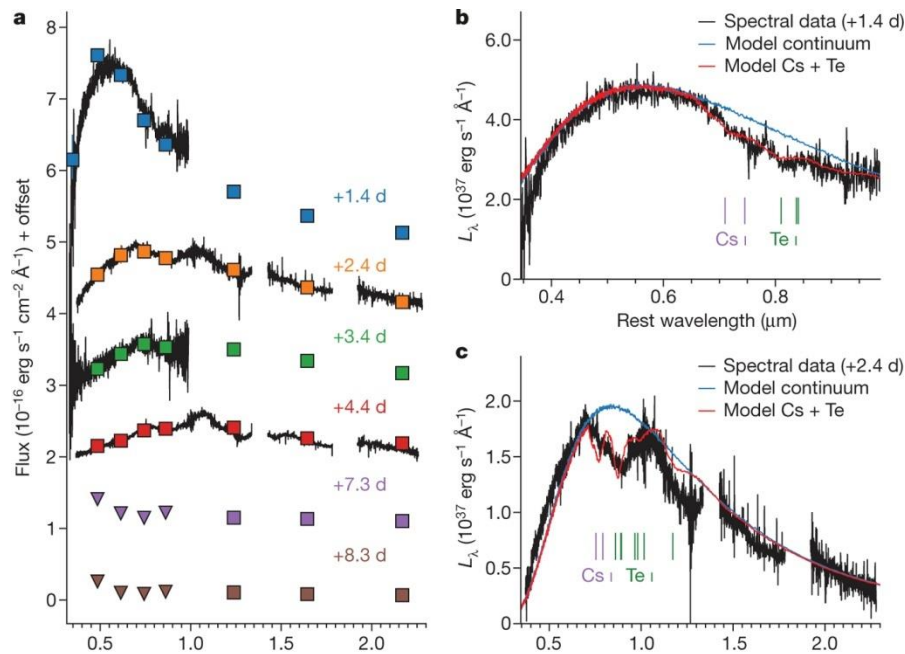
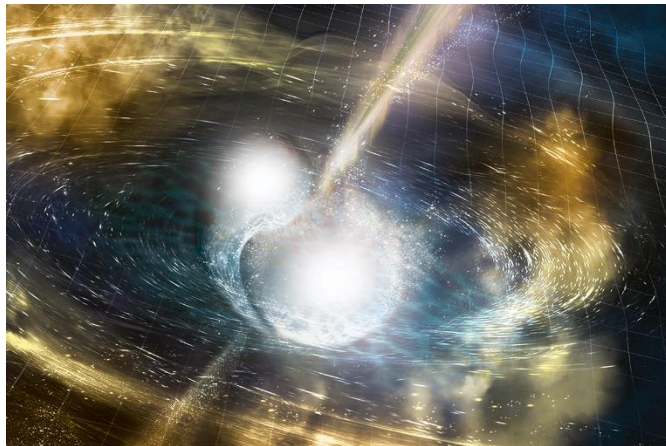
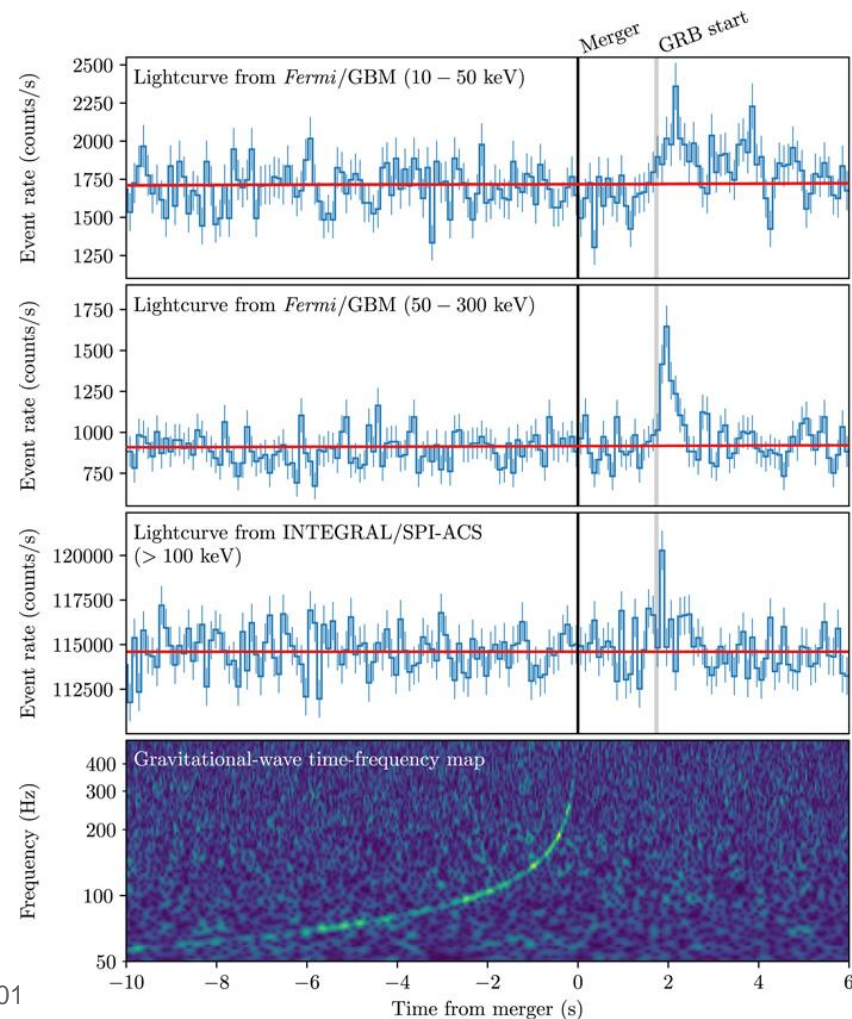
SOLAR VERSUS NEUTRON-START MERGER ABUNDANCES



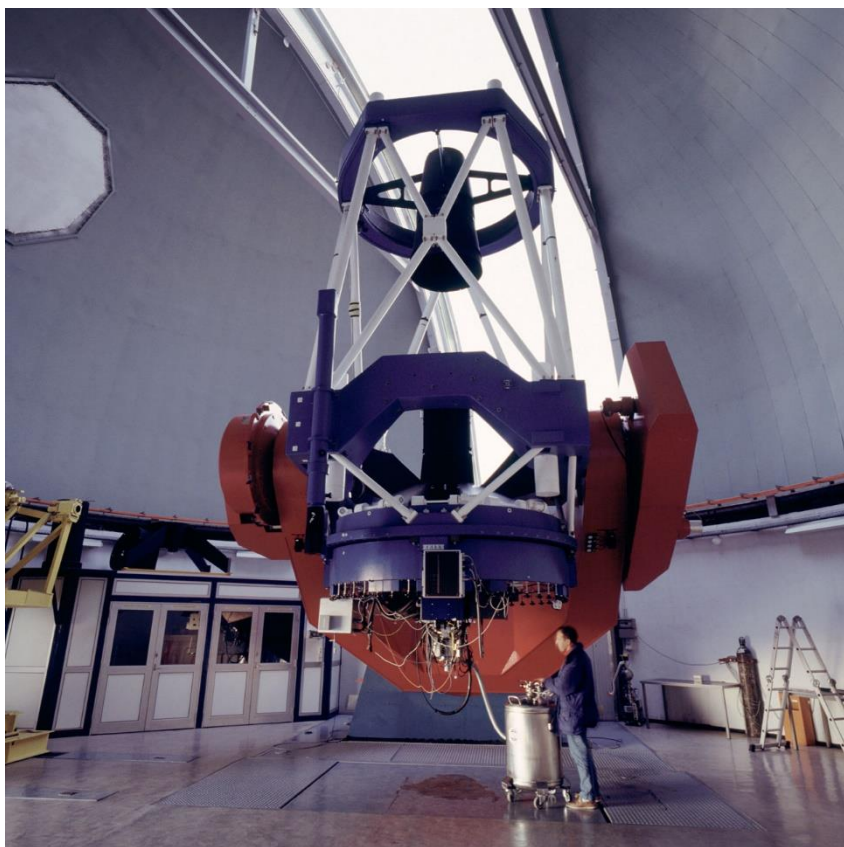
NPA 944 (2015) 158



NEUTRON STAR MERGER 2017 08 17

Multi-messenger Observations
[Abbott et al. ApJ 848 \(2017\) L12](#)

MPG/ESO telescope at ESO's La Silla Observatory



A vast program with great hopes (and great fakes)

Search in meteorites, moon samples, cosmic rays, terrestrial ores, water, etc...

See e.g.

[Ter-Akopian and Dimitriev NPA 944 \(2015\) 177](#)

[Korschineka and Kutschera NPA 944 \(2015\) 190](#)

And references therein

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

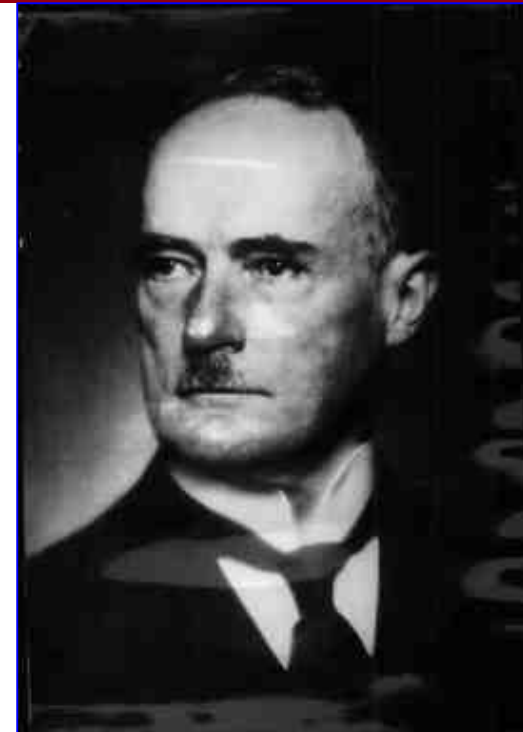
Found in pitchblende ores. Chemical solution
acidified with nitric acid then thallium nitrate added
«Just as expected a vermillion coloured crystalline
sediment appeared ».

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)



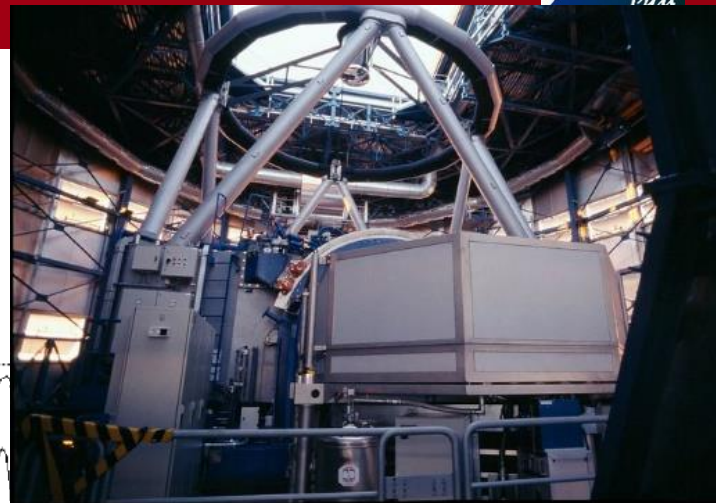
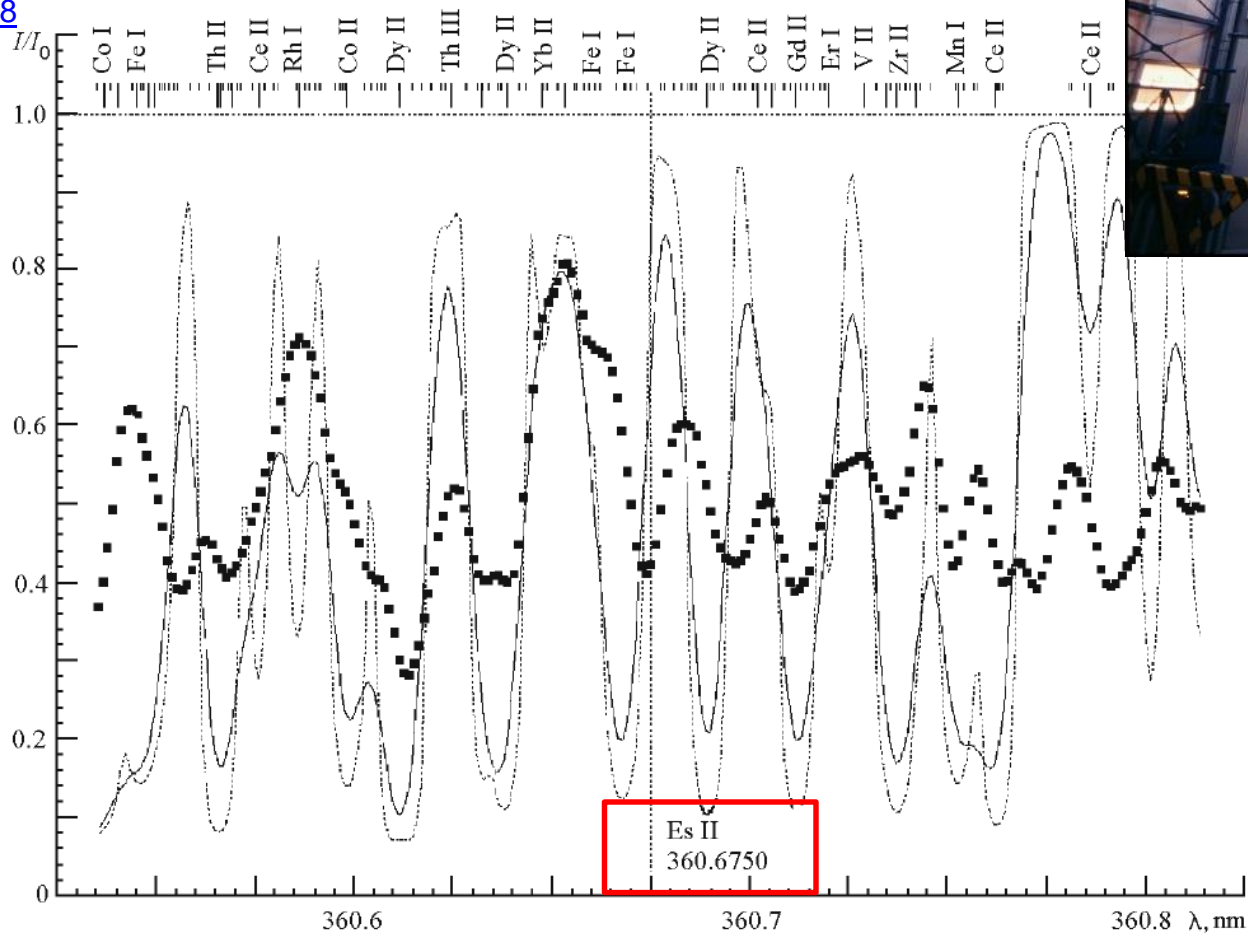
Odolen Koblic

X-RAYS FROM THE PRZYBYLSKI'S STAR



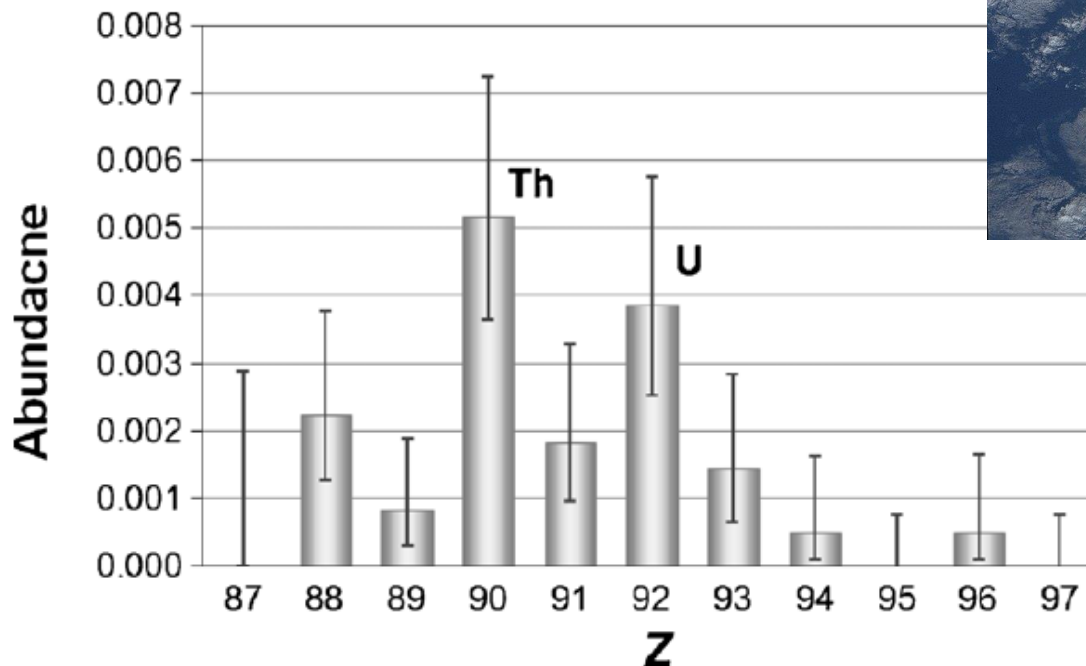
VTL telescope, UVES spectrograph

[V. F. Gopka, A. V. Yushchenko, V. A. Yushchenko, I. V. Panov and Ch. Kim Kinematics and Physics of Celestial Bodies 24\(2\):89-98](#)



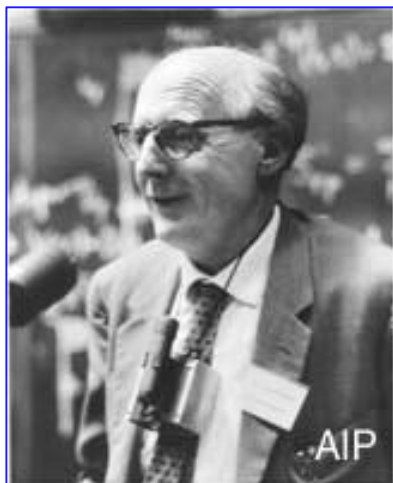
NASA LDEF Mission
Long Duration Exposure Facility
Launched by challenger space
Shuttle, 1984

UHCORE instrument:
solid state nuclear track detector



[Donnelly,](#)
[The astrophysical journal 747 \(2012\) 40](#)

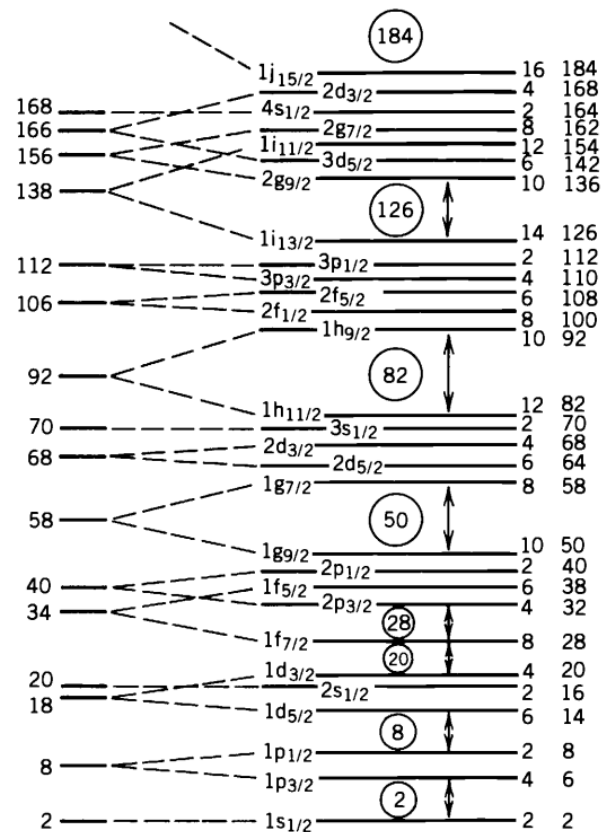
1 event Cm



D. Jensen



M. Goeppert Mayer

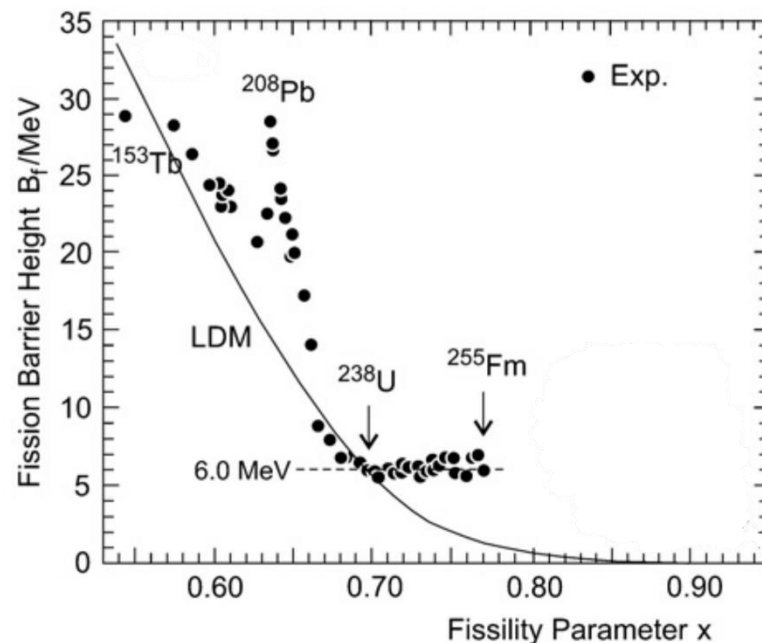


FISSION VS LIQUID DROP MODEL



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

Swiatecki 1955 : correcting the liquid drop-model for shell structure may improve the description of spontaneous fission half-lives
[PR 100 \(1955\) 937](#)



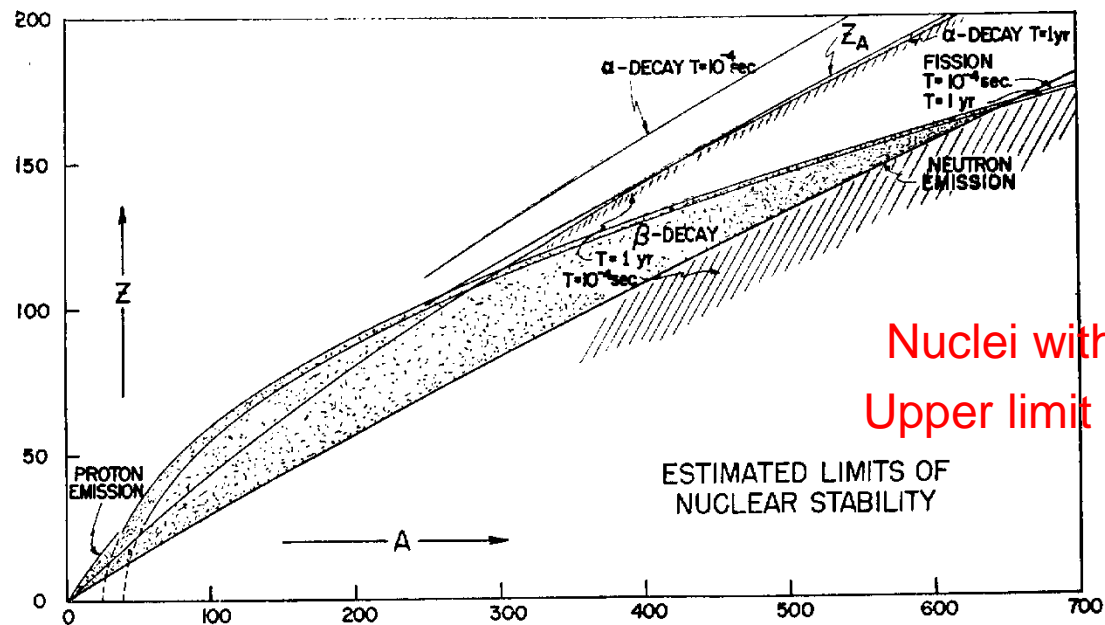
Oganessian J. Phys. G 34 (2007) R165

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

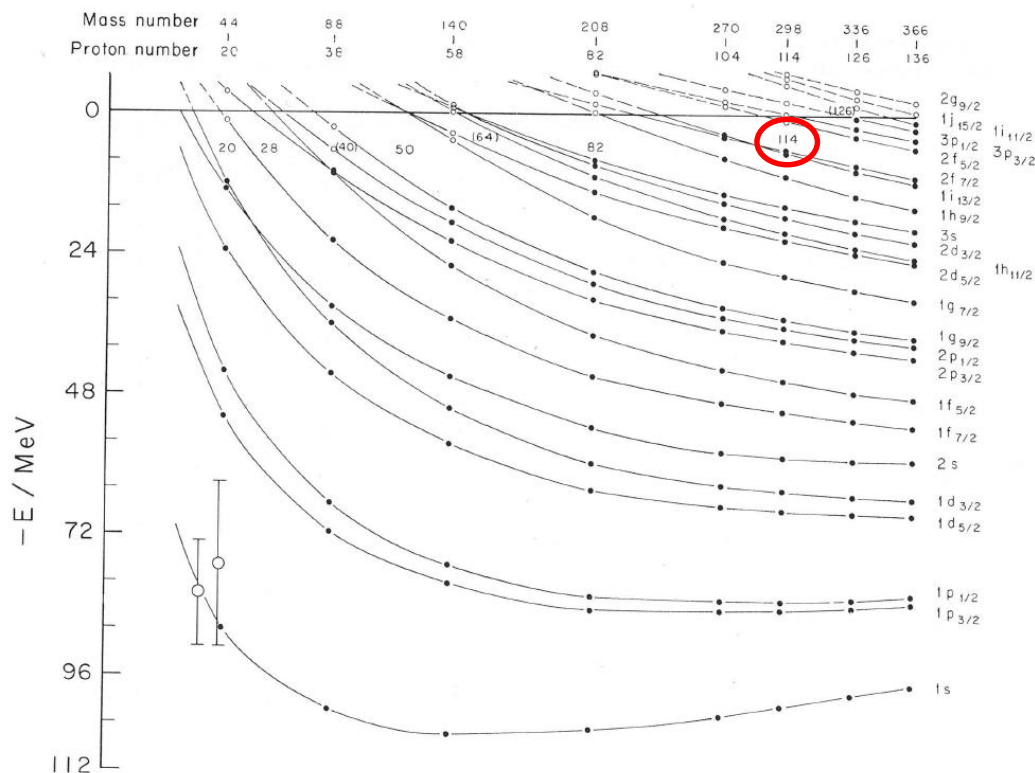


Estimates based mostly on the liquid drop model. Shell effects are introduced in an approximate way.

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 ${}_{126}^{310}\text{X}$ "
- 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)

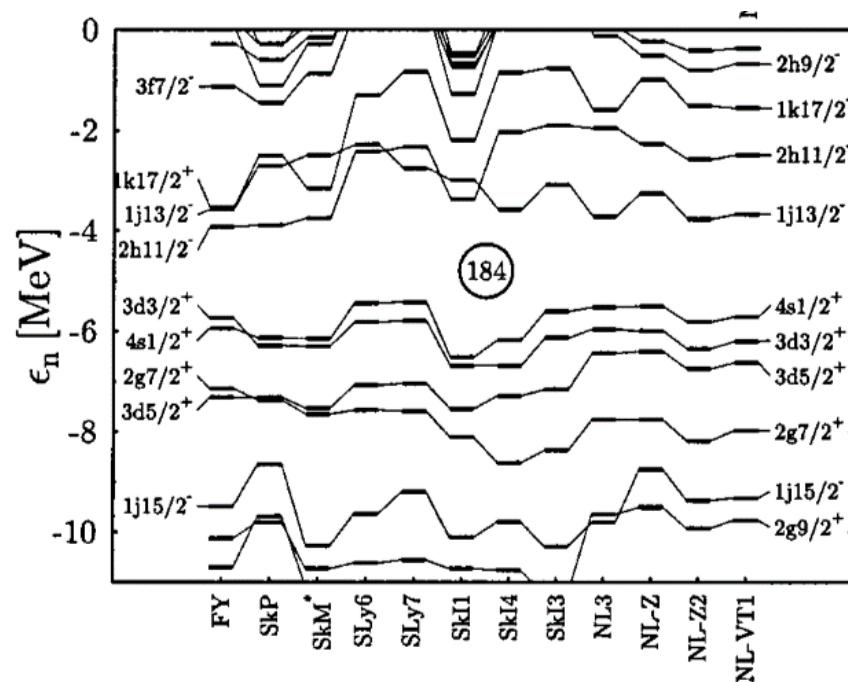
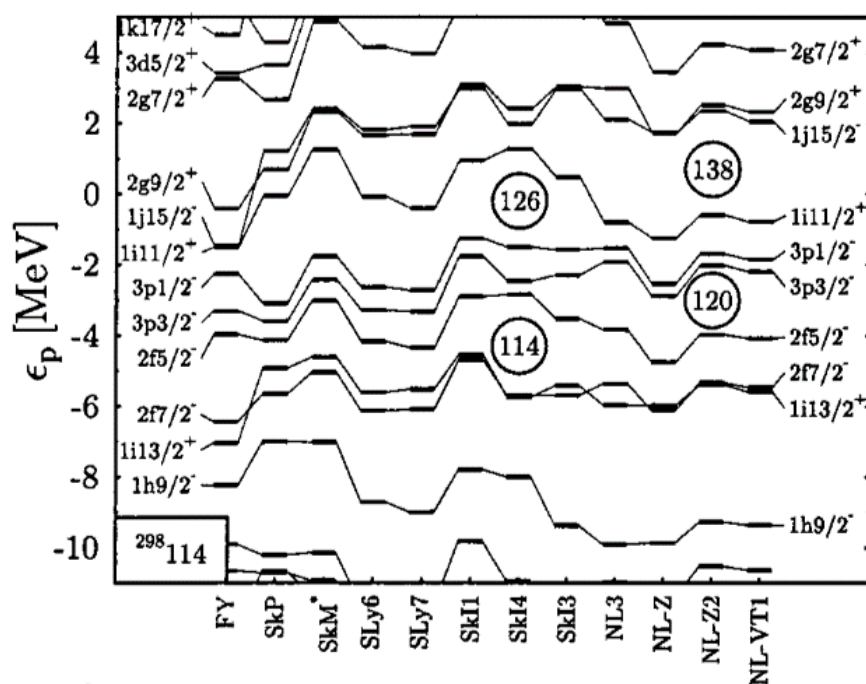
...

= calculations using phenomenological potentials

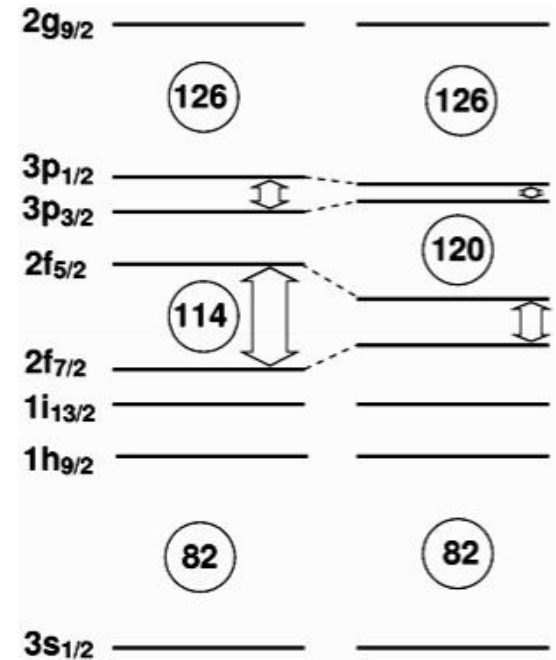
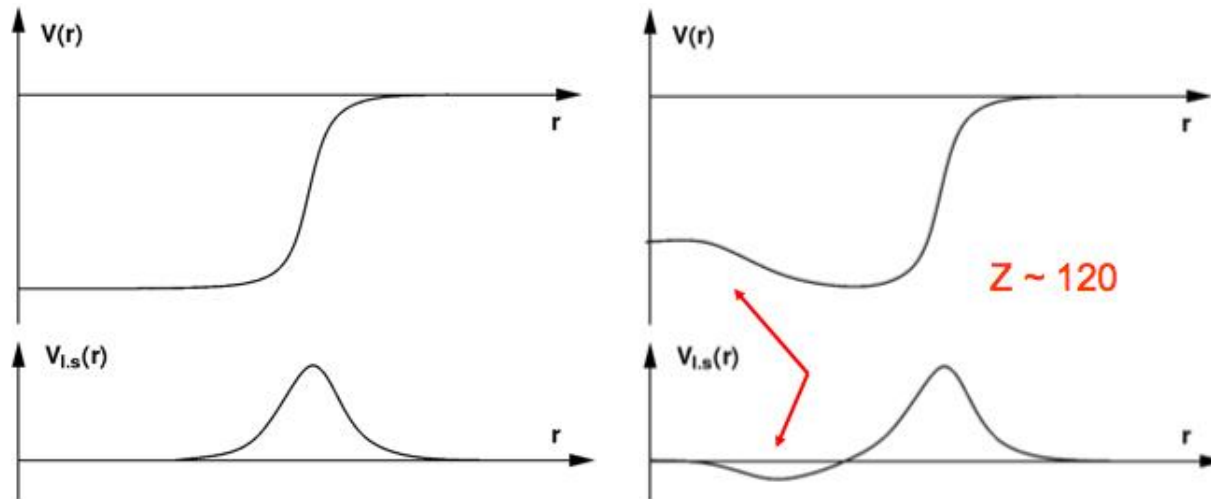
systematic calculations using self-consistent models (spherical nuclei)

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](#)



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



Effect of spin orbit contribution cancelled or reversed
Splitting $2f_{5/2} - 2f_{7/2}$

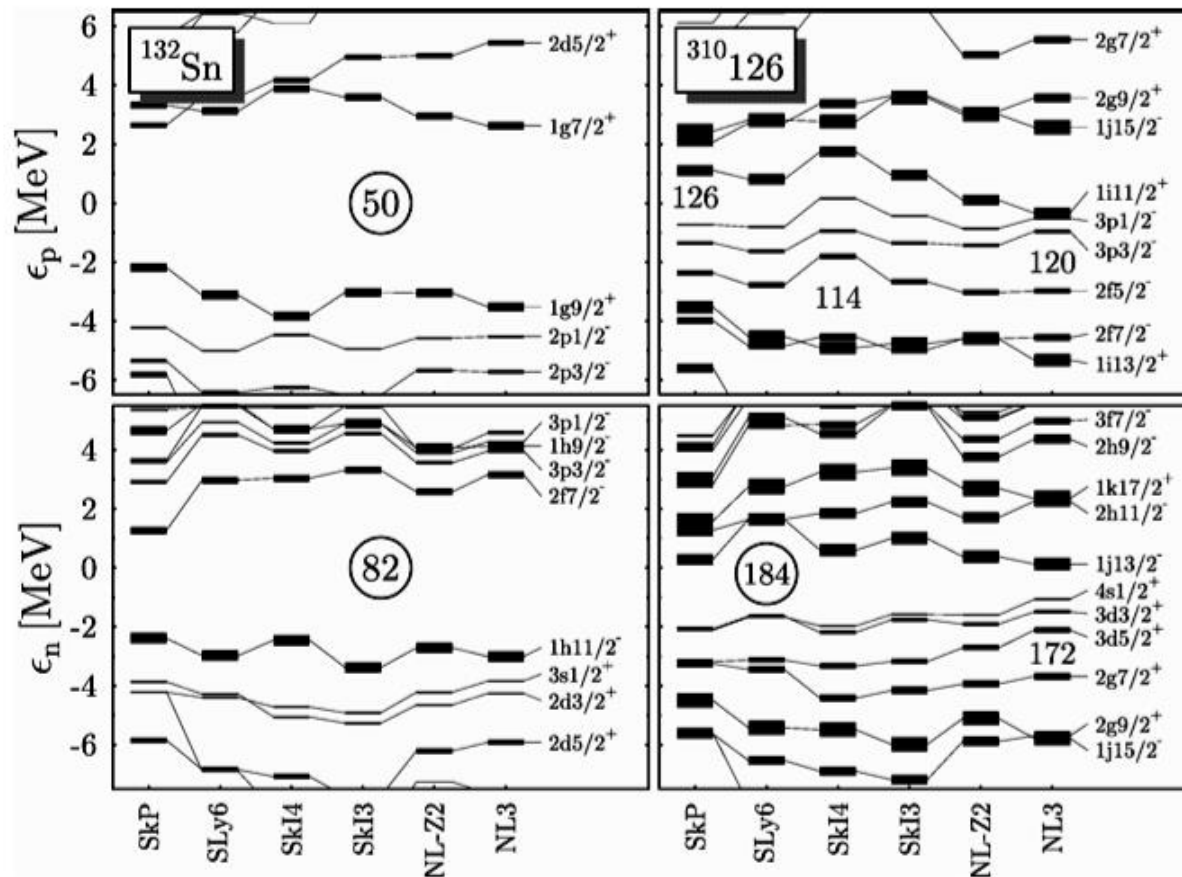
COMPLEX NATURE OF SHN



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

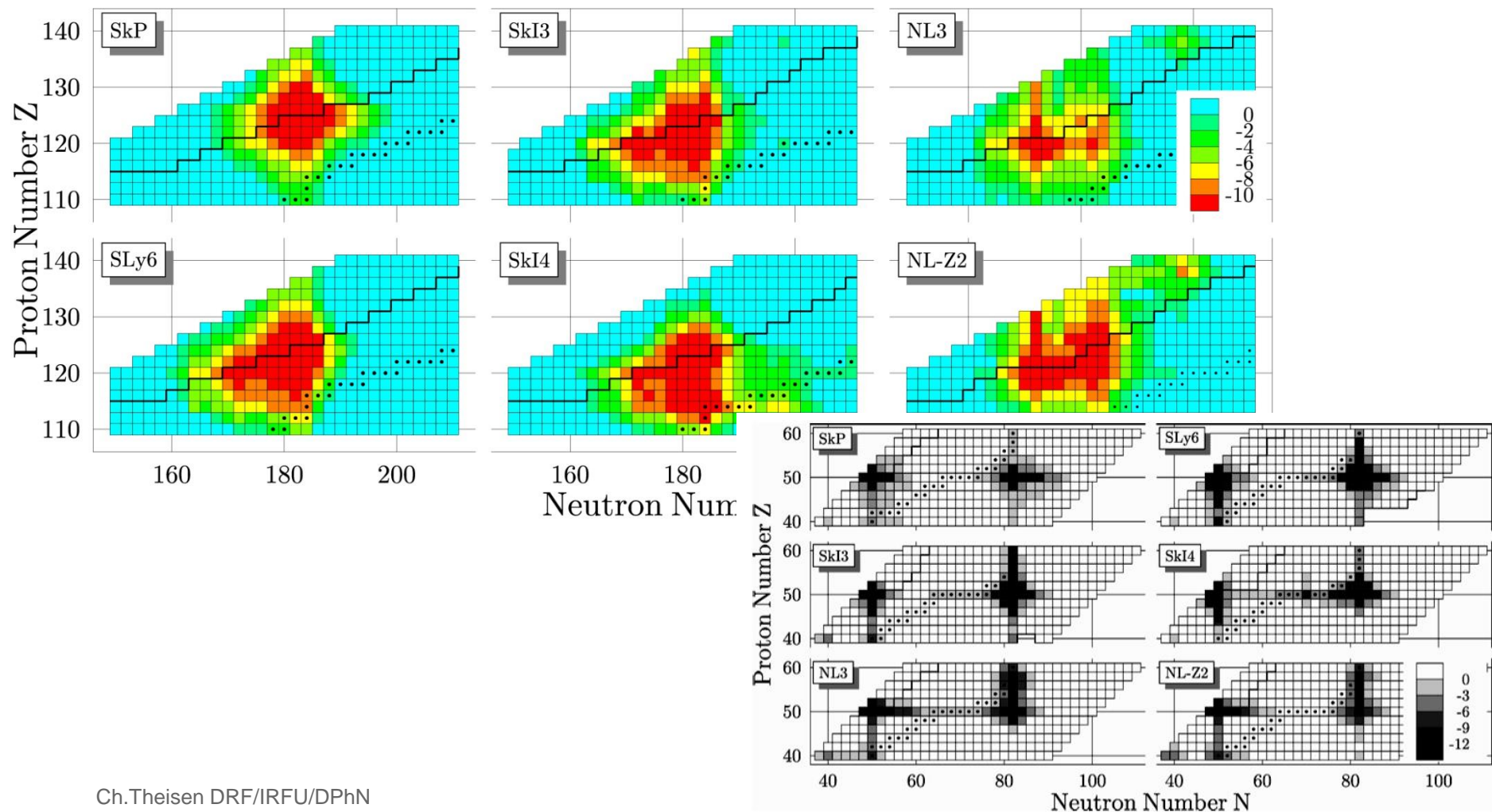


THEORETICAL CHALLENGES



Doubly magic character of predicted SHN not as marked as lighter Nuclei such as ^{48}Ca , ^{208}Pb , ...

Island of stability smooth and not well localized.



First evidence by Schüler and Schmidt (1935) in $^{151,153}\text{Eu}$, atomic spectroscopy → atomic structure is influenced by the nuclear deformation [ZP 94\(1935\) 457](#)

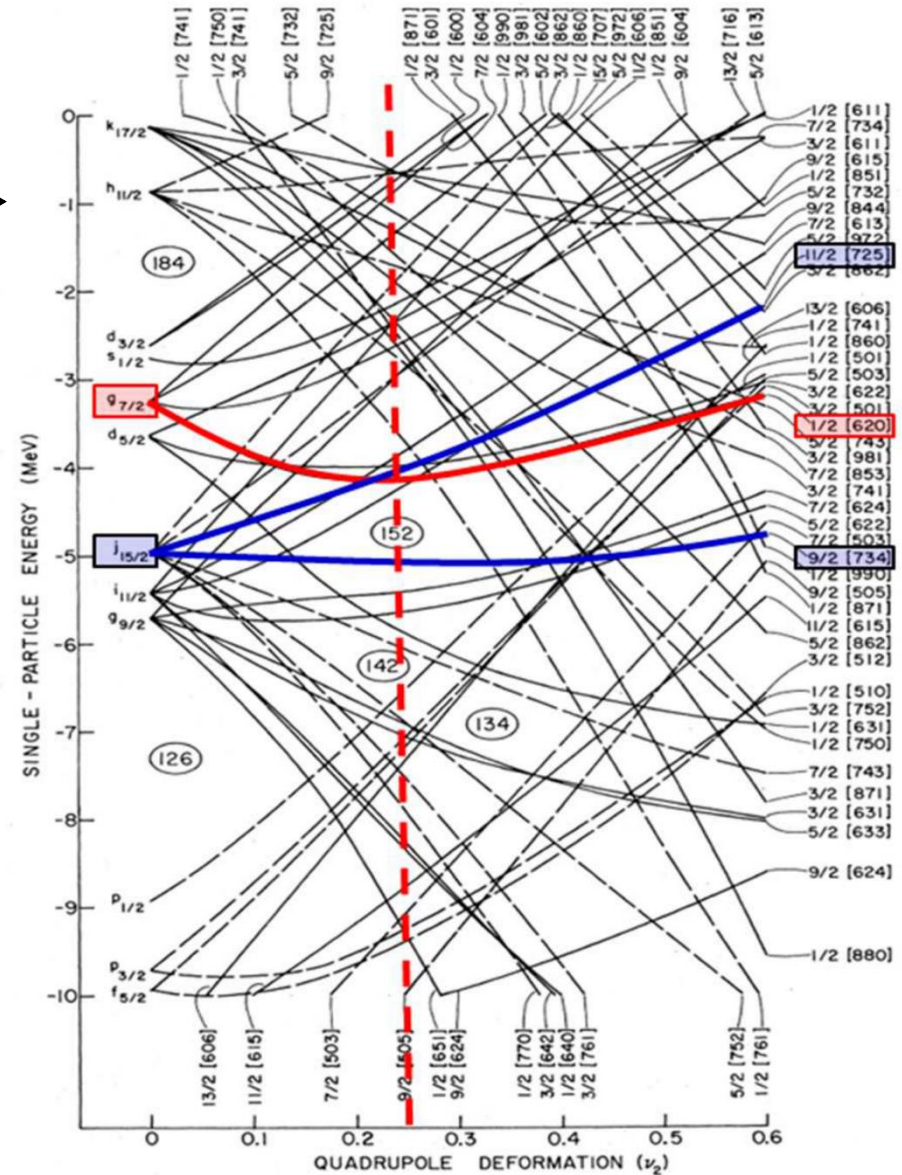
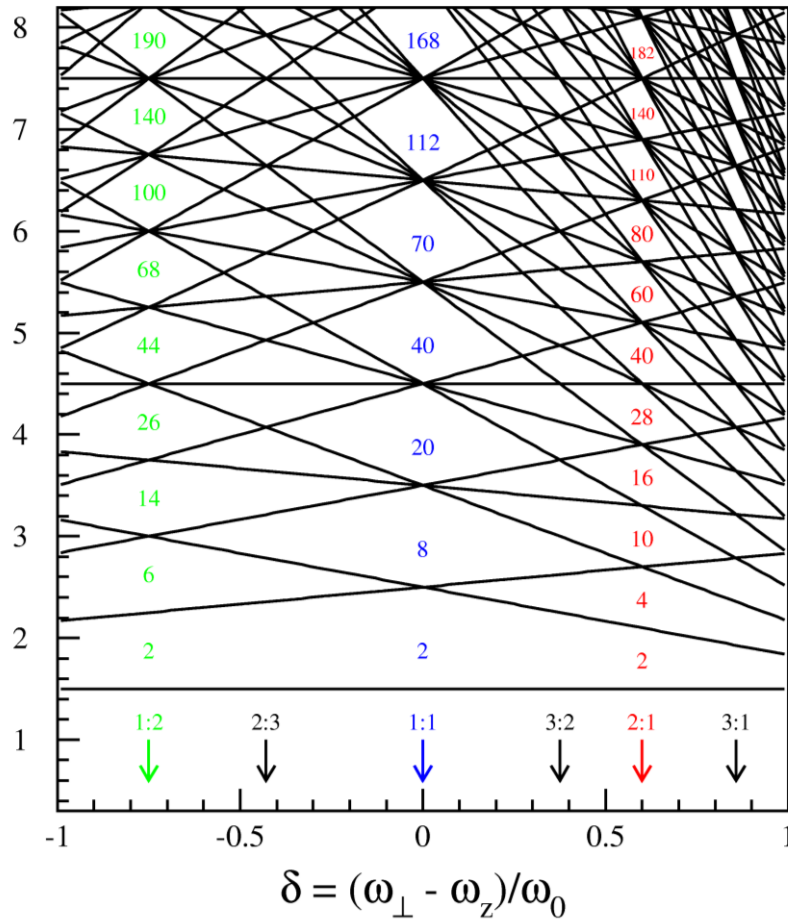
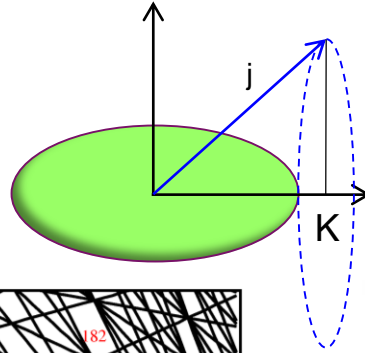
Townes systematics (1949) of electric quadrupole moments [PR 76 \(1949\) 1415](#)

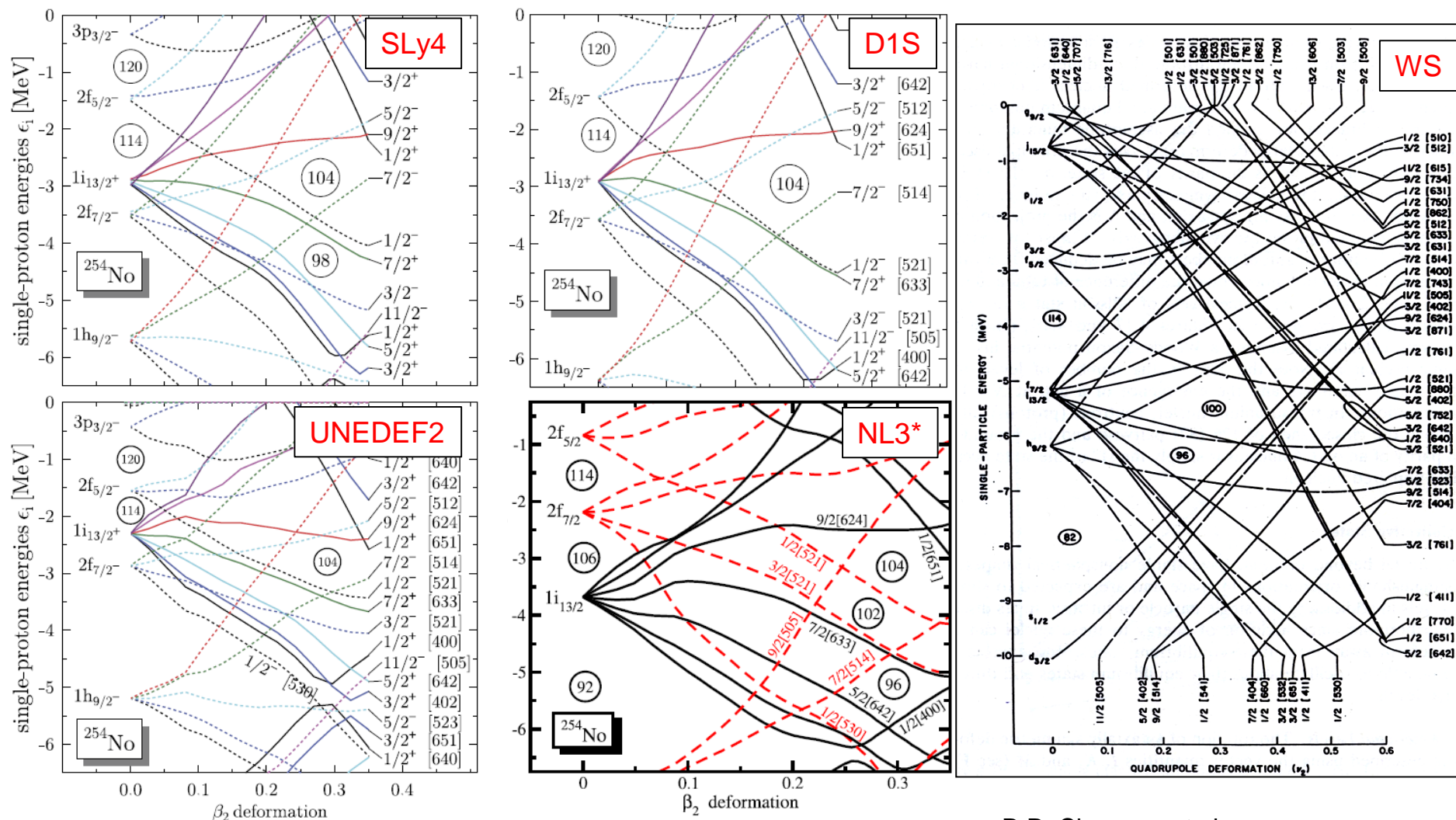
1950 : spheroidal model by J. Rainwater, unified model by Bohr and Mottelson

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



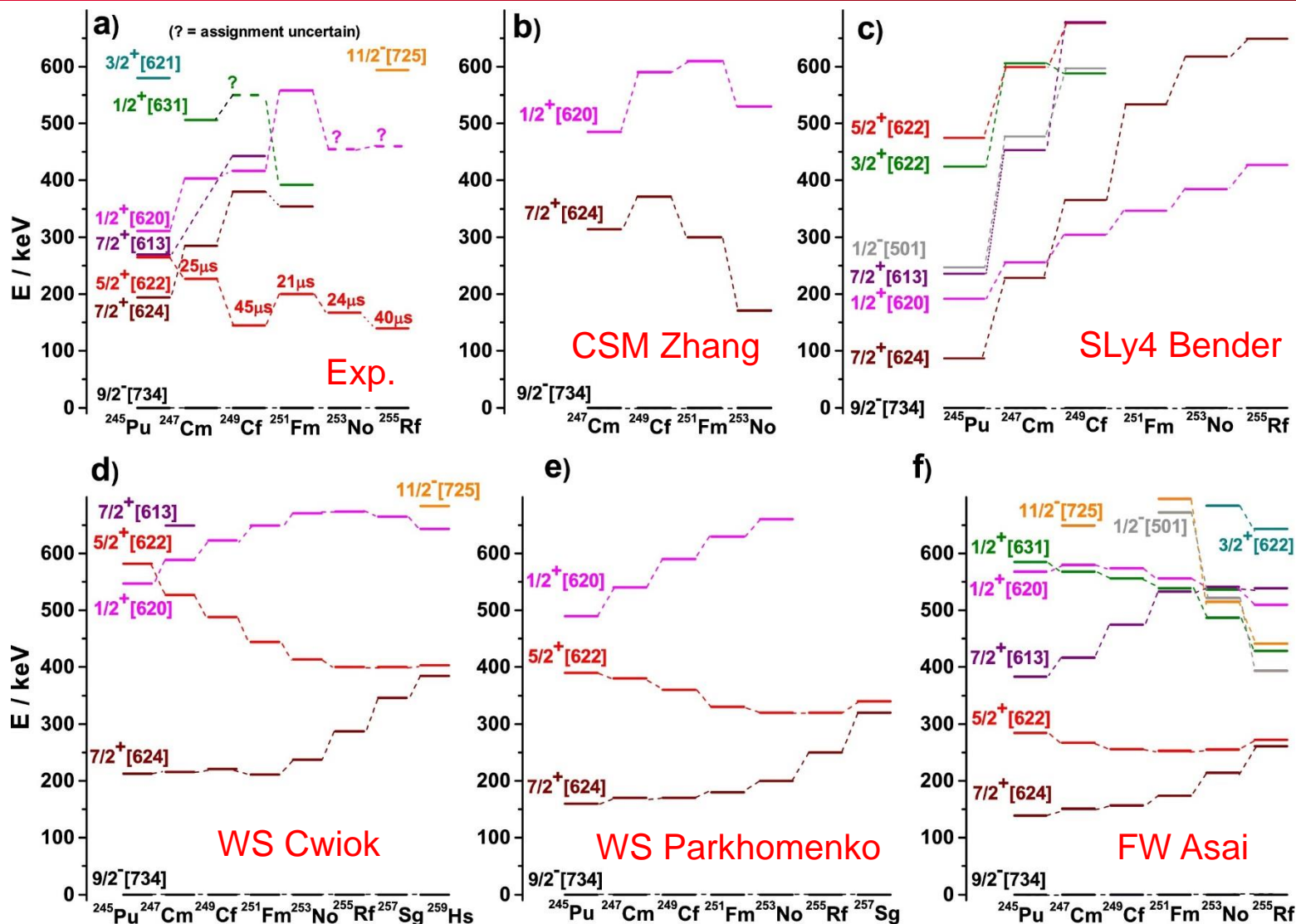
HARMONIC OSCILLATOR → NILSSON MODEL



Dobaczewski et al. [NPA 944 \(2015\) 388](#)

R.R. Chasman et al.,
[Rev. Mod. Phys. 49, 833 \(1977\)](#)

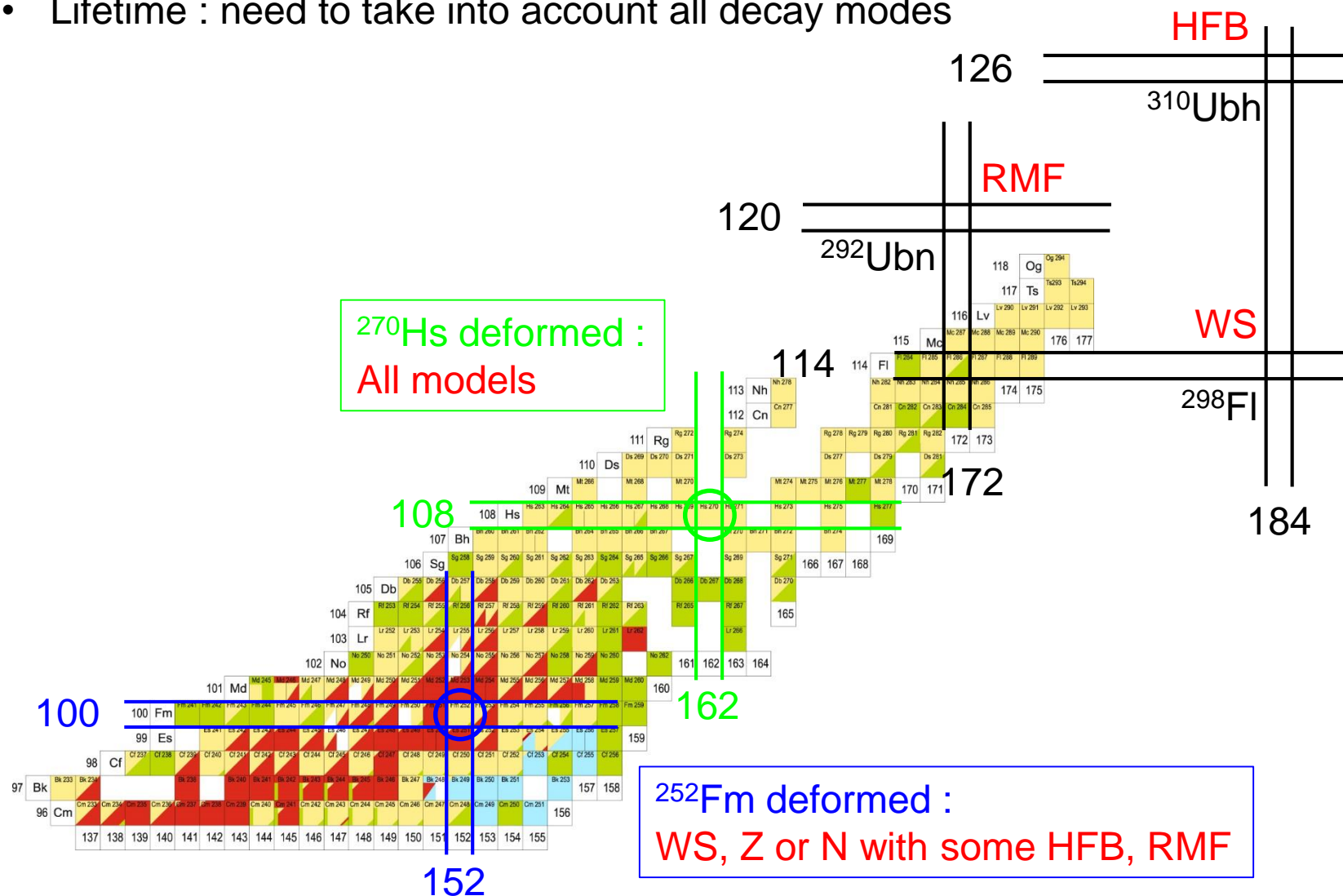
SPECTROSCOPIC DATA VS THEORY. N=151



WHERE IS THE ISLAND OF STABILITY ?



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

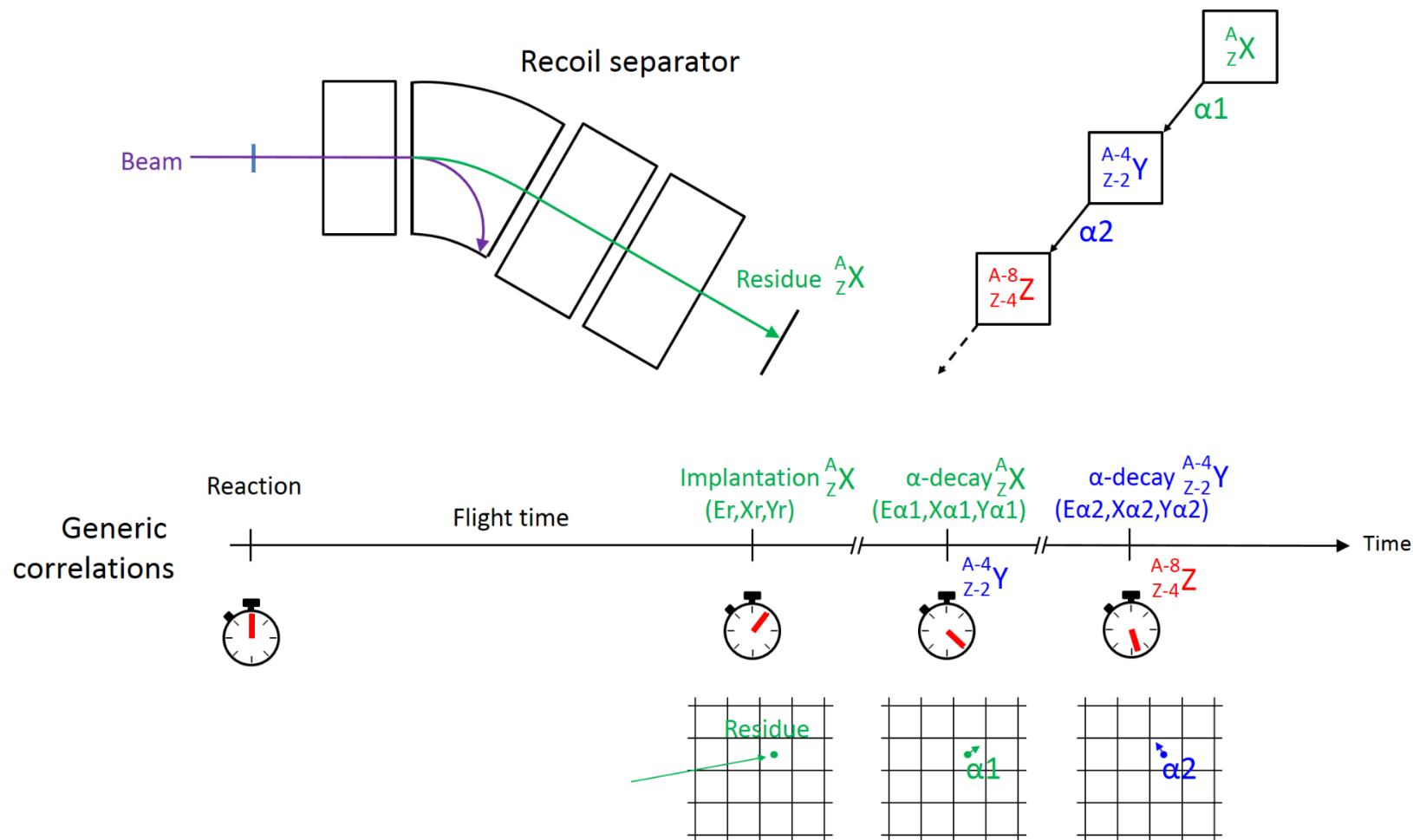


HOW TO IDENTIFY AN SHN ?



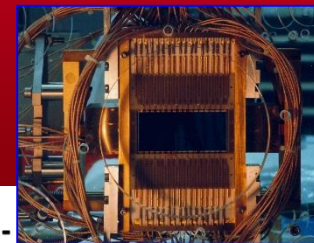
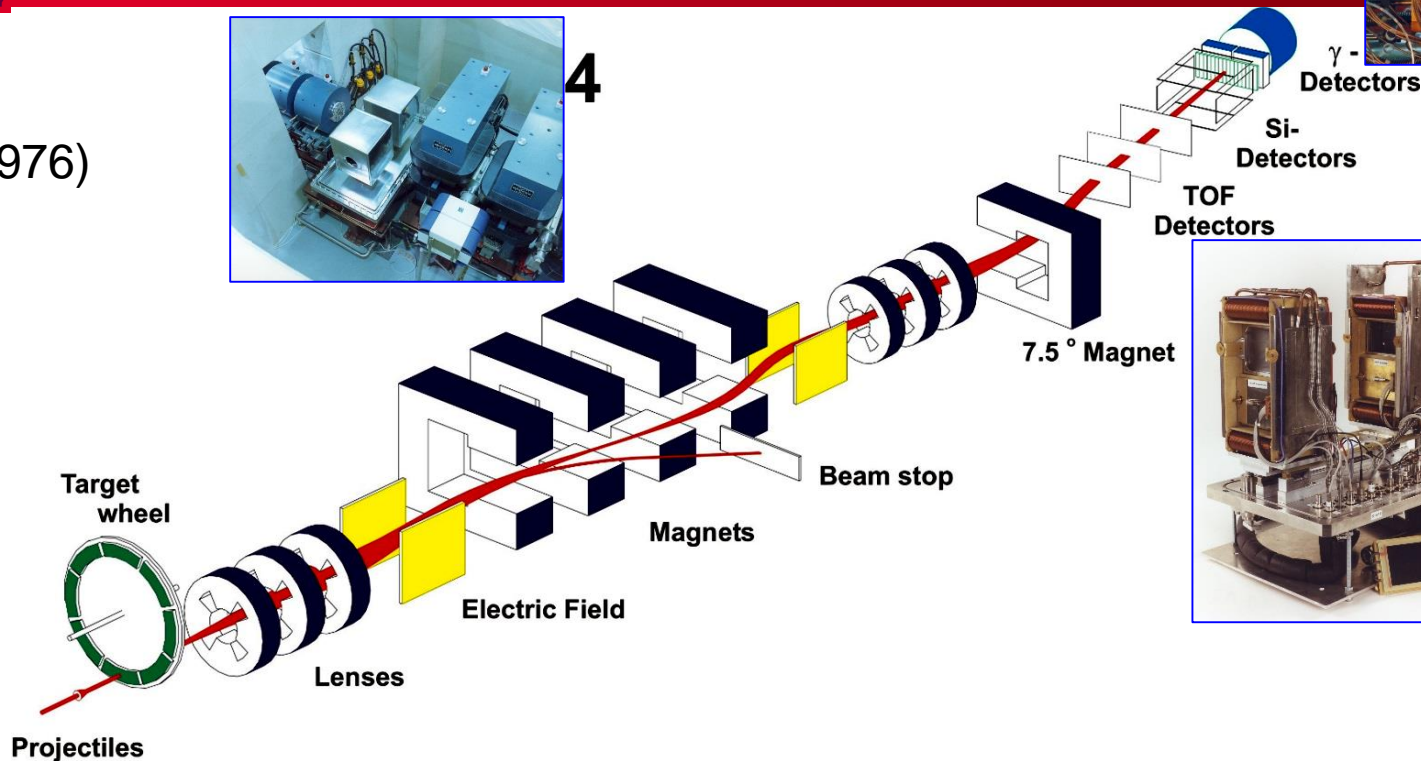
Requirement: recoil at the detection station with as little as possible contaminants (direct or scattered beam, scattered target, unwanted reaction channels)

→ use of a recoil separator



SEPARATOR : SHIP

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

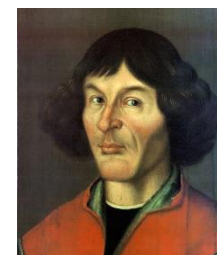
S. Hofmann

G. Münzenberg

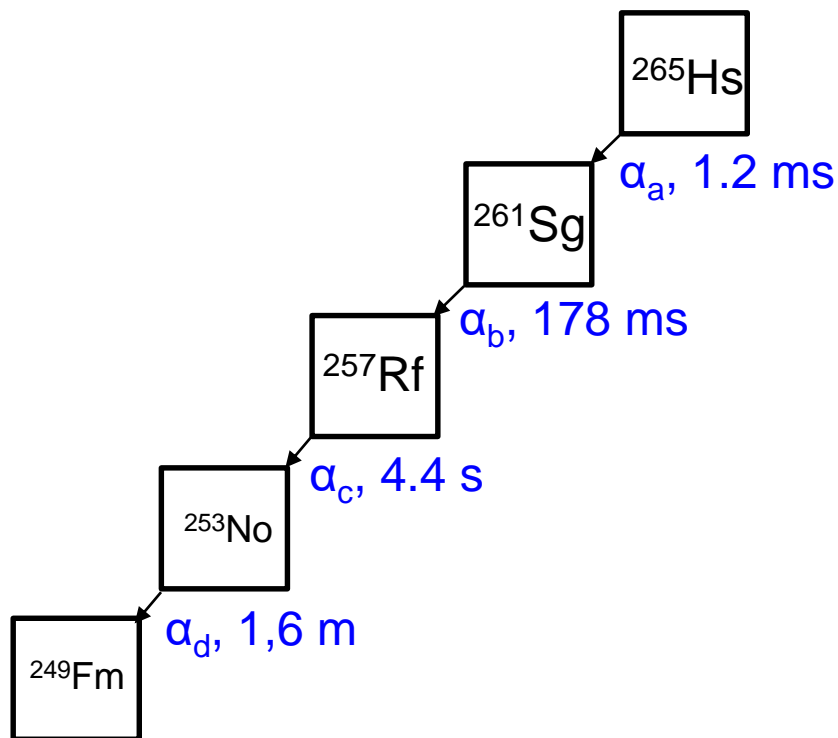


70th : G.S.I.; S.H.I.P. (P. Ambruster); 1975 : first UNiversal Linear ACcelerator beam

- 1981 $_{107}\text{Bh}$ (G. Münzenberg *et al.* [ZPA 300 \(1981\) 107](#))
 $_{209}\text{Bi}(^{54}\text{Cr}, 1n)^{262}\text{Bh} \rightarrow ^{258}\text{Db} \rightarrow \dots \rightarrow ^{250}\text{Fm}$
- 1982 $_{109}\text{Mt}$ (G. Münzenberg *et al.* [ZPA 309 \(1982\) 89](#))
 $_{209}\text{Bi}(^{58}\text{Fe}, 1n)^{266}\text{Mt} \rightarrow ^{262}\text{Bh} \rightarrow ^{258}\text{Db}$
- 1984 $_{108}\text{Hs}$ (G. Münzenberg *et al.* [ZPA 317 \(1984\) 235](#))
 $_{208}\text{Pb}(^{58}\text{Fe}, 1n)^{265}\text{Hs} \rightarrow ^{261}\text{Sg} \rightarrow ^{257}\text{Rf}$
- 1994 $_{110}\text{Ds}$, $_{111}\text{Rg}$ (S. Hofmann *et al.*)
 $_{208}\text{Pb}(^{62}\text{Ni}, n)^{269}\text{Ds} \rightarrow ^{265}\text{Hs} \rightarrow \dots$ [ZPA 350 \(1995\) 277](#)
 $_{209}\text{Bi}(^{64}\text{Ni}, n)^{272}\text{Rg} \rightarrow ^{268}\text{Mt} \rightarrow \dots$ [ZPA 350 \(1995\) 281](#)
- 1996 $_{112}\text{Cn}$ (S. Hofmann *et al.* [ZPA 354 \(1996\) 229](#))
 $_{208}\text{Pb}(^{70}\text{Zn}, 1n)^{277}\text{Cn} \rightarrow ^{273}\text{Ds} \rightarrow \dots$

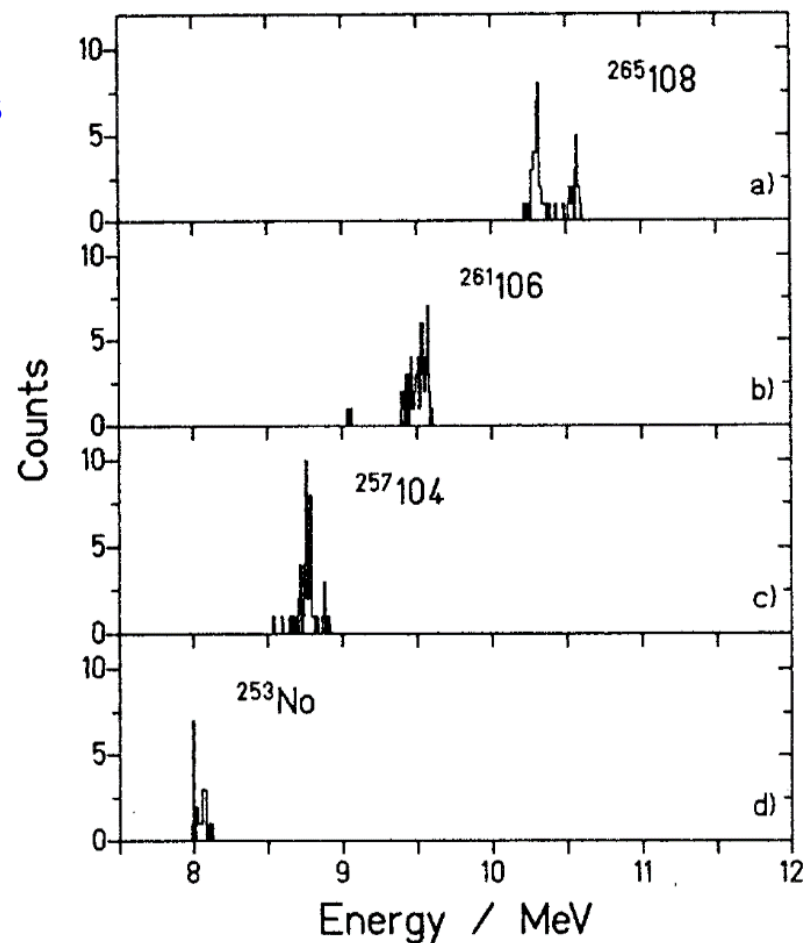


EXAMPLE OF GENETIC CORRELATIONS

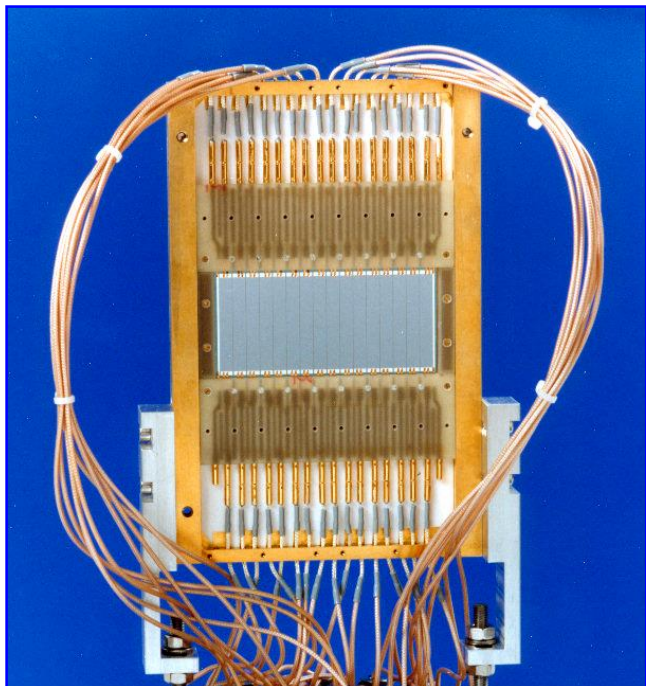


Position sensitivity of the implantation detector needed : total counting rate much larger than Implantation decay rate

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

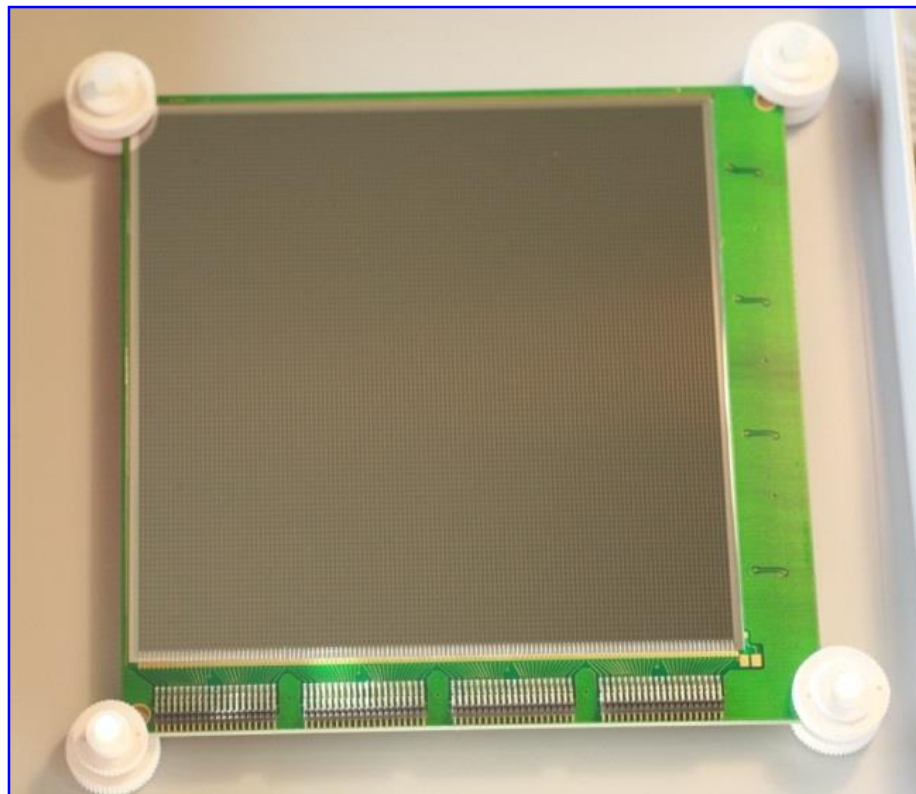


Hofmann et al., [ZPA 350 \(1995\) 277](#)



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

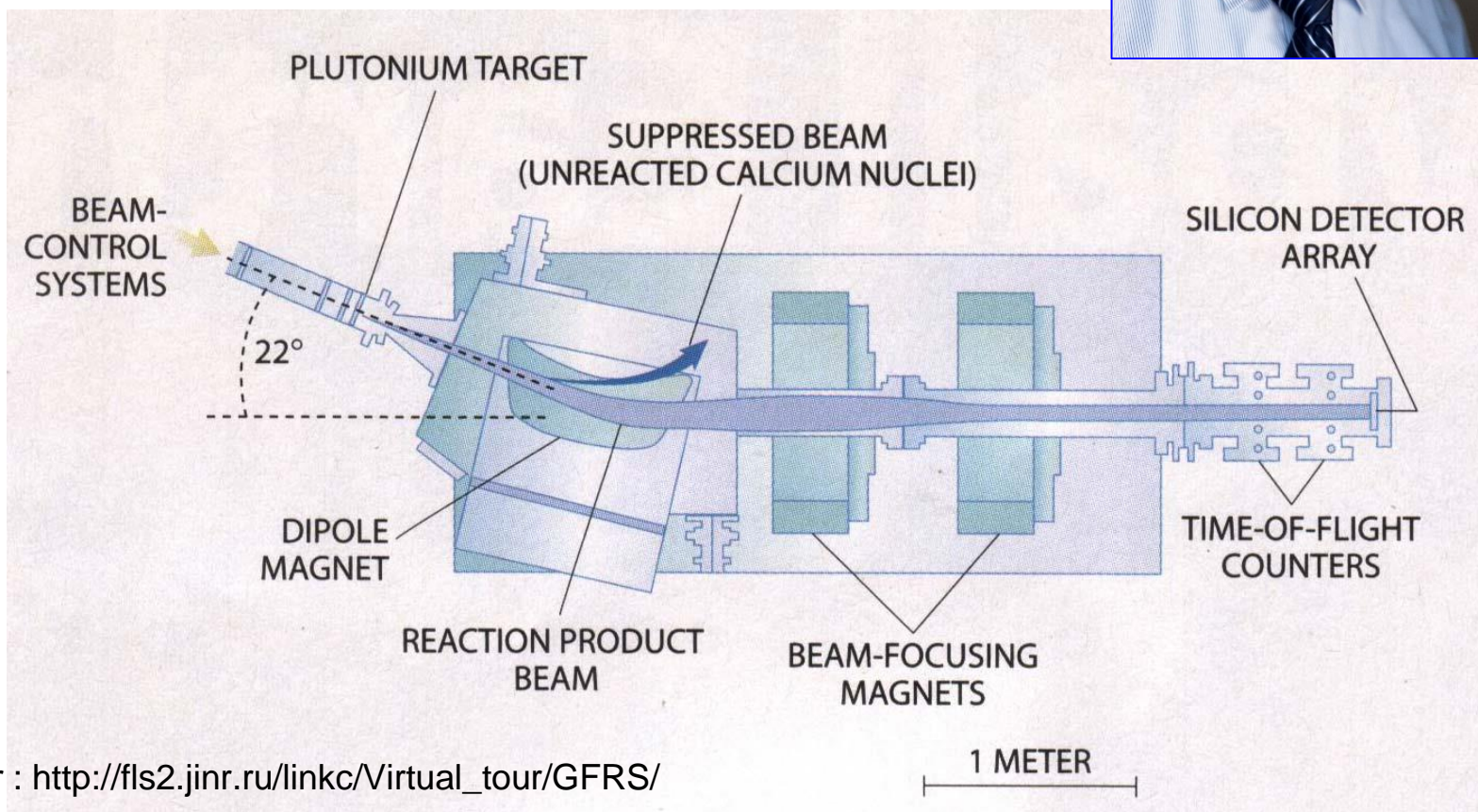
DSSD = Double-sided Silicon Strip Detector
used in most modern focal plane detectors



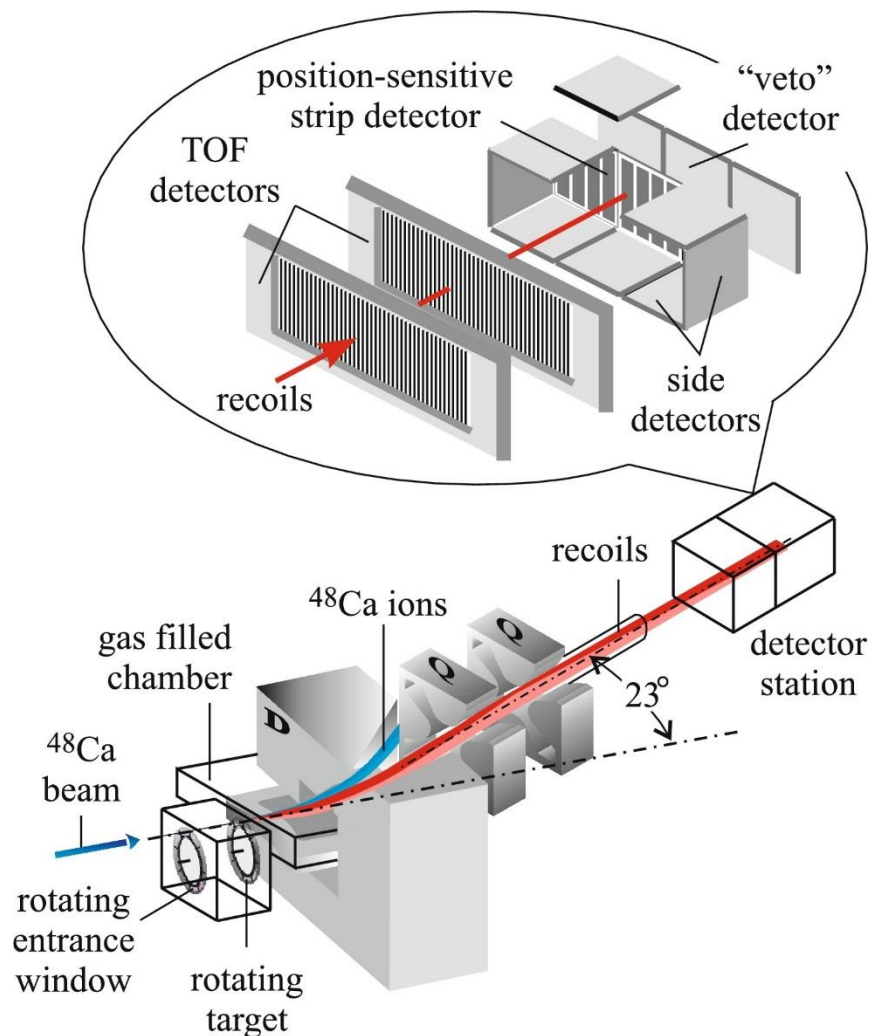
Si detector for VAMOS & S3 (GANIL),
SHELS (Dubna)
10x10 cm², 128(X)+128(Y) strips
2019 03 02 PHENIICS

DGFRS Dubna gas-filled recoil separator (1989)
Discovery of elements 114-118 by Oganessian et al.

Typical transmission for Ca+Pb : ~ 45 %



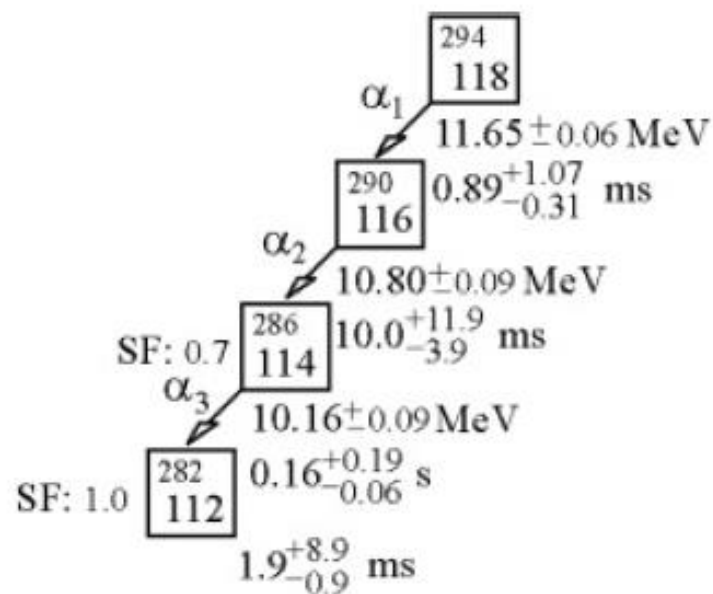
Virtual tour : http://fls2.jinr.ru/linkc/Virtual_tour/GFRS/



4 decay chains observed

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

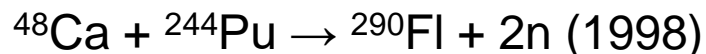
$\sigma \sim 0,5 \text{ pb}$



Y. Oganessian et al.

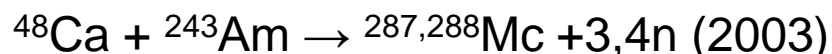
[PRC 74 \(2006\) 044602](#)

Z=114, Flerovium



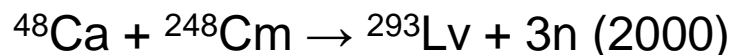
Oganessian et al., [PRL 83 \(1999\) 3154](#)

Z=115, Moscovium



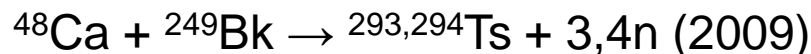
Oganessian et al., [PRC 69 \(2004\) 021601](#)

Z=116, Livermorium



Oganessian et al., [PRC 63 \(2000\) 011301](#)

Z=117, Tennessine

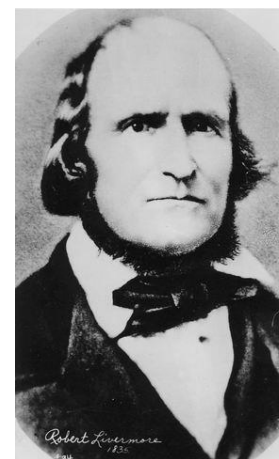


Oganessian et al., [PRL 104 \(2010\) 142502](#)

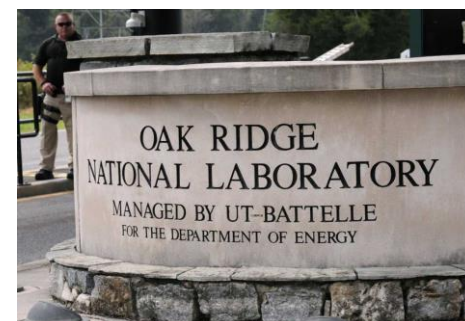
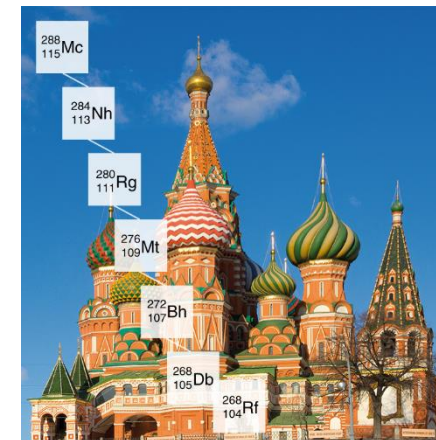
Z=118, Oganesson



Oganessian et al [PRC 74 \(2006\) 044602](#)

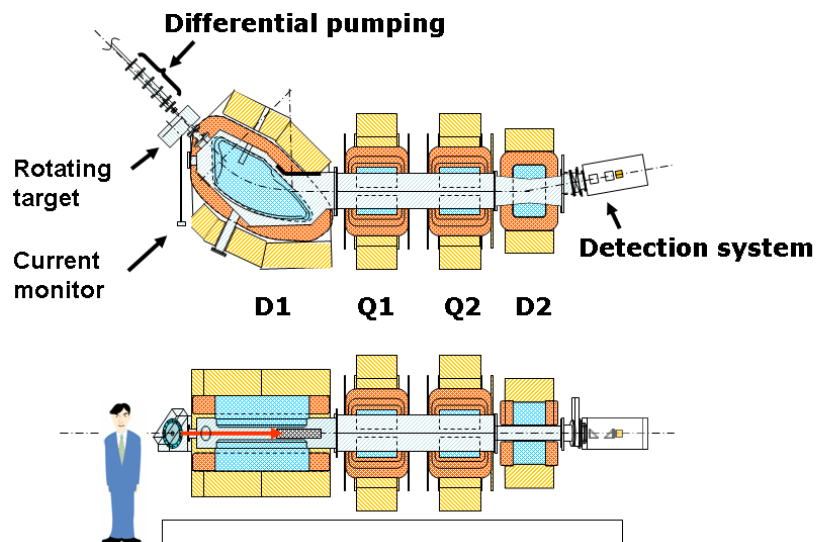


Courtesy of the Livermore Heritage Guild

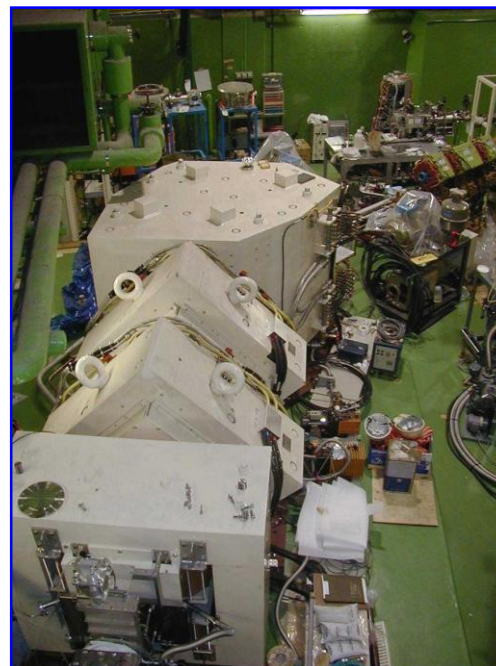
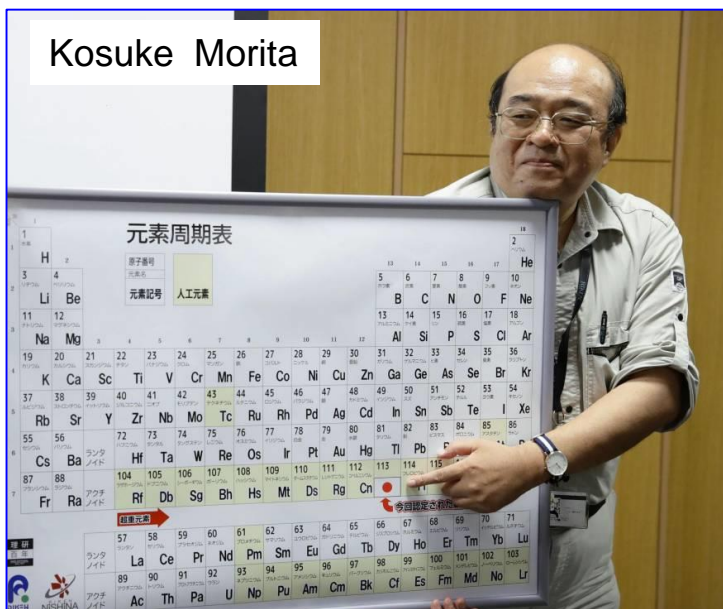


Z = 113 USING GARIS, RIKEN

Overview of the gas-filled recoil ion separator GARIS



Kosuke Morita



Discovery of Nh, Z=113

 $^{209}\text{Bi}(^{70}\text{Zn}, n)^{278}\text{Nh} \sigma \sim 22 \text{ fbarn (2004)}$

3 events, 553 days of beam time

K. Morita et al. [J. Phys. Soc. Jpn. 81 \(2012\) 103201](https://doi.org/10.1143/JPSJ.81.103201)

Reminder probability of alpha decay.

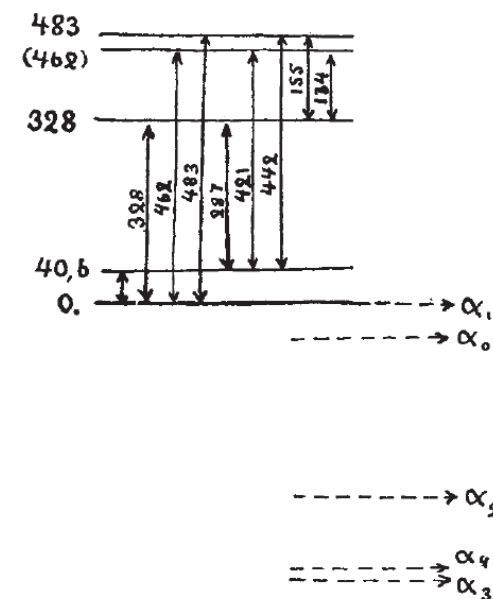
Macroscopic part :

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

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 in the daughter nucleus

→ Alpha decay is a tool for spectroscopy

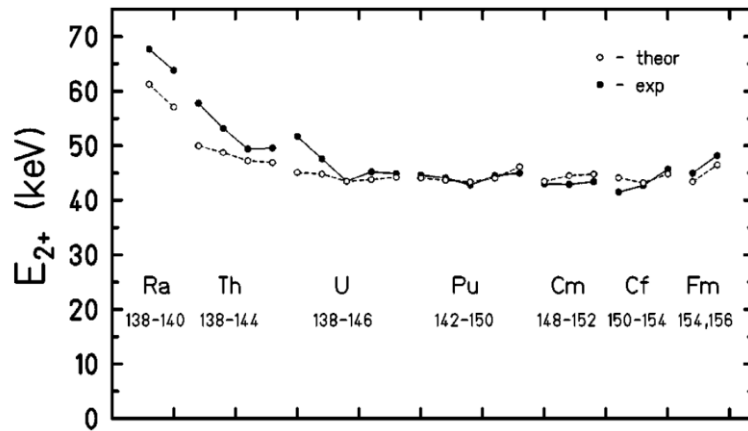


Gamow, [Nature 126 \(1930\) 397](#)

TRIVIAL CASE : A-DECAY IN EVEN-EVEN NUCLEI



- $0^+ \rightarrow 0^+$ transition favoured
- then $0^+ \rightarrow 2^+$ 20-30 %



E_{2^+} energy

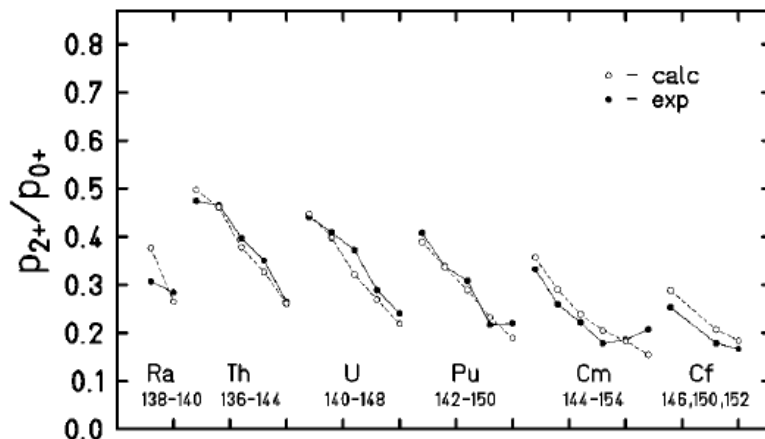
→ moment of inertia \mathfrak{J}

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

→ deformation of the nucleus

However, no access to high angular momenta states

→ High-spin states using in-beam spectroscopy



Sobiczewski, Muntian and Patyk [PRC 63 \(2001\) 034306](#)

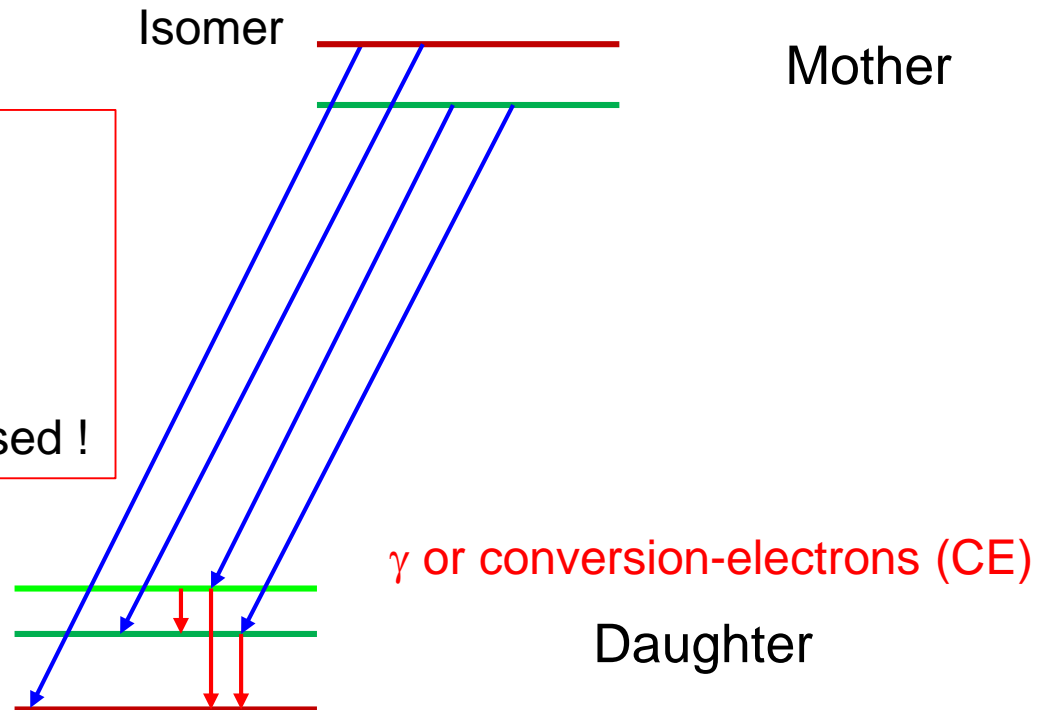
MORE COMPLEX CASE (ODD NUCLEI)



Odd nuclei :

In most cases the g.s.
 α -decay does not feed
the daughter g.s.

Daughter g.s. can be missed !



Goal: deduce (at least)

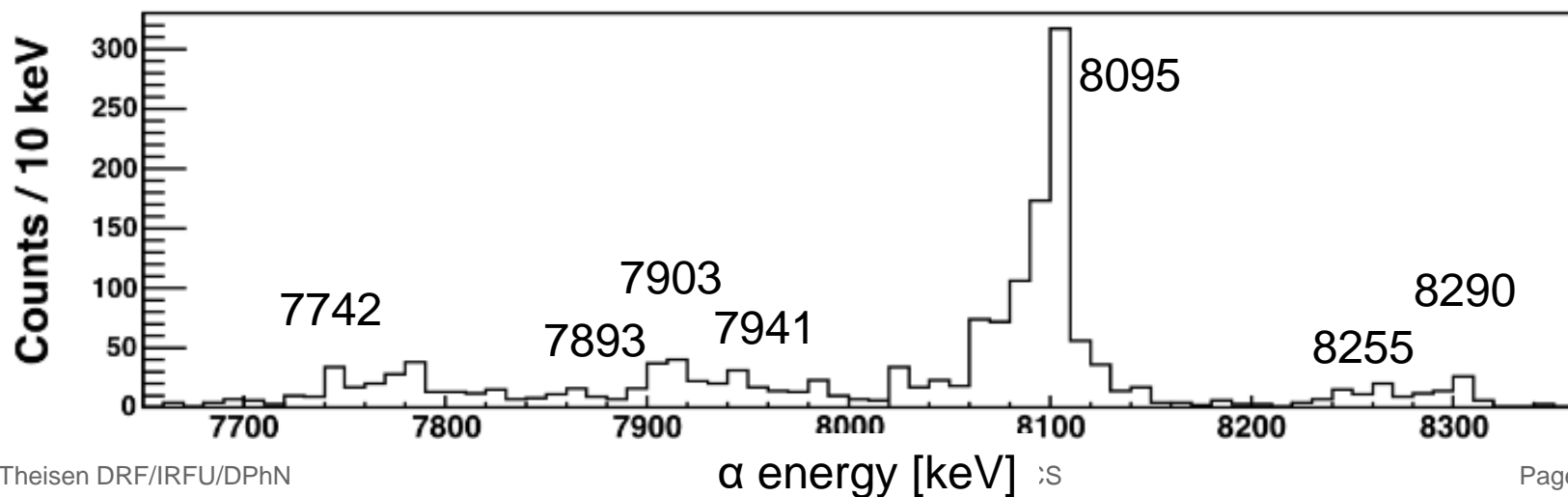
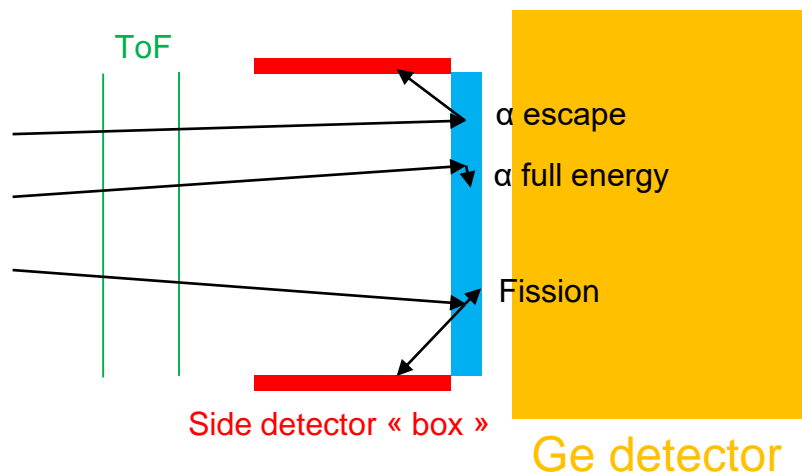
- Q_α
- level energies
- Spin and parity of levels (including g.s.)
 - α, γ, e^- coincidences
 - Energies and multipolarities of the gamma and CE
 - Alpha decay hindrance factor

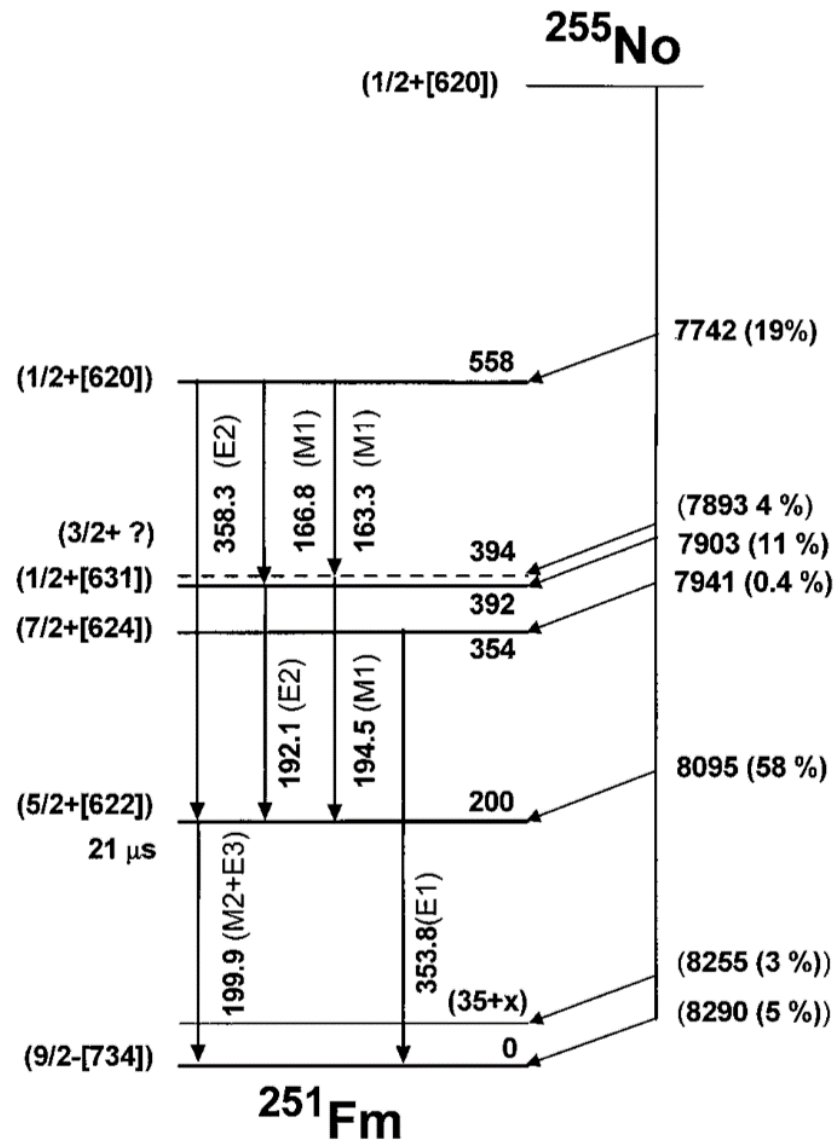
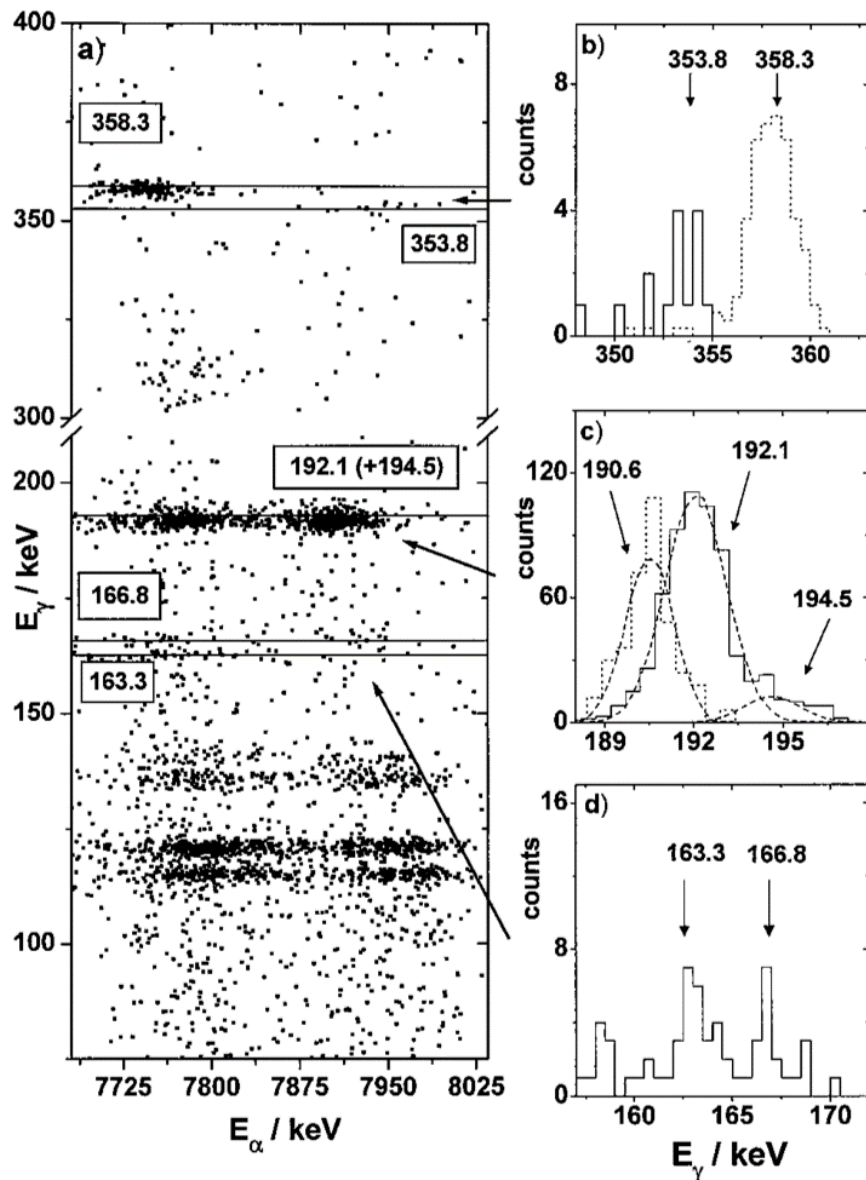
^{255}No AS AN EXAMPLE

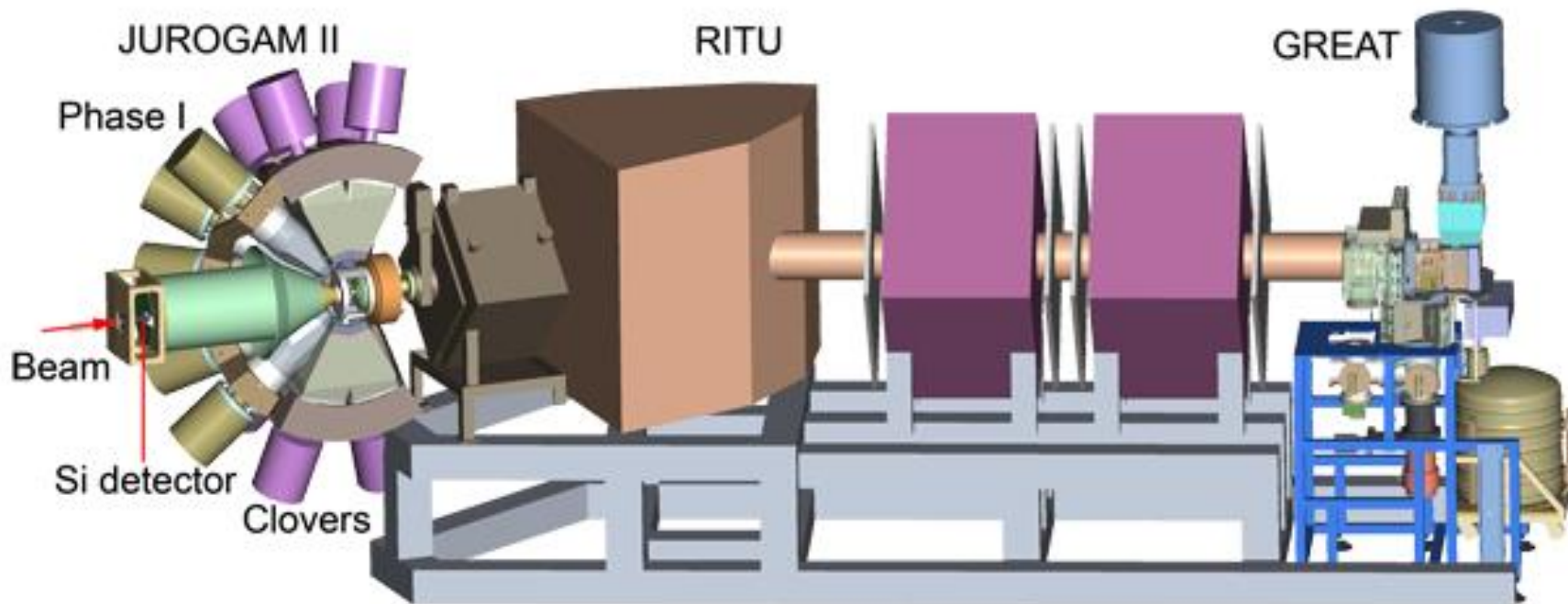


SHIP, GSI. Hessberger et al, [EPJA 29 \(2006\) 165](#)

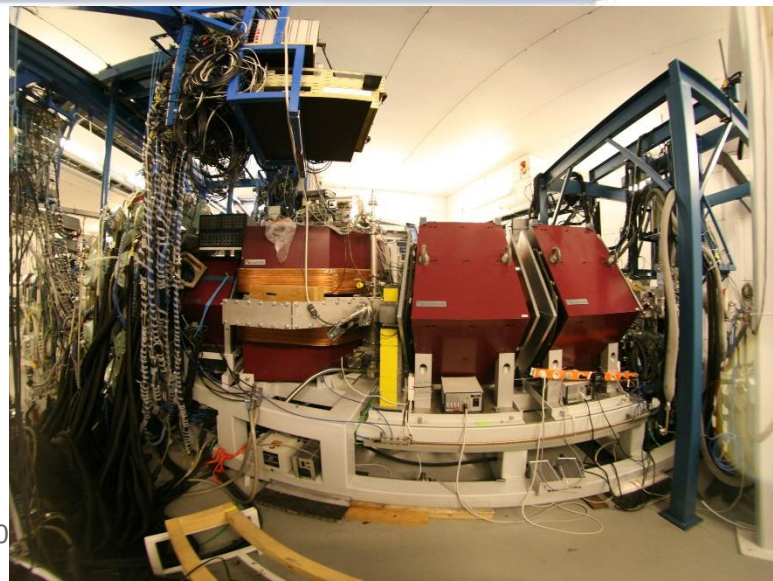
Setup = Silicon strip detector 80x35 mm², 300μm thick + Ge “clover” detector



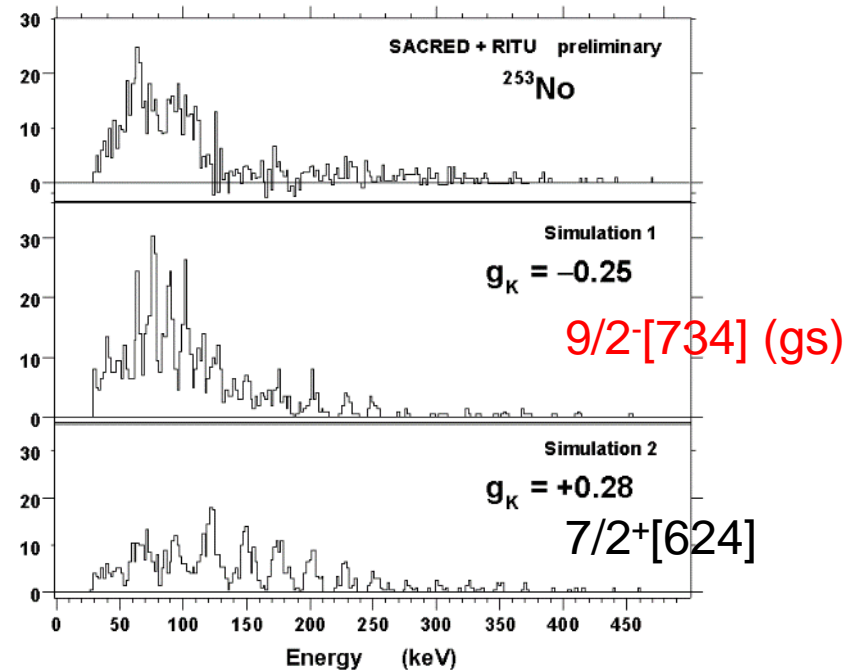
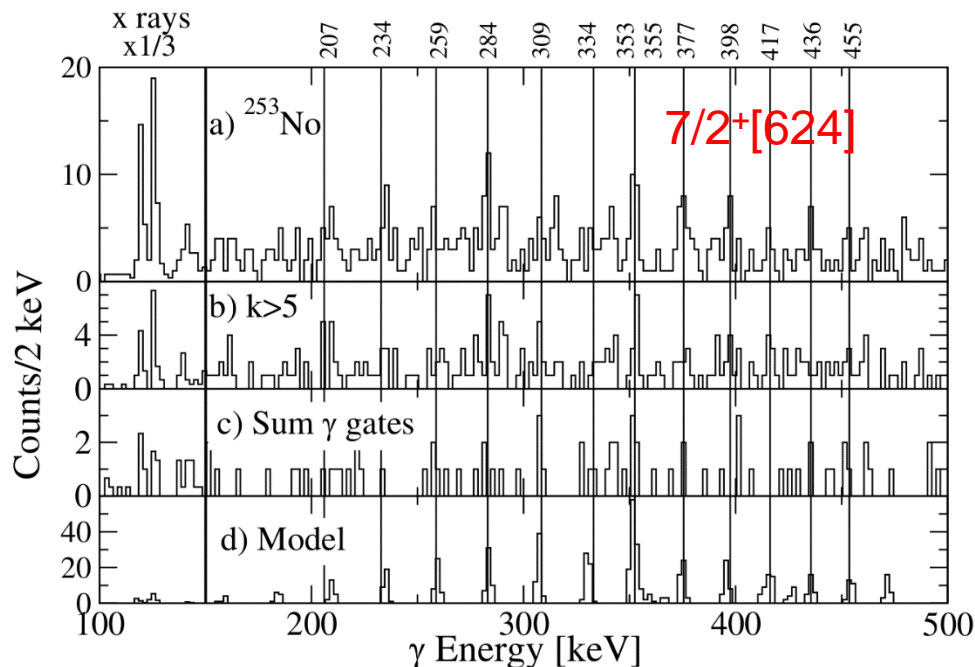




Setup at Jyväskylä, Finland

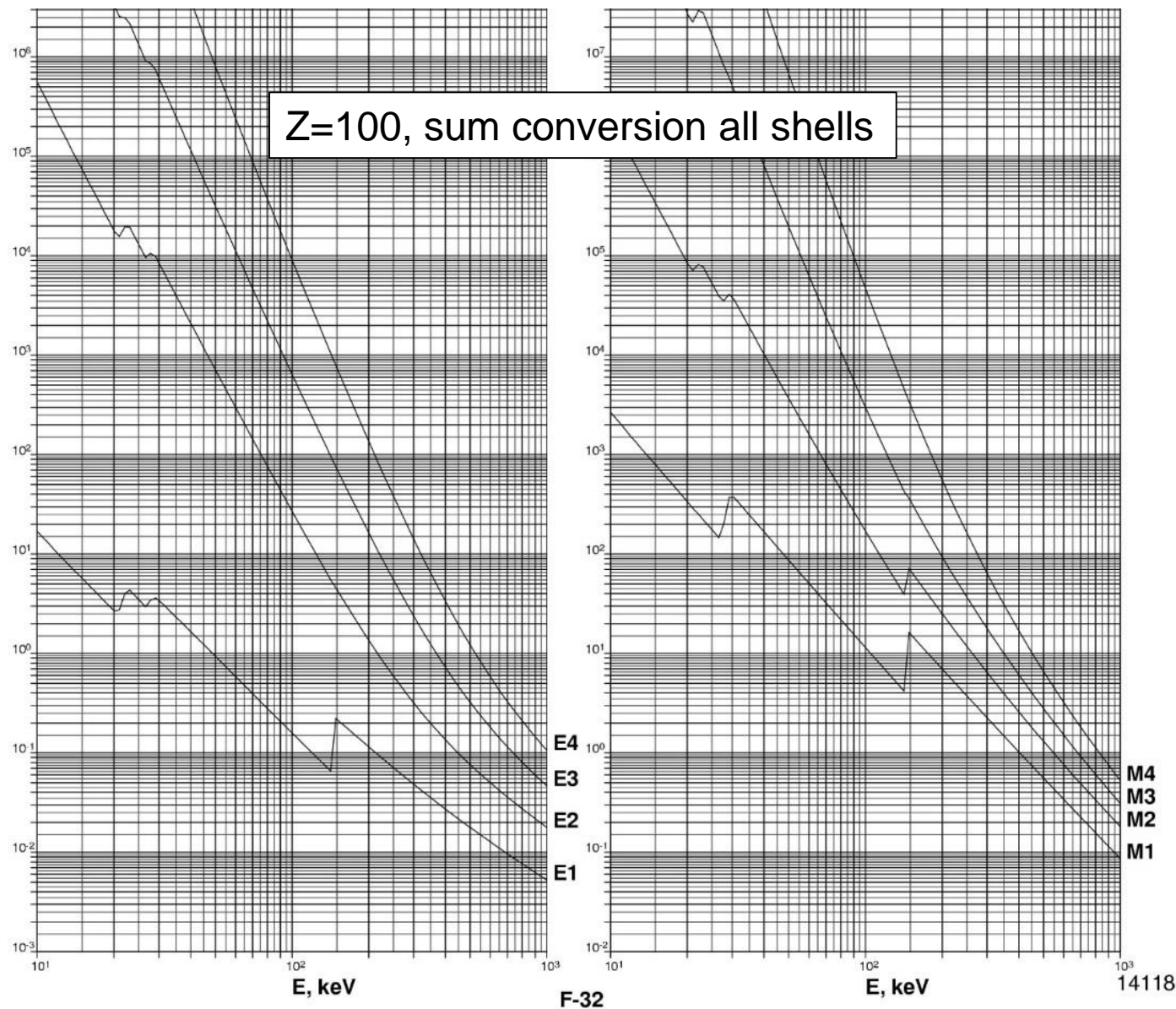


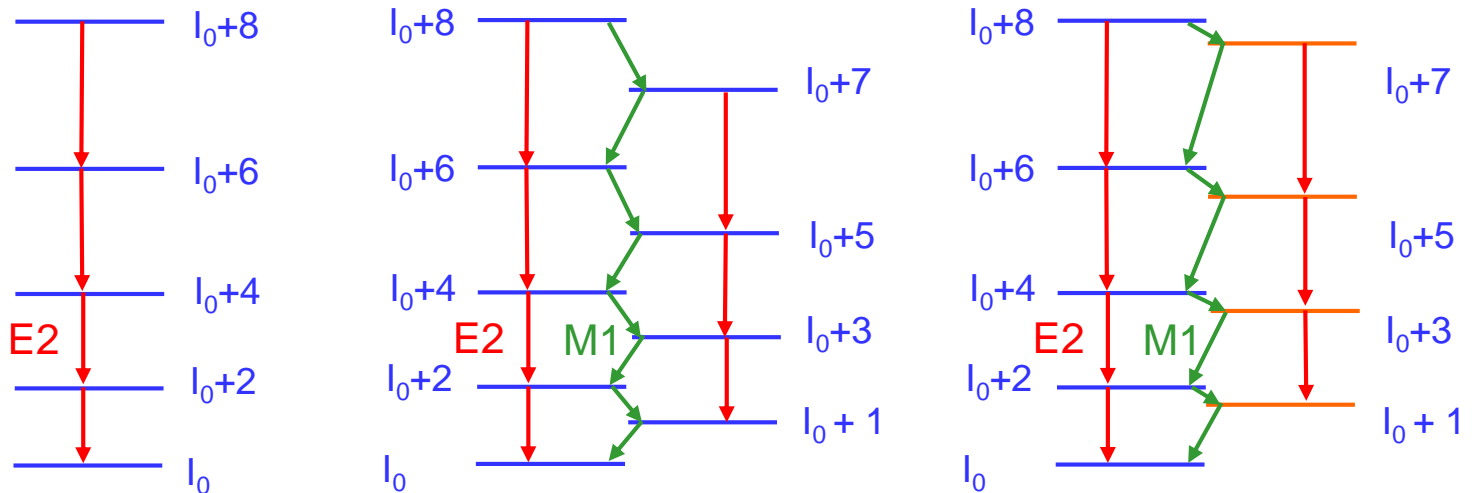
- Electron spectroscopy
JYFL
R.-D. Herzberg, et al.,
[Eur. Phys. J. A 15 \(2002\) 205.](#)



- Gamma spectroscopy ANL
P. Reiter et al. [PRL 95 \(2005\) 032501](#)

INTERNAL ELECTRON CONVERSION





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

$$- K^2$$

$$+ a\delta_{K,1/2}(-1)^{(I+1/2)}(I+1/2) \}$$

M1/E2 ratio

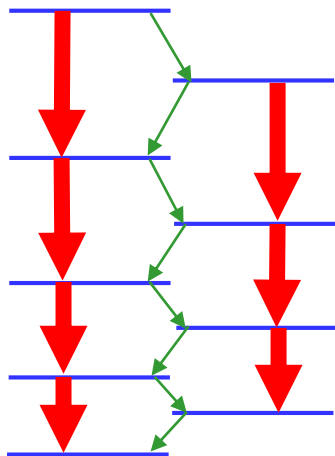
→ magnetic moment

→ configuration

$$B(M1)/B(E2) \propto K^2(g_K - g_R)^2/Q_0^2$$

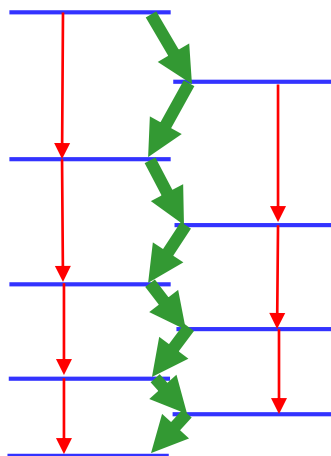
$$g_K \sim 1/K(g_s \Sigma + g_l \Lambda)$$

EXAMPLE : ^{253}No



$[624]7/2^+$

$g_K = 0.28$

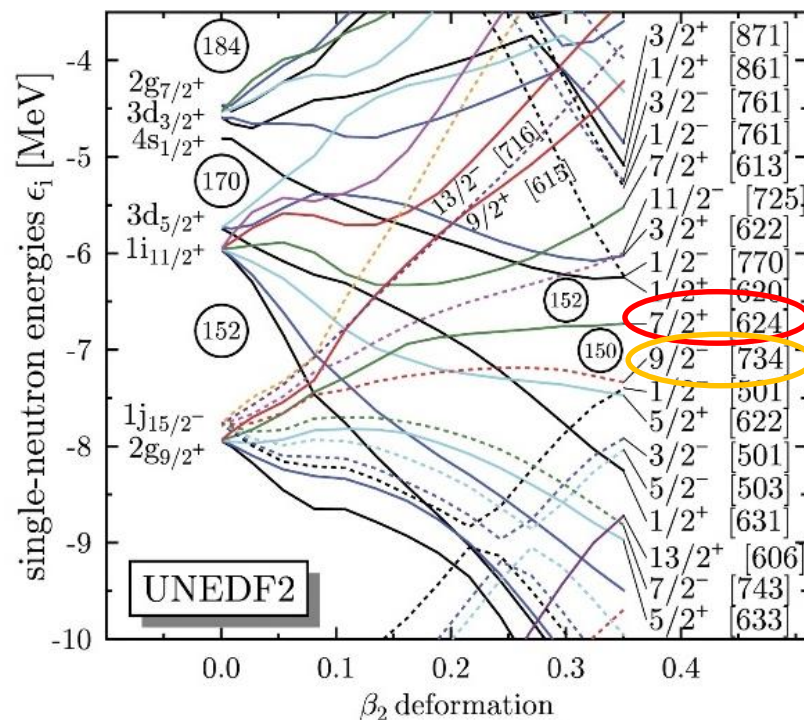


$[734]9/2^-$

$g_K = -0.25$

$$B(M1)/B(E2) \propto K^2(g_K - g_R)^2/Q_0^2$$

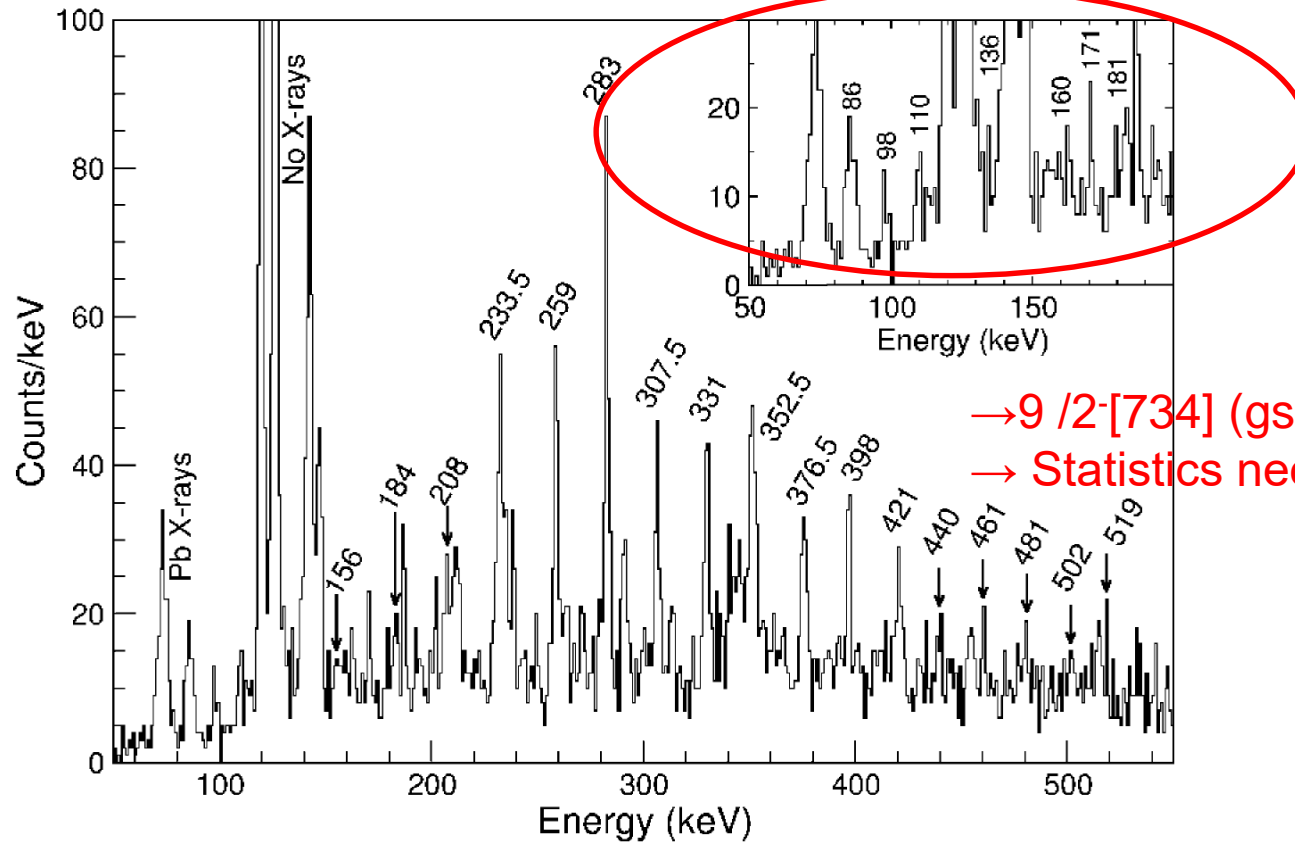
$$g_K \sim 1/K(g_s \Sigma + g_l \Lambda)$$



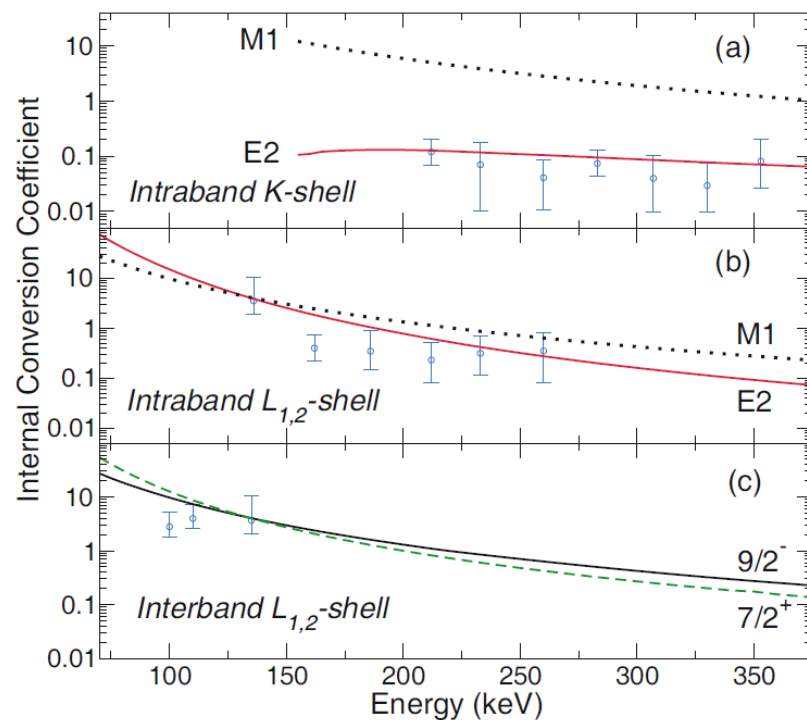
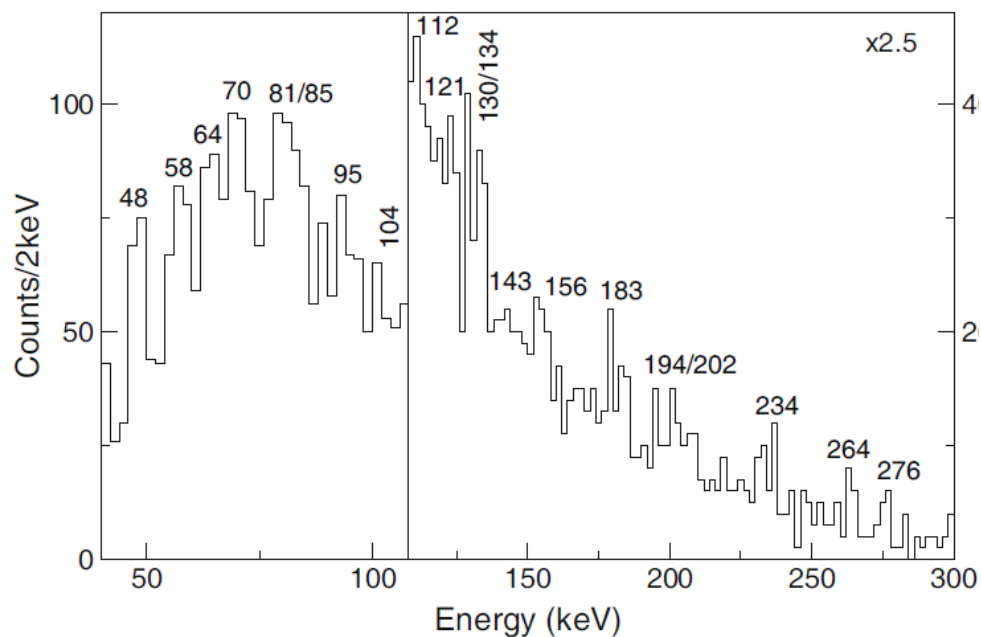
- Gamma spectroscopy JYFL

Herzberg et al. [EPJA 42 \(2009\) 333](#)

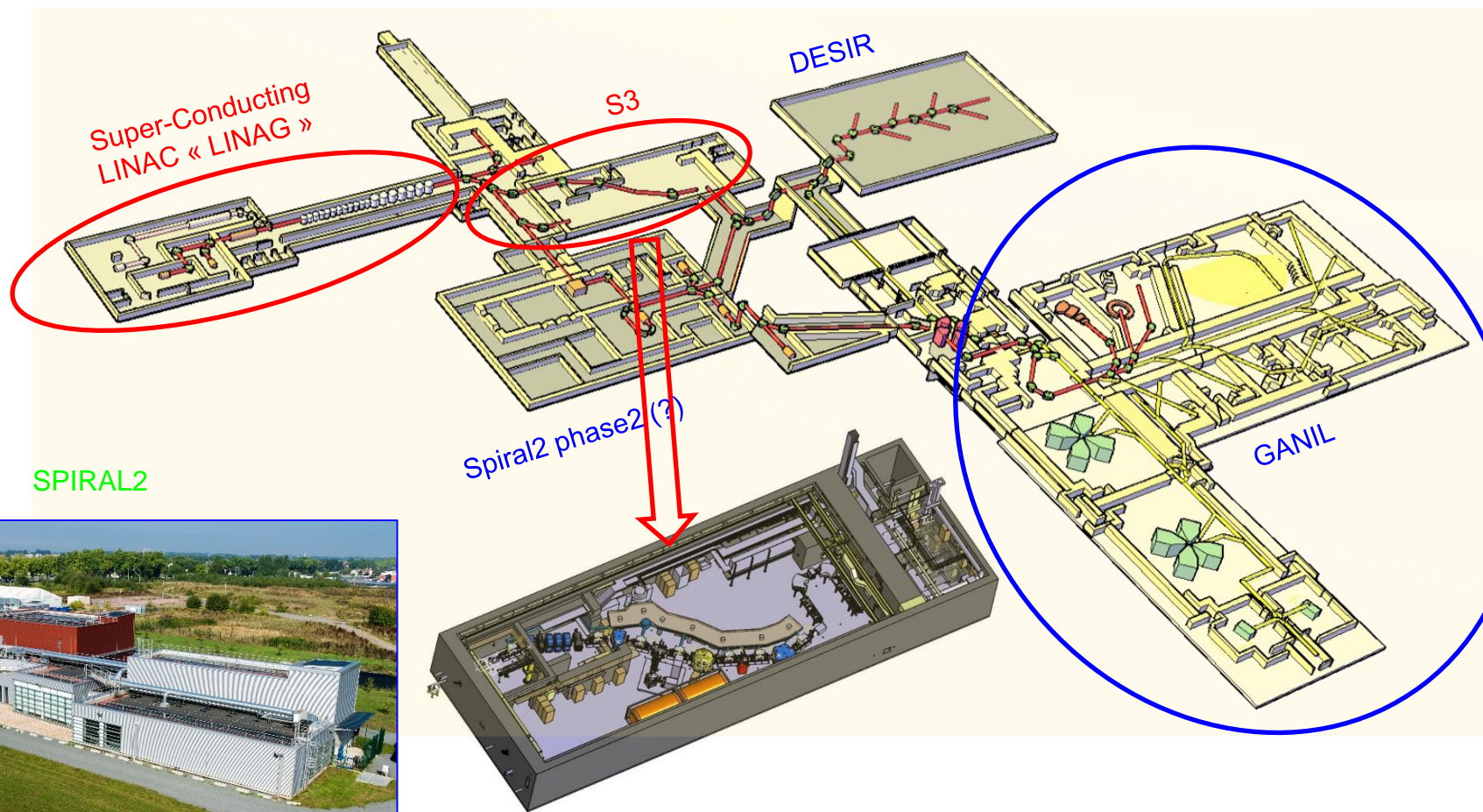
M1 transitions



Mistry et al. EPJA 53 (2017) 24

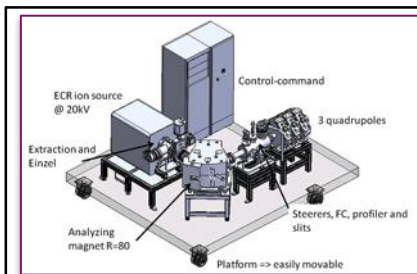


→ $9/2^- [734]$ (gs)

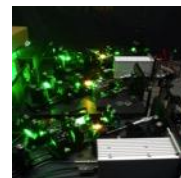




Primary beam dump



Atomic Physics
FISIC =
Fast Ion Slow
Ion Collisions
Electron exchange



Ground state properties
Low energy branch
REGLIS

Achromatic Point

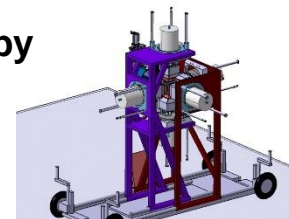
Spectrometer

Separator

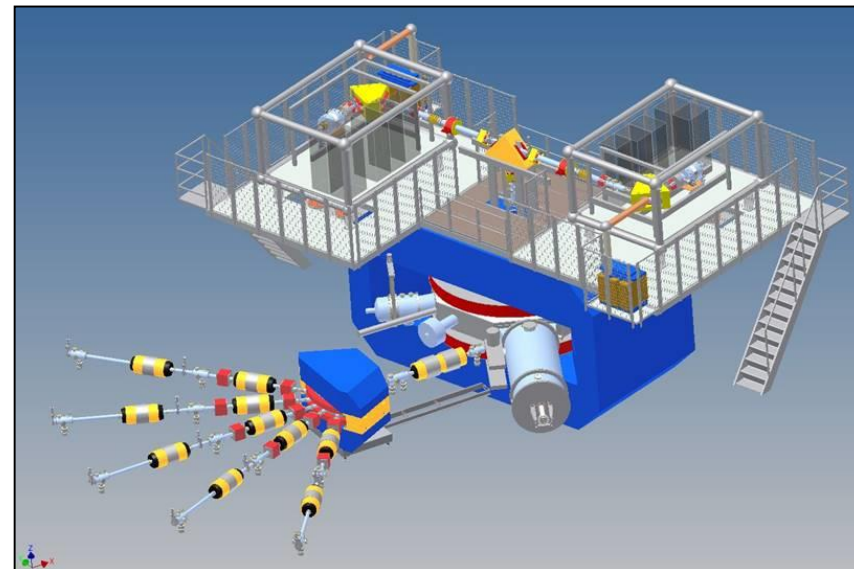
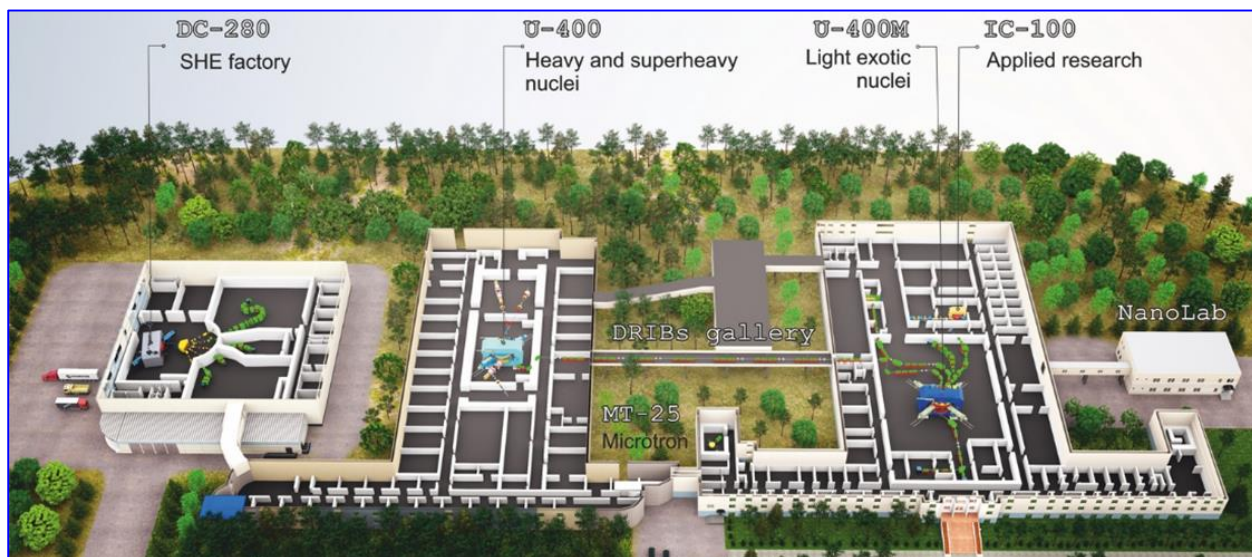
To DESIR

Target cave

Decay Spectroscopy
SIRIUS Station
 α , γ , electron,
fission



SHE FACTORY, DUBNA



Further reading

- 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 61 \(2008\) 674](#)
- 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 [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)

END