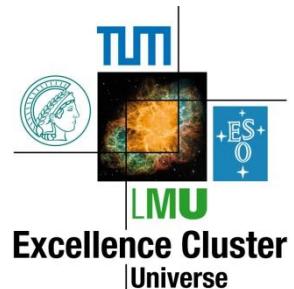




# The Race for the Superheavy Elements

Thessaloniki, November 24, 2010

Peter Ring



Technical University Munich

Excellence Cluster  
“Origin of the Universe”



- Introduction
  - General properties of Atoms
- Problem of stability of nuclei
  - The valley of stability
  - Neutrons and protons at the drip lines
  - Surface tension and Coulomb repulsion
- Synthesis of heavy and superheavy elements
  - Radioactivity
  - Neutron capture and  $\beta$ -decay
  - Fusion with light and heavy ions
- Experiments
  - Historical development
  - Synthesis of elements  $108 < Z < 112$  in Darmstadt
  - Synthese of elemente  $Z > 113$  in Dubna

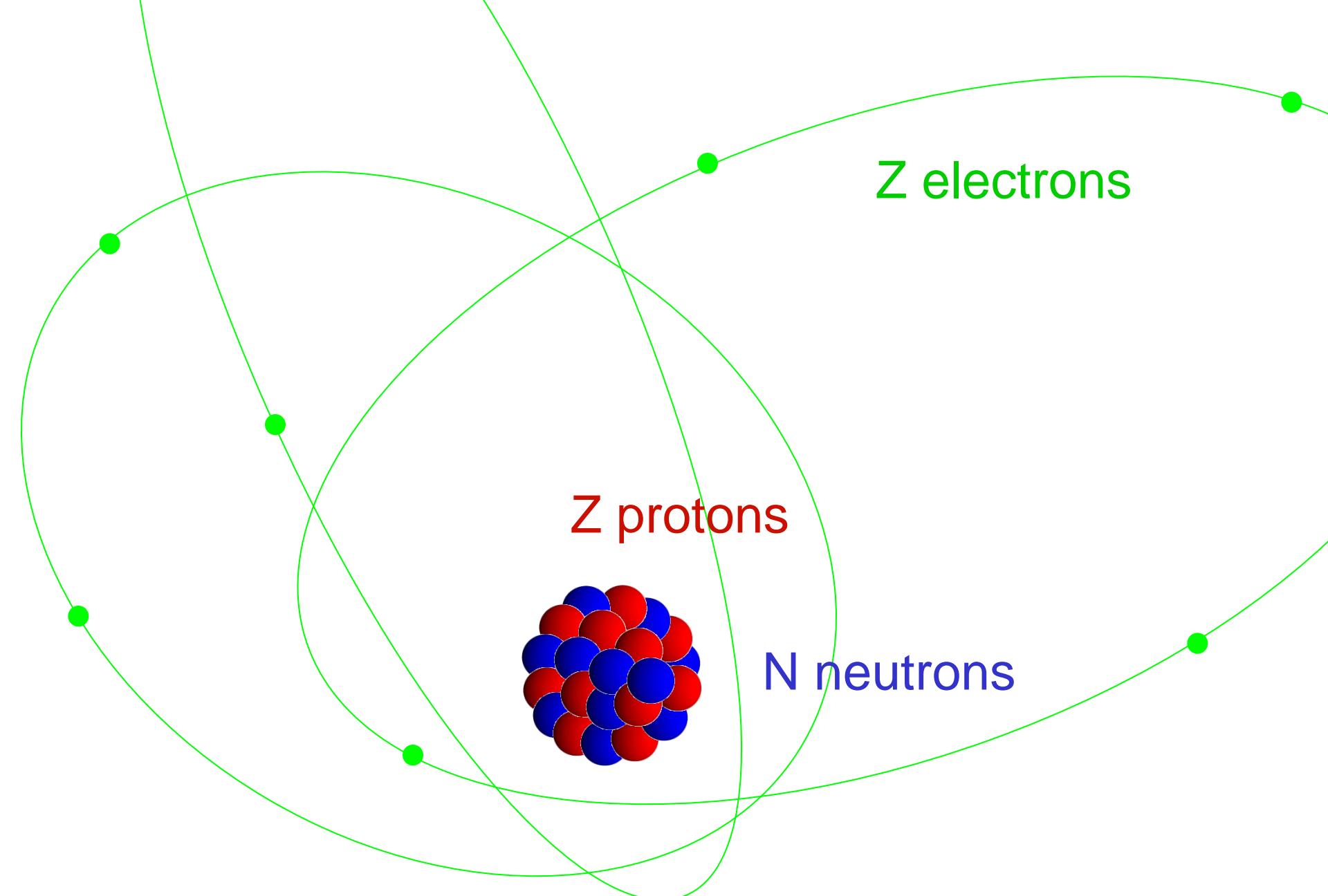
# Periodic system of elements

|             |          |              |           |           |           |           |          |          |          |          |          |           |           |           |           |           |          |           |
|-------------|----------|--------------|-----------|-----------|-----------|-----------|----------|----------|----------|----------|----------|-----------|-----------|-----------|-----------|-----------|----------|-----------|
| 1           |          |              |           |           |           |           |          |          |          |          |          |           |           |           |           |           |          | 18        |
| 1<br>H      | 2<br>Be  |              |           |           |           |           |          |          |          |          |          |           |           |           |           |           |          | 2<br>He   |
| 3<br>Li     | 4<br>Be  |              |           |           |           |           |          |          |          |          |          |           |           |           |           |           |          | 10<br>Ne  |
| 11<br>Na    | 12<br>Mg | 3            | 4         | 5         | 6         | 7         | 8        | 9        | 10       | 11       | 12       |           |           |           |           |           |          | 18<br>Ar  |
| 19<br>K     | 20<br>Ca | 21<br>Sc     | 22<br>Ti  | 23<br>V   | 24<br>Cr  | 25<br>Mn  | 26<br>Fe | 27<br>Co | 28<br>Ni | 29<br>Cu | 30<br>Zn | 31<br>Ga  | 32<br>Ge  | 33<br>As  | 34<br>Se  | 35<br>Br  | 36<br>Kr |           |
| 37<br>Rb    | 38<br>Sr | 39<br>Y      | 40<br>Zr  | 41<br>Nb  | 42<br>Mo  | 43<br>Tc  | 44<br>Ru | 45<br>Rh | 46<br>Pd | 47<br>Ag | 48<br>Cd | 49<br>In  | 50<br>Sn  | 51<br>Sb  | 52<br>Te  | 53<br>I   | 54<br>Xe |           |
| 55<br>Cs    | 56<br>Ba | 57-71<br>Hf  | 72<br>Ta  | 73<br>W   | 74<br>Re  | 75<br>Os  | 76<br>Ir | 77<br>Pt | 78<br>Au | 79<br>Hg | 80<br>Tl | 81<br>Pb  | 82<br>Bi  | 83<br>Po  | 84<br>At  | 85<br>Rn  |          |           |
| 87<br>Fr    | 88<br>Ra | 89-103<br>Rf | 104<br>Db | 105<br>Sg | 106<br>Bh | 108<br>Hs |          |          |          |          |          | 109<br>Mt | 110<br>Ds | 111<br>Rg | 112<br>-- |           |          | 118<br>-- |
|             |          |              |           |           |           |           |          |          |          |          |          |           |           |           |           |           |          |           |
| Lanthanoide |          | 57<br>La     | 58<br>Ce  | 59<br>Pr  | 60<br>Nd  | 61<br>Pm  | 62<br>Sm | 63<br>Eu | 64<br>Gd | 65<br>Tb | 66<br>Dy | 67<br>Ho  | 68<br>Er  | 69<br>Tm  | 70<br>Yb  | 71<br>Lu  |          |           |
| Actinoide   |          | 89<br>Ac     | 90<br>Th  | 91<br>Pa  | 92<br>U   | 93<br>Np  | 94<br>Pu | 95<br>Am | 96<br>Cm | 97<br>Bk | 98<br>Cf | 99<br>Es  | 100<br>Fm | 101<br>Md | 102<br>No | 103<br>Lr |          |           |

Elementes are defined through the nuclei

The chemical properties depend  
on the shell structure of the electrons

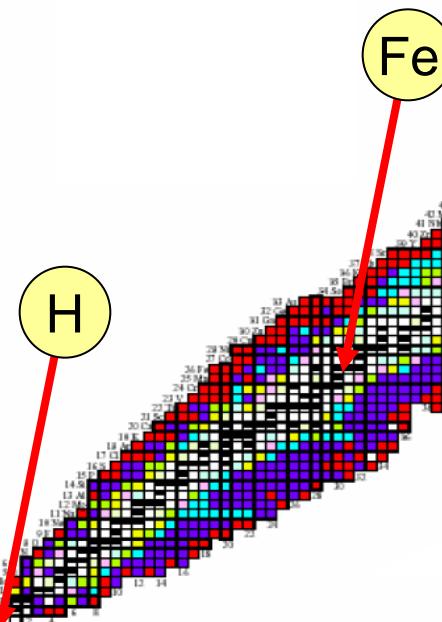
The number of electrons is determined  
by the number of protons in the nucleus



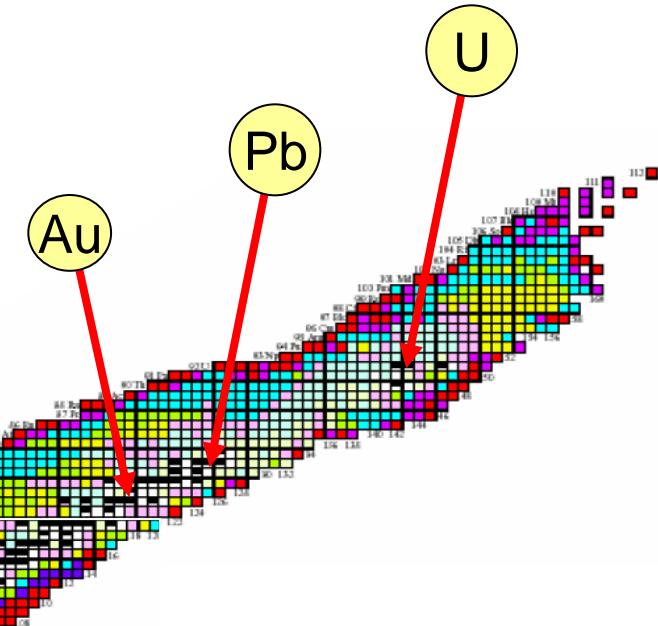
proton number Z



- Publication Year
- 1940
  - 1944
  - 1948
  - 1953
  - 1958
  - 1967
  - 1978
  - 1995
  - 2000
  - Naturally Abundant

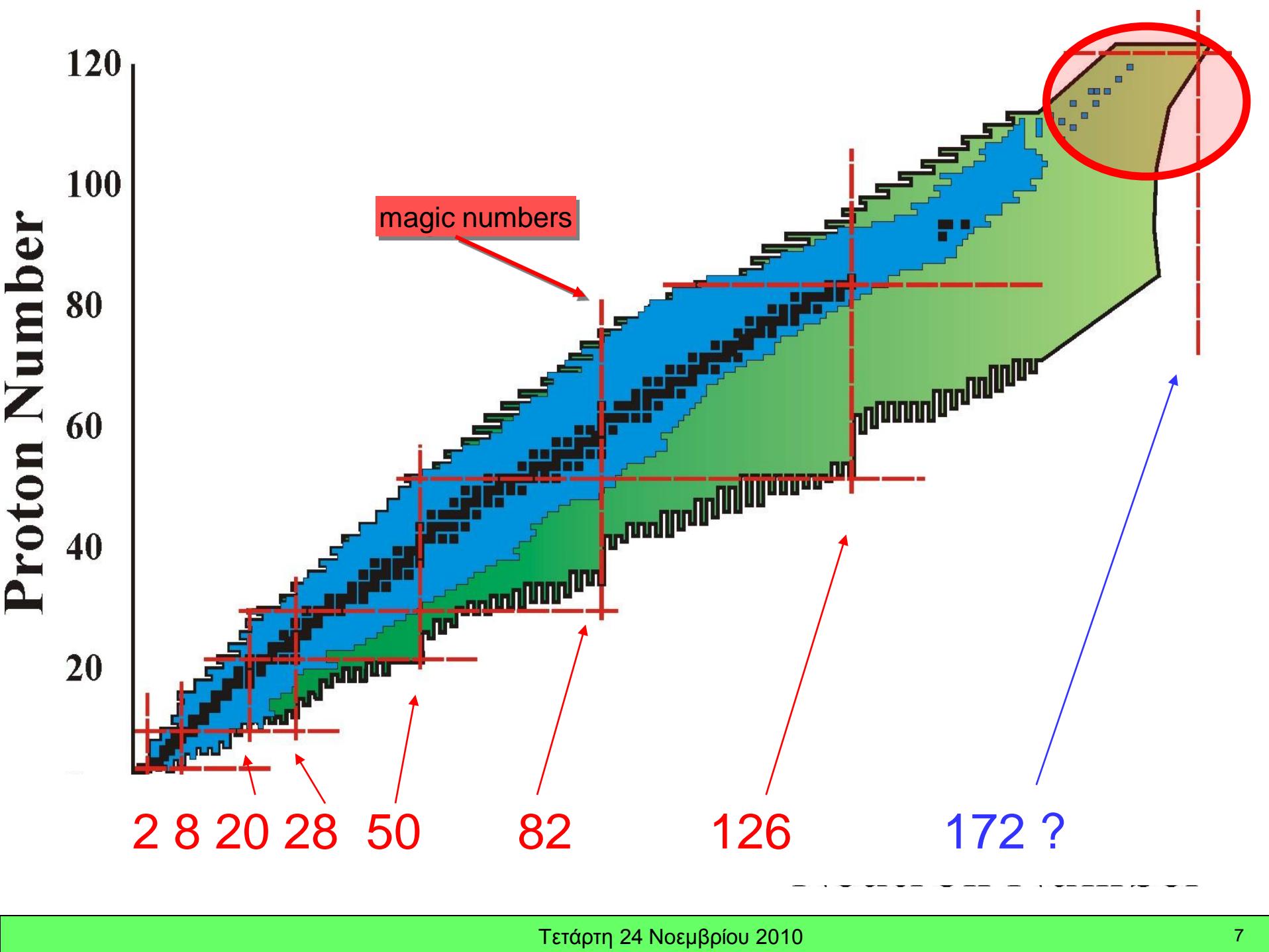


neutron number N

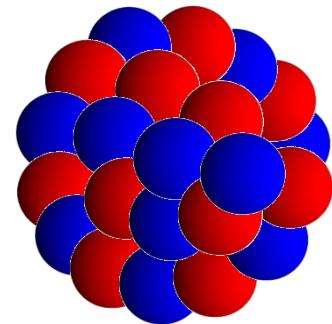


Pulsars in SN remnants:  
1054 - Crab





## Which forces act in the nucleus?

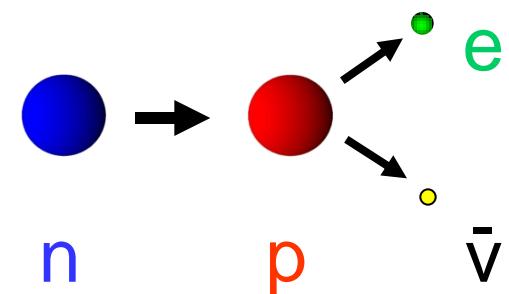


the **Coulomb force** repels the protons

the **strong interaction** ("nuclear force") causes binding  
it is stronger for pn-systems than for nn-systems

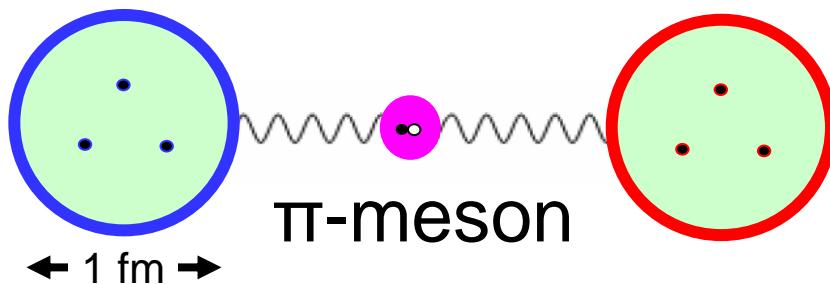
neutrons alone form no bound states  
exception: neutron stars (**gravitation!**)

the **weak interaction** causes  $\beta$ -decay:

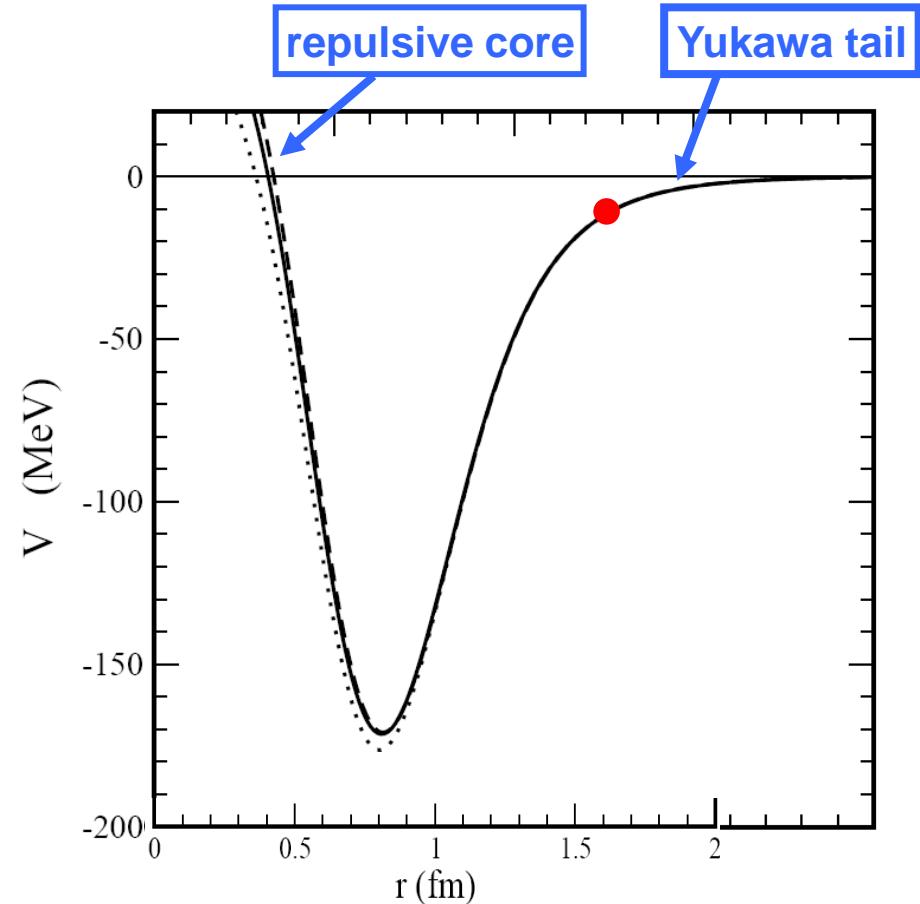
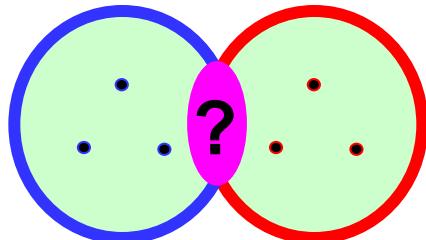


# The bare nucleon-nucleon interaction:

distance > 1 fm: attractive



distance < 0.8 fm: repulsive



three-body forces

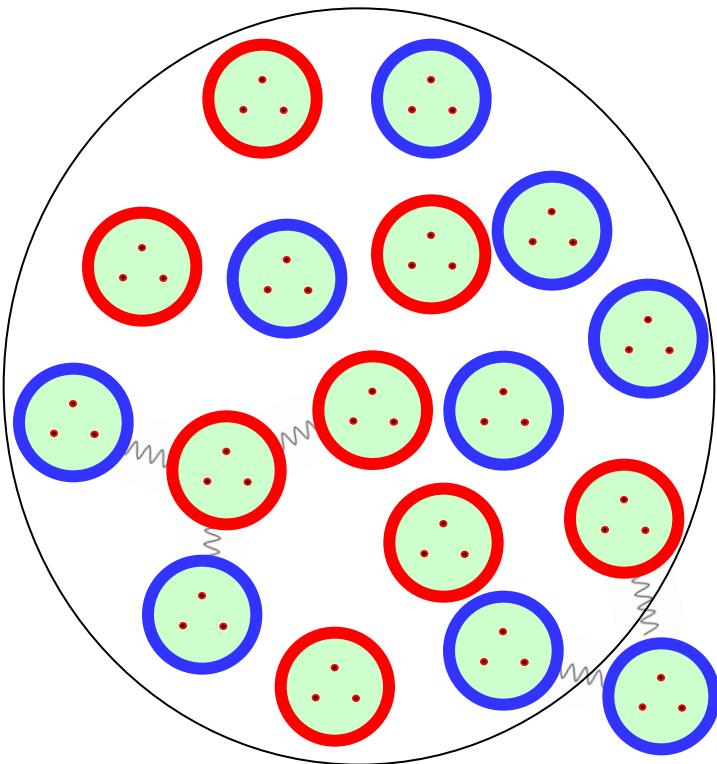
# What is special in nuclei?

- size: nuclei are very small objects: Uncertainty relation

$$\Delta x^2 \Delta p^2 \geq \frac{\hbar^2}{4} \quad E_{kin} \geq 10 \frac{fm^2}{r^2} \text{ MeV} = 10^{-5} \frac{nm^2}{r^2} \text{ eV}$$

- degrees of freedom: spin and isospin:  $4^A$  possibilities
- very complicated interaction: strongly repulsive
  - tensor forces
  - 3-body forces
- many particles: Pauli principle:  
effective interaction inside the nucleus is quenched (Brueckner)
- required accuracy (for masses):  
 $100 \text{ keV} / 1000 \text{ MeV} \approx 10^{-4}$

# nucleons in the nucleus:



- each nucleon feels only the next neighbors
- binding energy is proportional to number of nucleons  $\sim A=N+Z$

## surface tension (attractive):

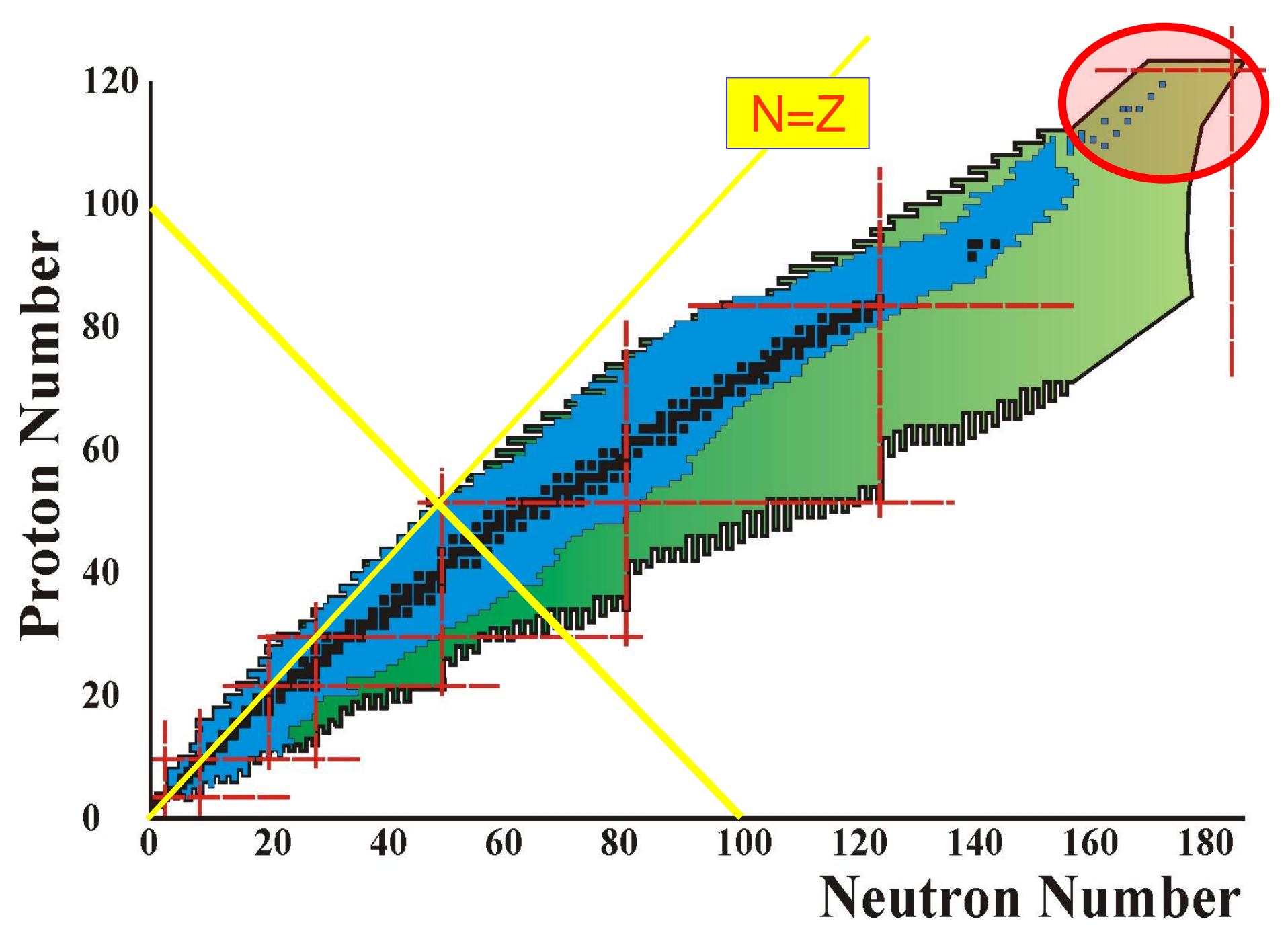
- nucleons in the surface are less bound
- surface energy  $\sim A^{2/3}$

## Coulomb-energy (repulsive):

- ~ to the number of proton pairs  $\sim Z^2$

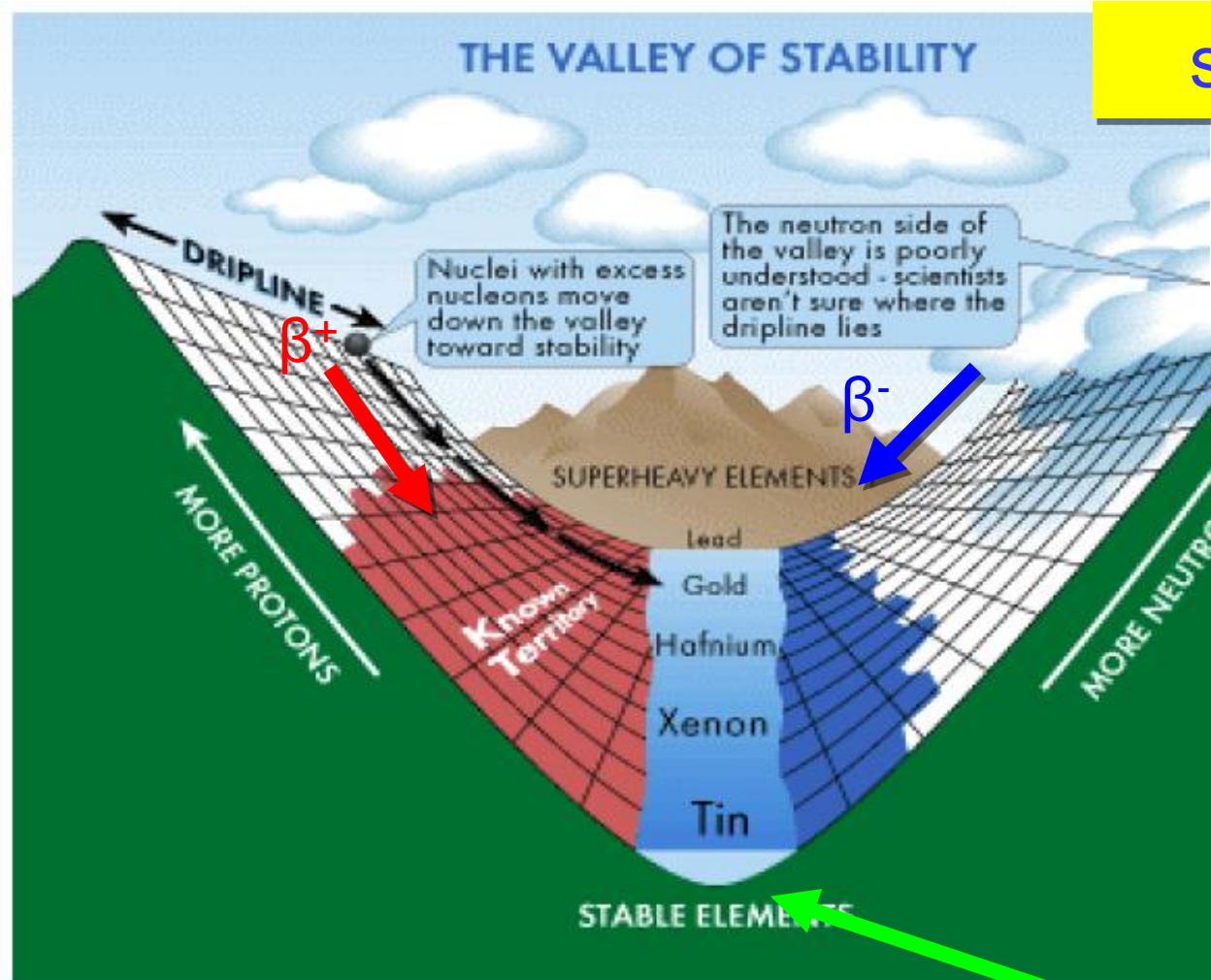
## symmetry-energy:

- proportional to  $\sim (N-Z)^2$

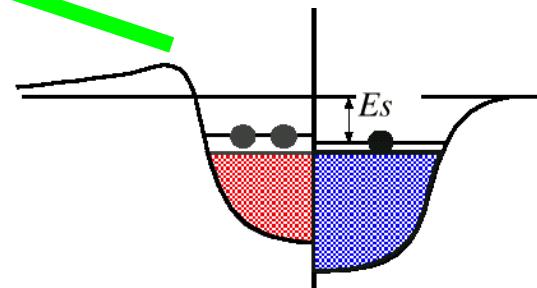


## THE VALLEY OF STABILITY

symmetry energy

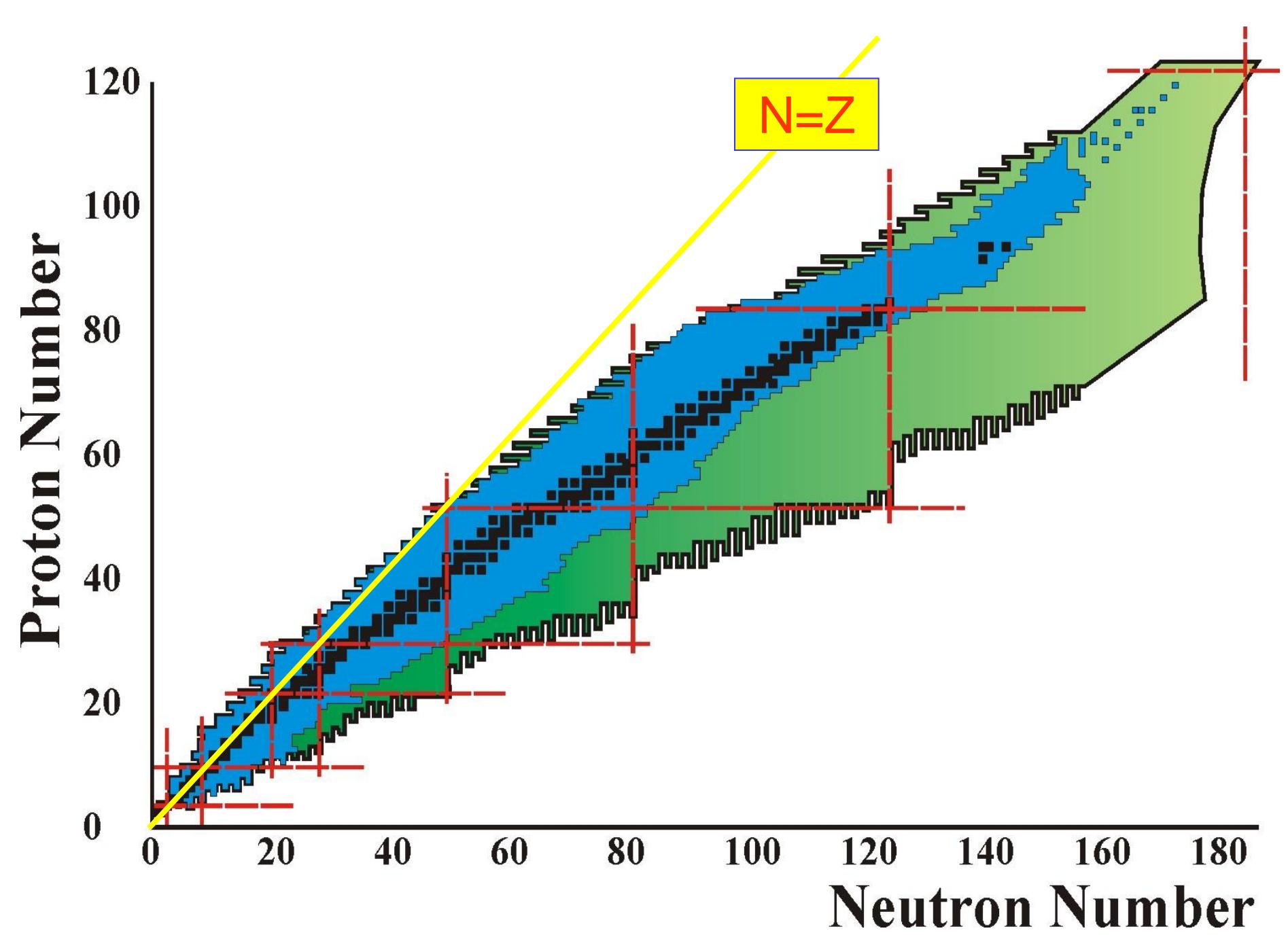


neutron drip line

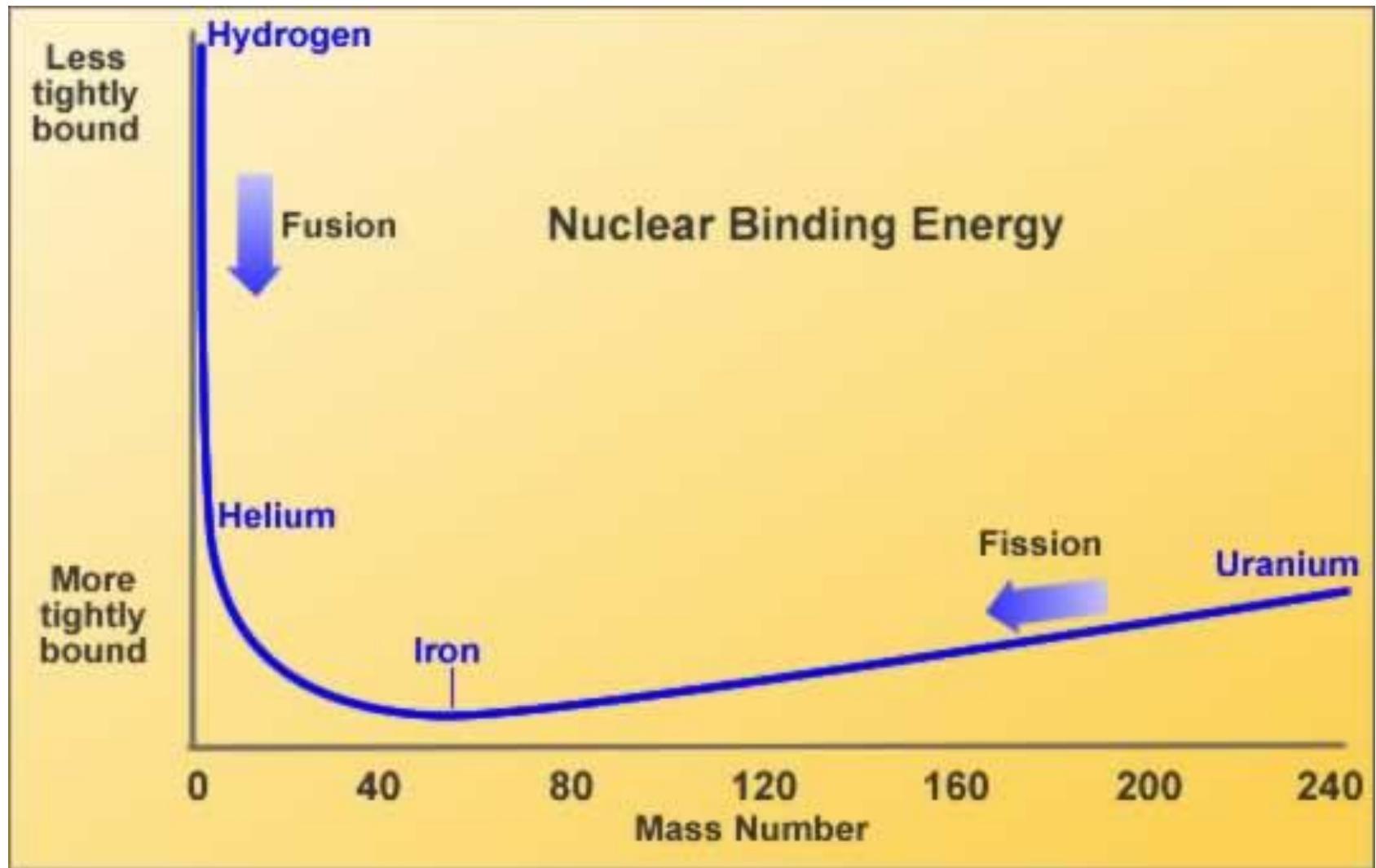


$N-Z \rightarrow$

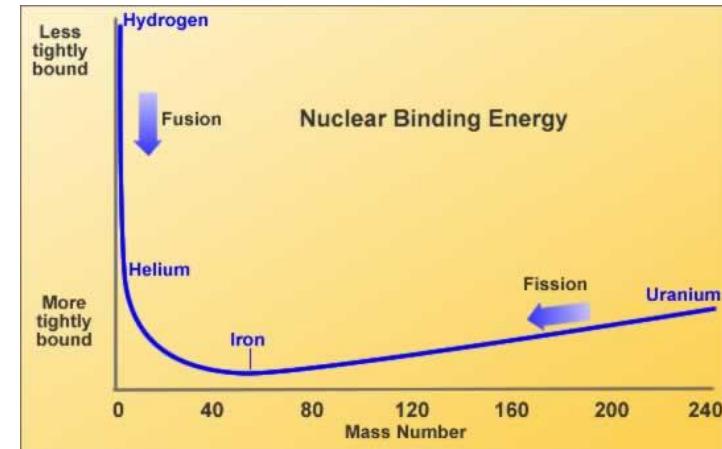
curvature is symmetry energy:  $S_2$



# Binding energy along the valley of stability:



# Phaenomenological description of the binding energy in nuclei: (Bethe-Weizsäcker-formula)



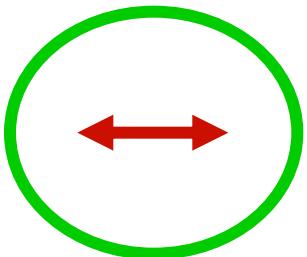
$$B(N,Z) = - a_V V - a_S S + a_C \frac{Z^2}{R} + a_I \frac{(N-Z)^2}{A} + \dots$$

surface tension

- bindes
- prefers sphere  $\sim A^{2/3}$

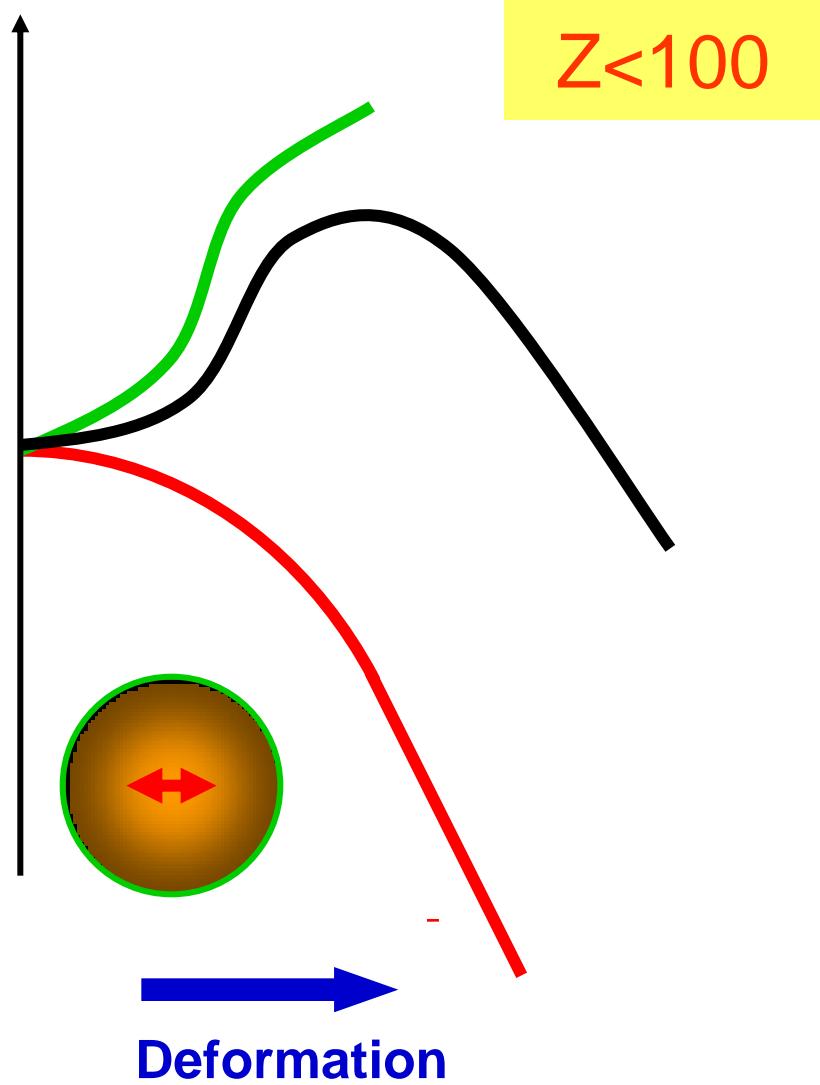
Coulomb repulsion

drives the nucleus  
towards fission  $\sim Z^2/A^{1/3}$



The stability of nuclei is defined  
by the interplay between surface tension  
and Coulomb repulsion

# classical nuclear droplet



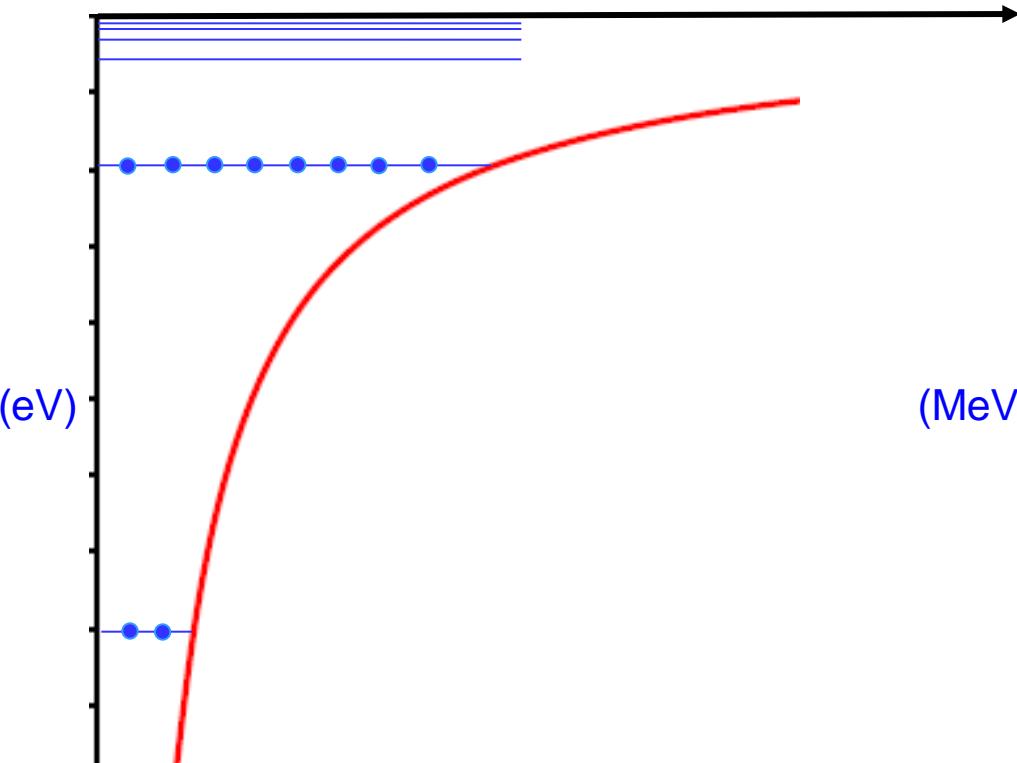
$Z < 100$



$Z > 100$

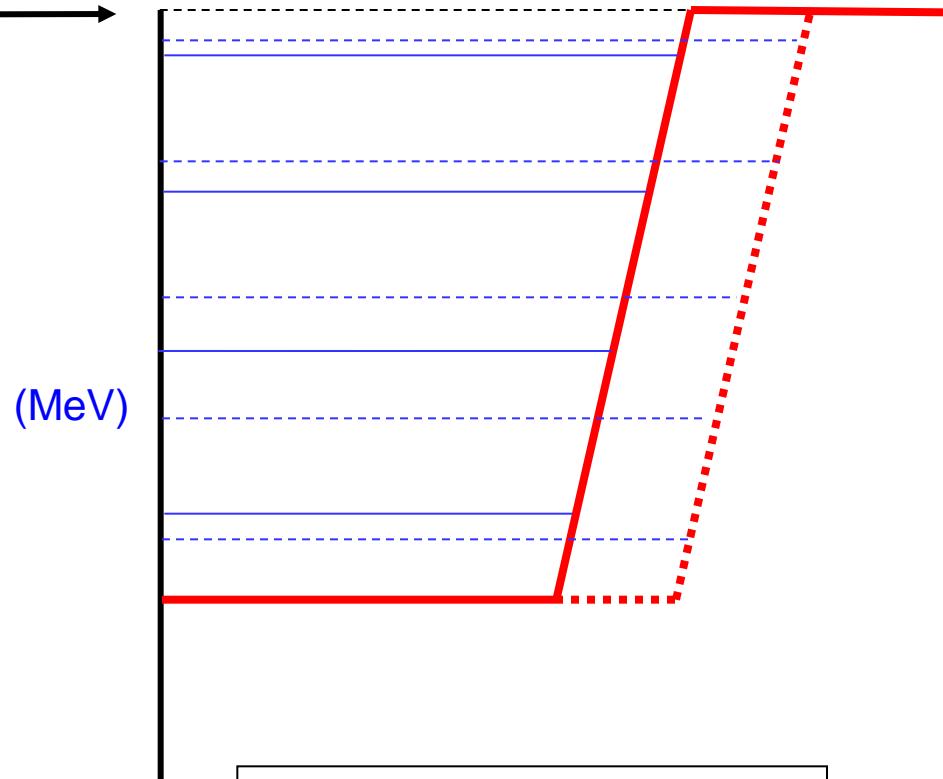
## shell effects:

atoms

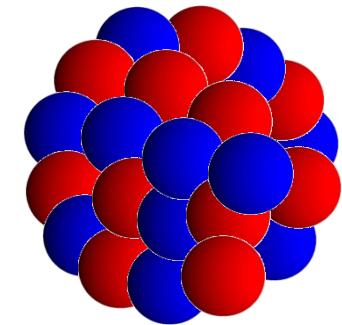


central potential  
small spin-orbit

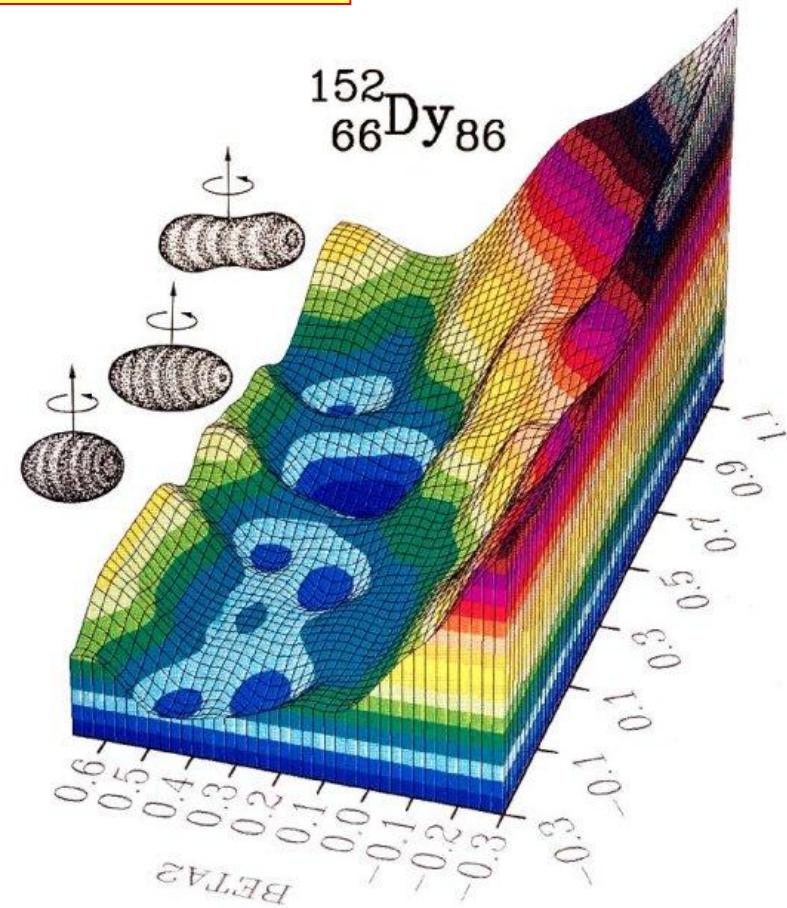
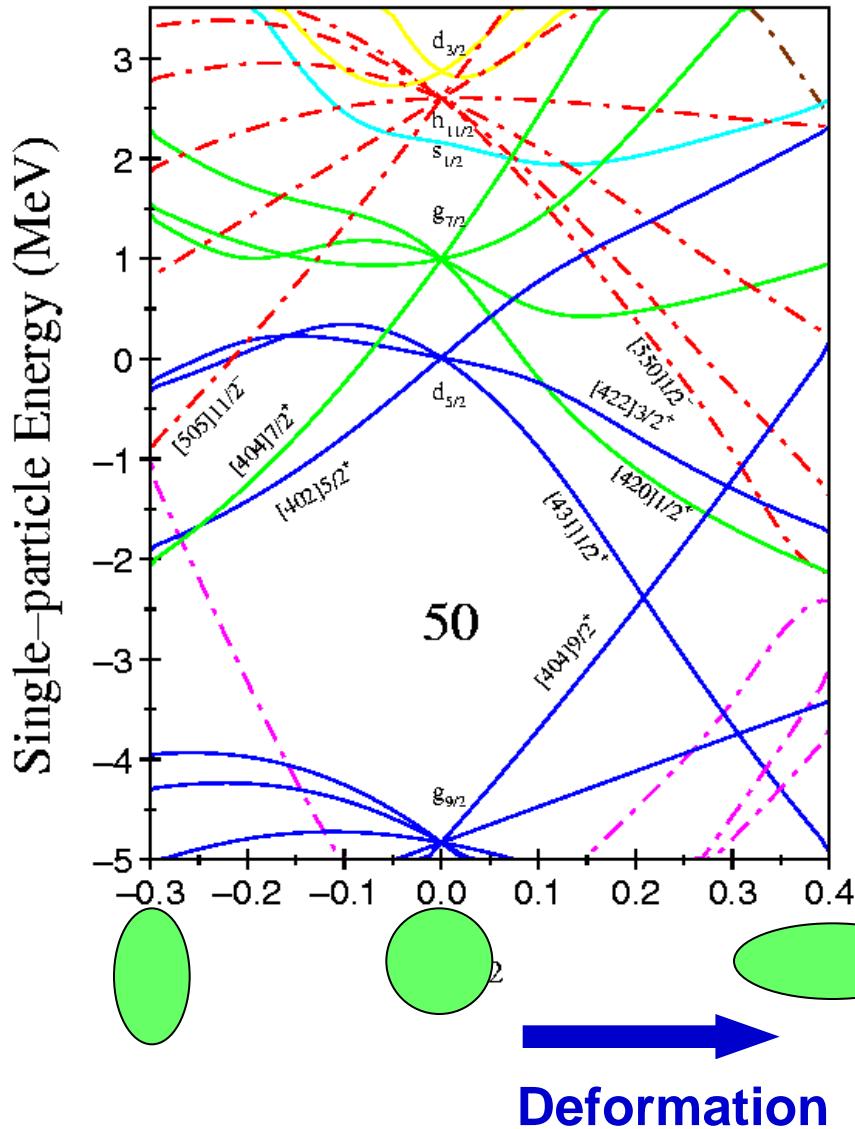
nuclei



self-bound system  
large spin-orbit

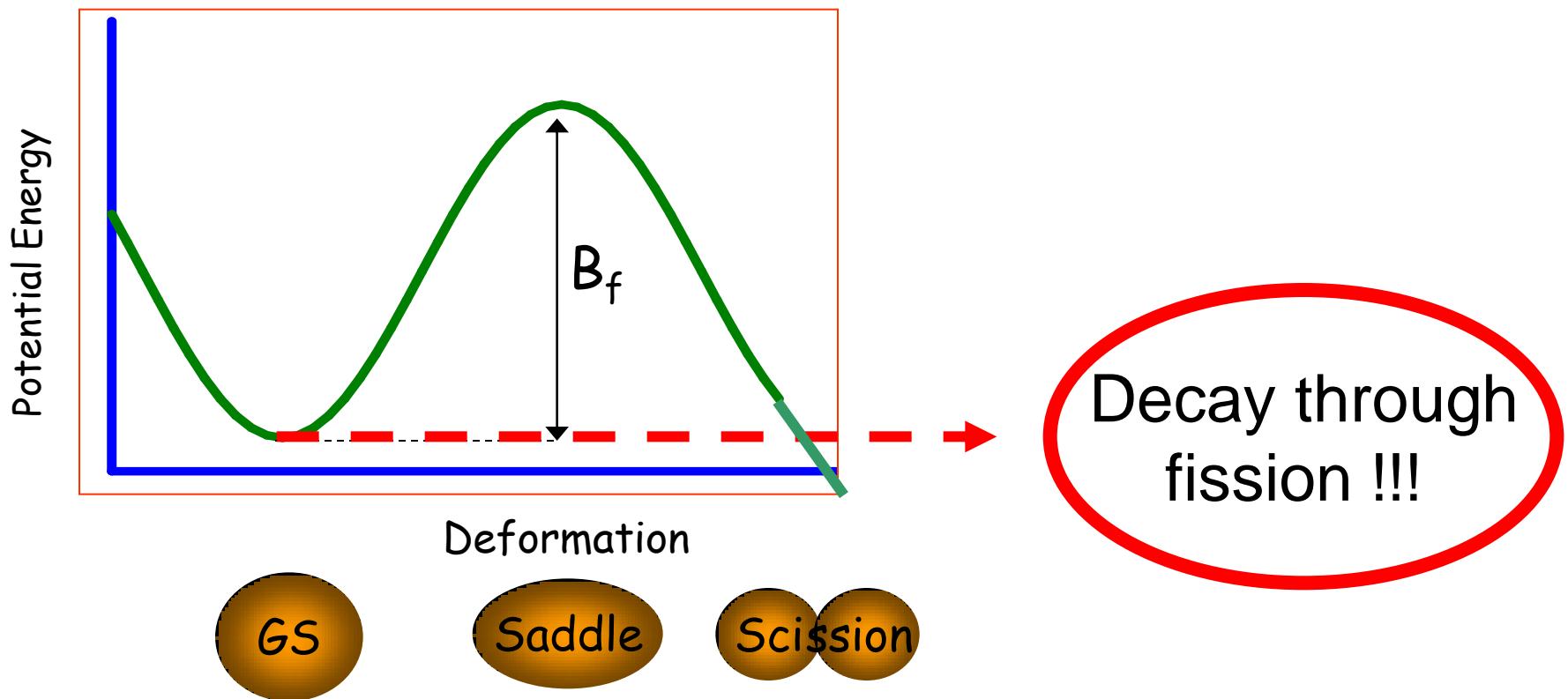


# Quantummechanical Shell Effects



Shell effects lead to a new stability at specific protonen- or neutron numbers (**magic numbers**)

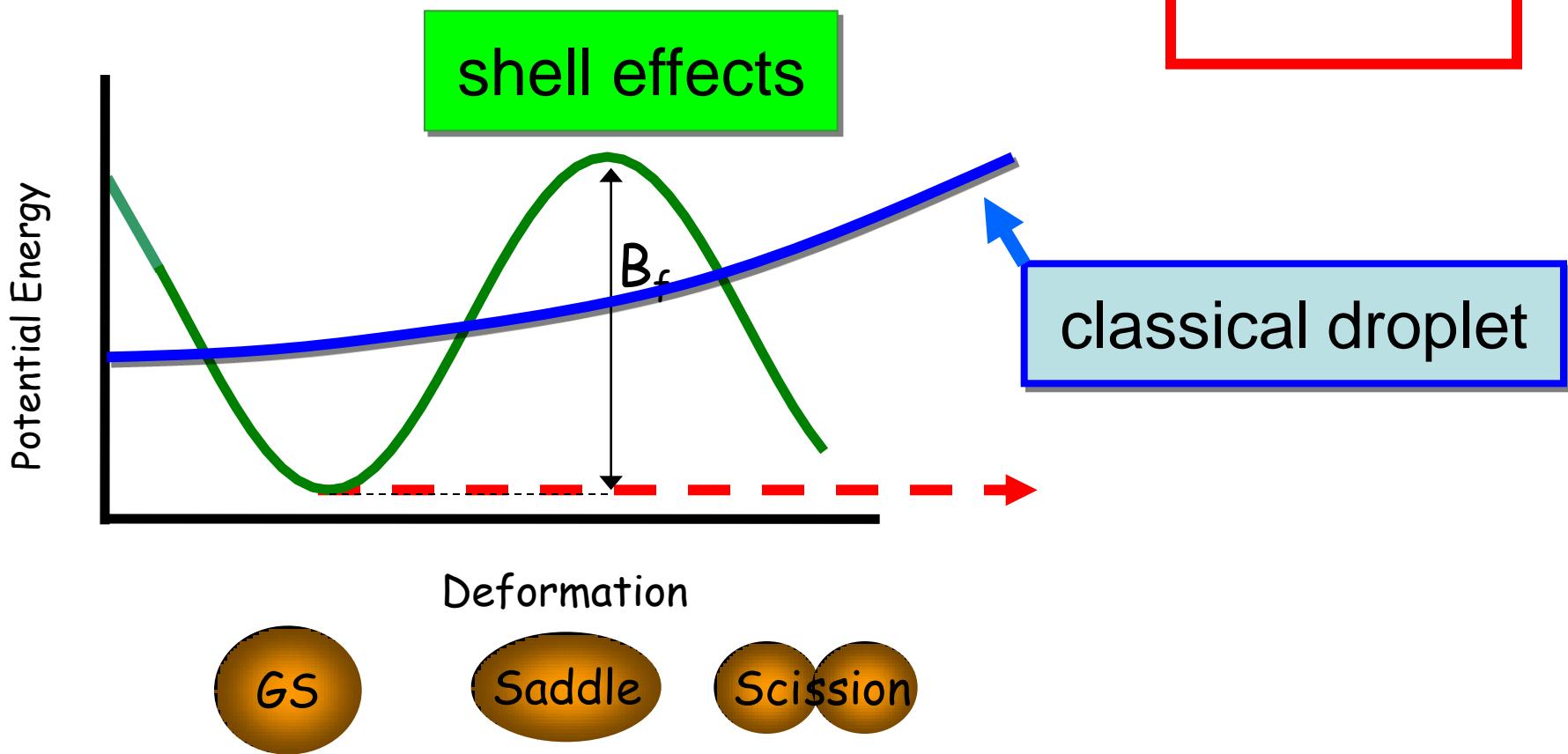
# Quantenmechanical Shell Effects



Elements with  $Z>100$  are stabilized through shell effects

# Quantum mechanical shell effects

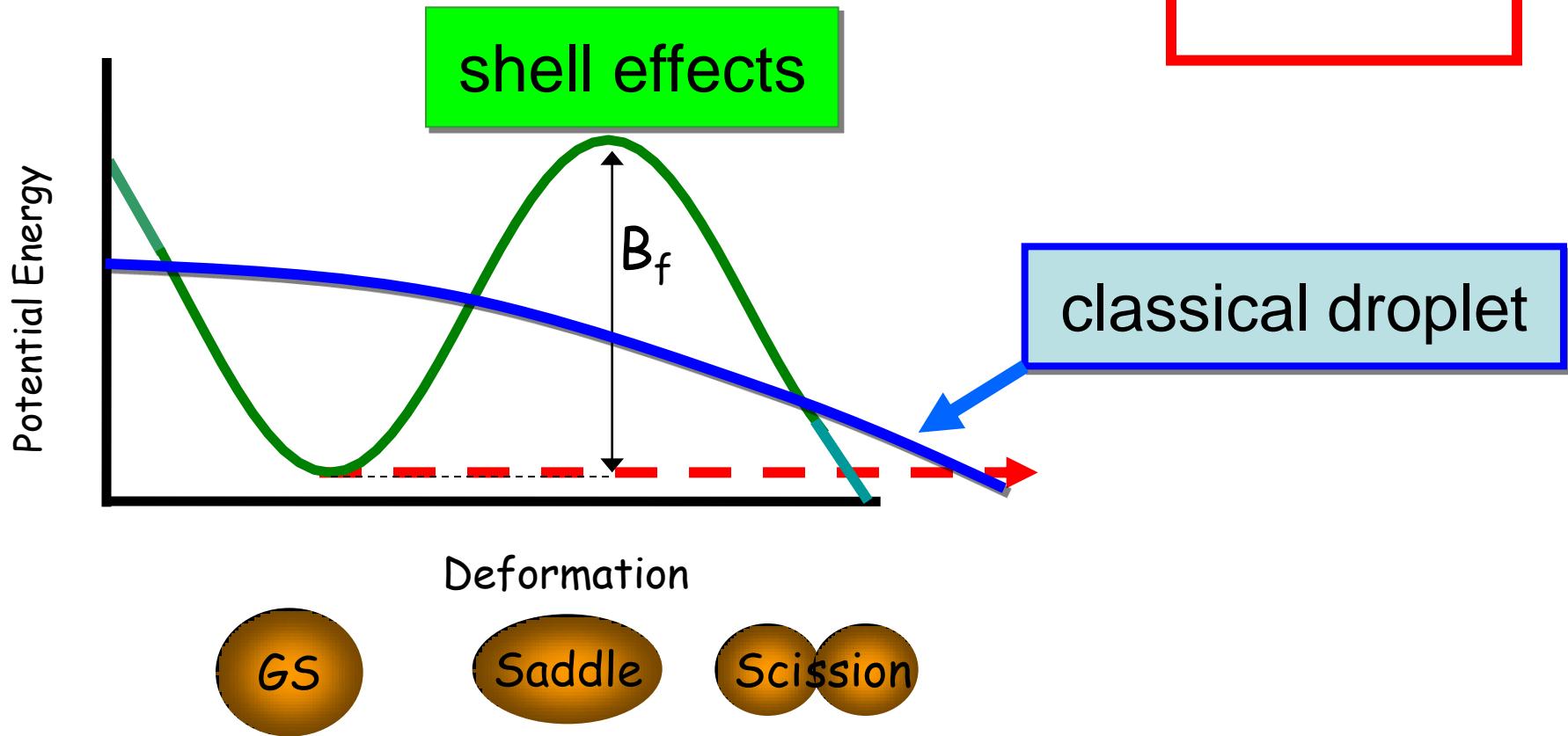
$Z < 100$



Elements with  $Z < 100$  are stabilized by surface energy and shell effects

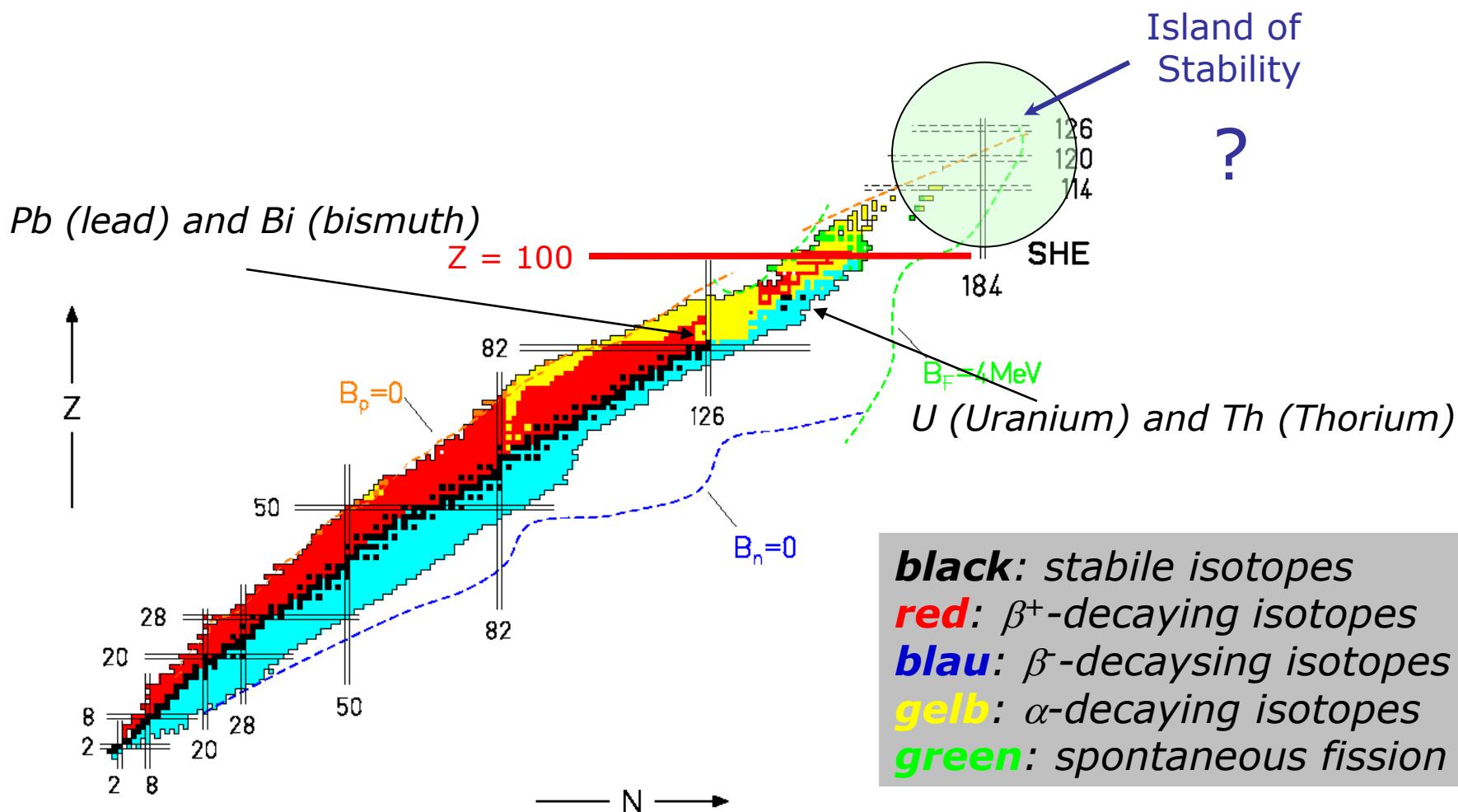
# Quantum mechanical shell effects

$Z > 100$



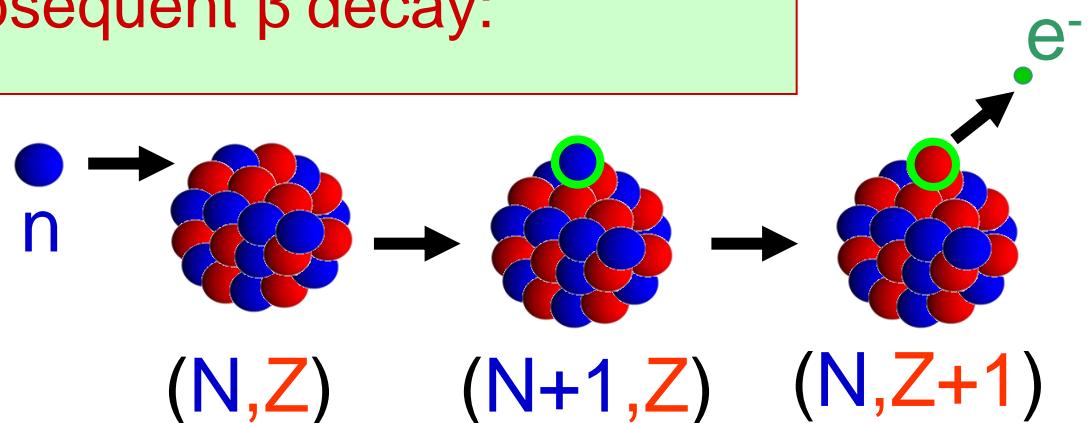
Elements with  $Z > 100$  are stabilized only by shell effects

# Limits of stability

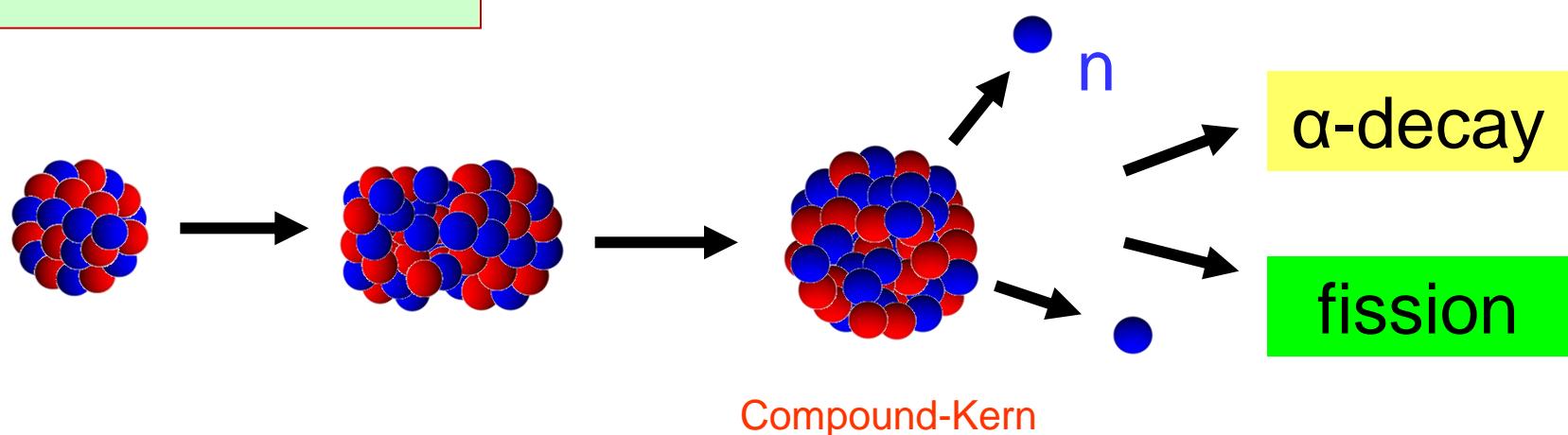


# Synthesis of heavy and superheavy elements

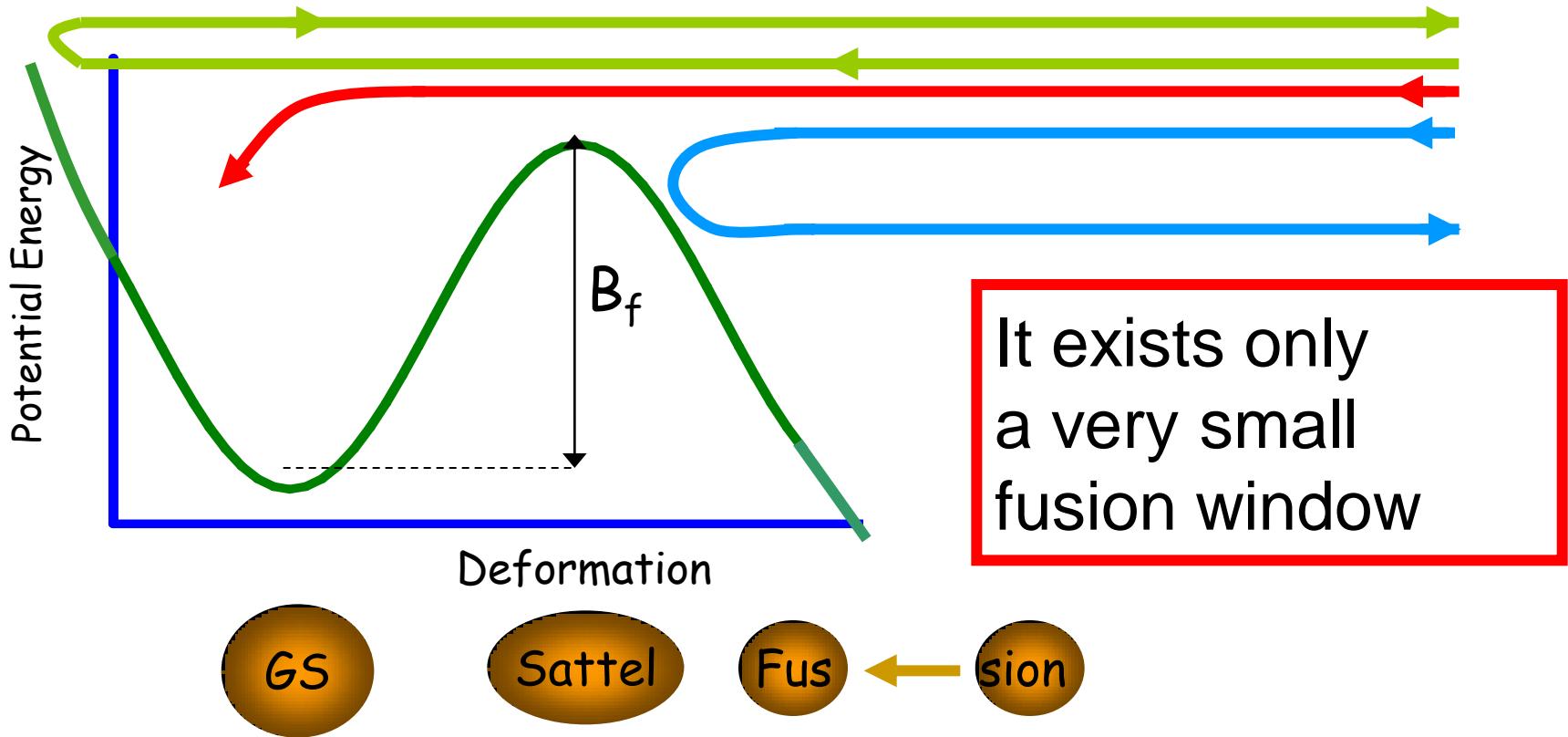
Neutron capture and subsequent  $\beta$ -decay:



Fusion of two nuclei:



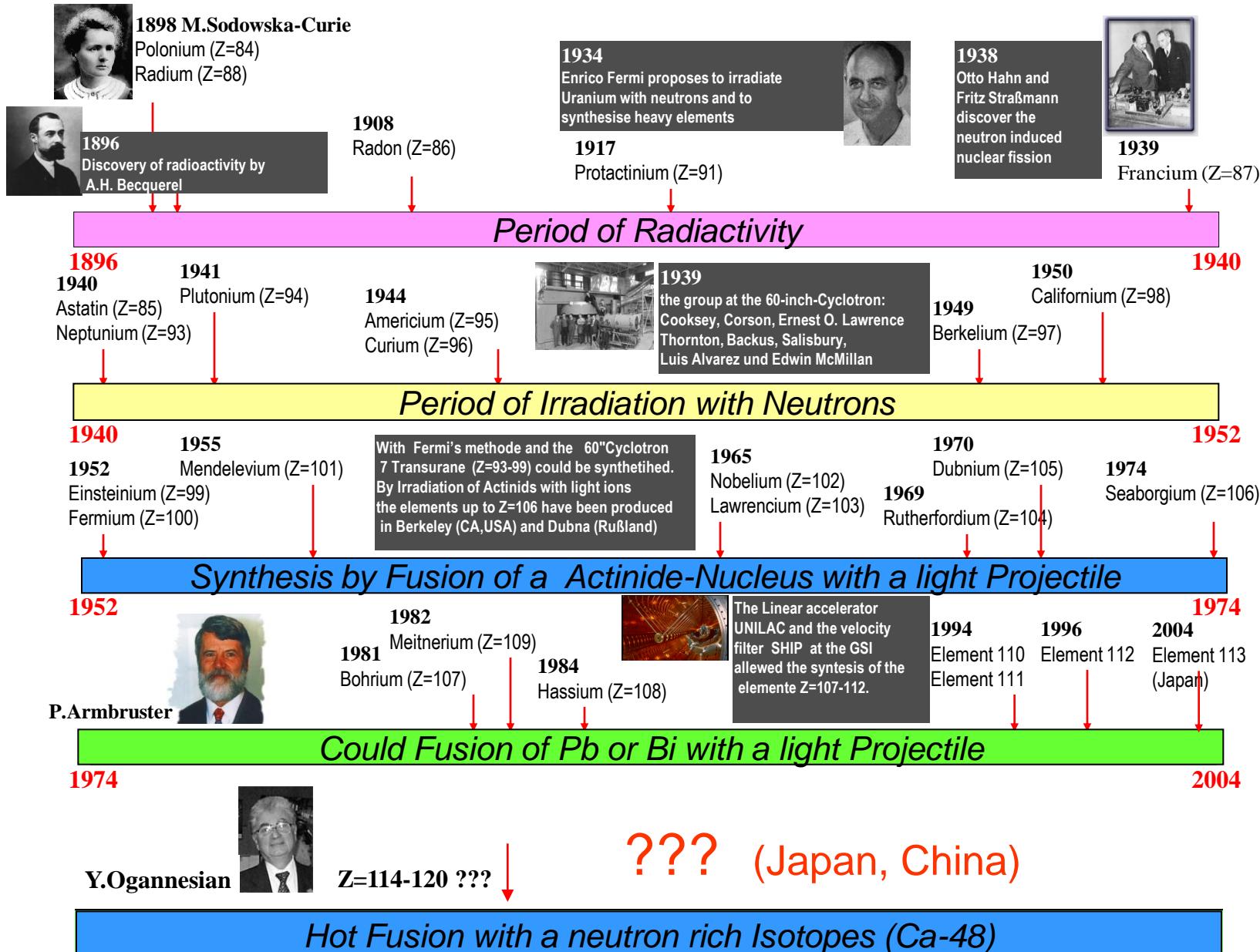
# Fusion over fusion barrier



Effects such as friction or reflexion  
at the inner barrier are important!

# History of Discoveries

(P. Armbruster, "Spektrum der Wissenschaft", Dezember 1996)



proton number

114

108

90

Pb  
continent

Th

Pu

MAP OF ISOTOPES

shoal of deformed nuclei

SEA OF

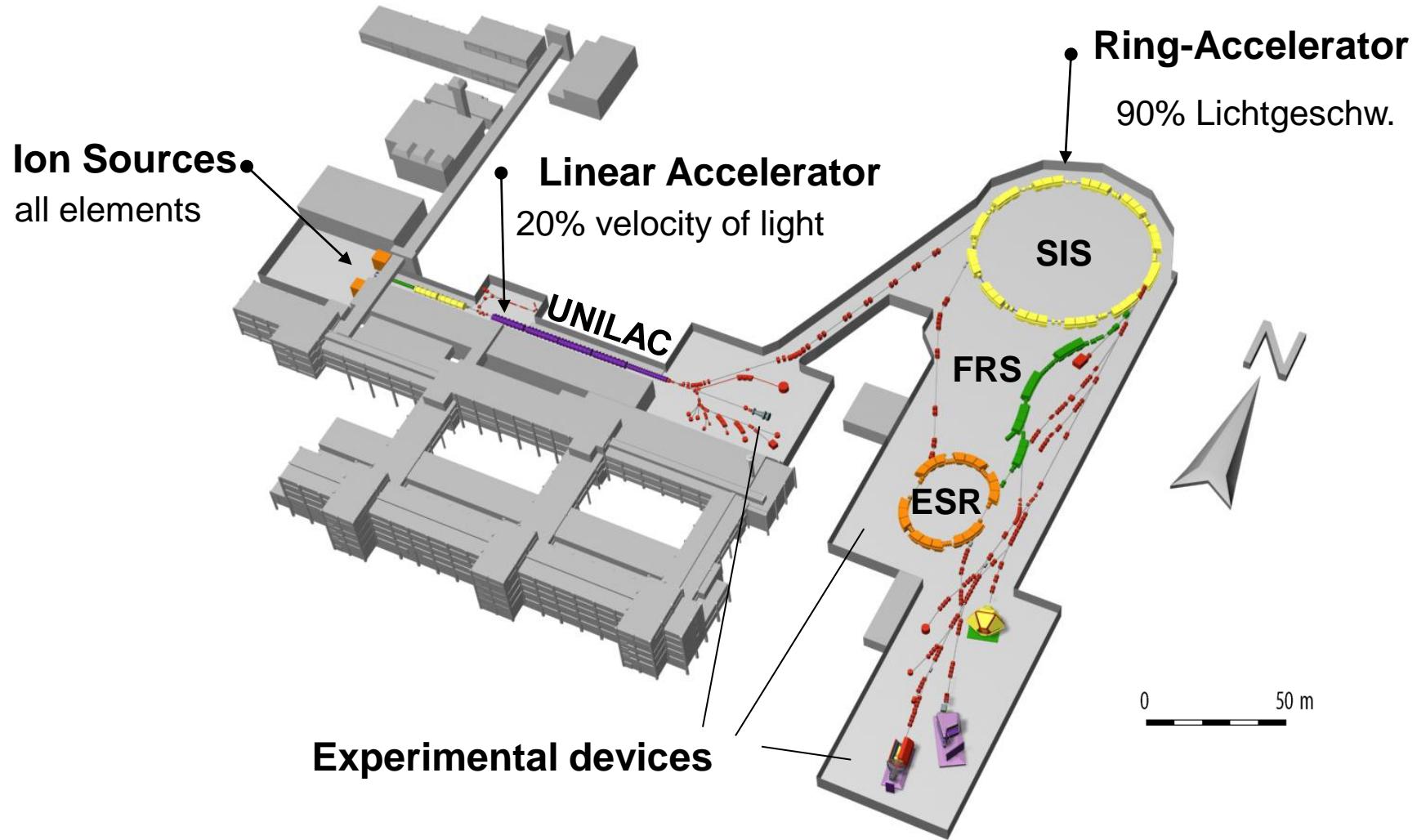
162

island of stability of superheavy nuclei

neutron number

184

# GSI Accelerator in Darmstadt



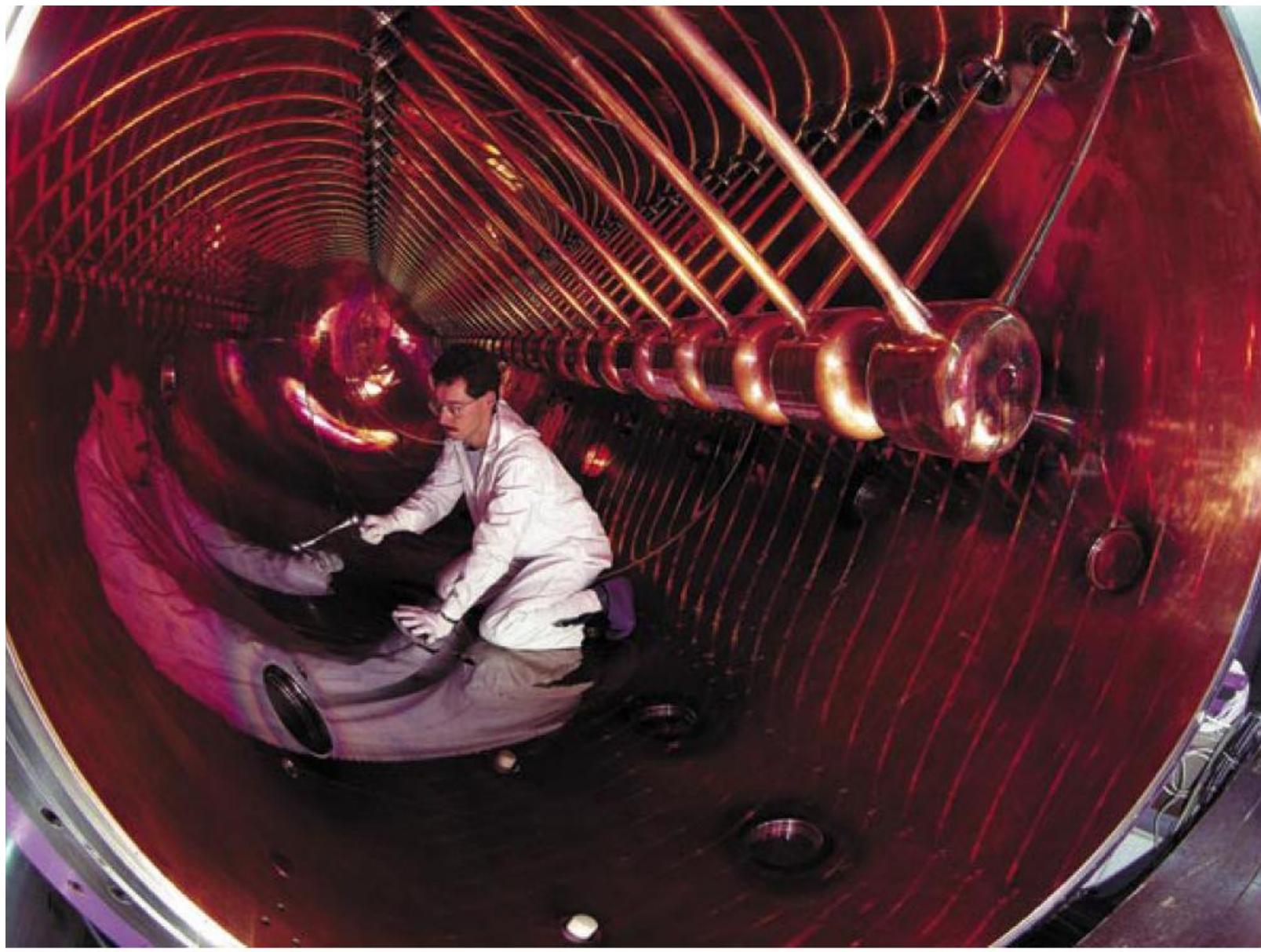
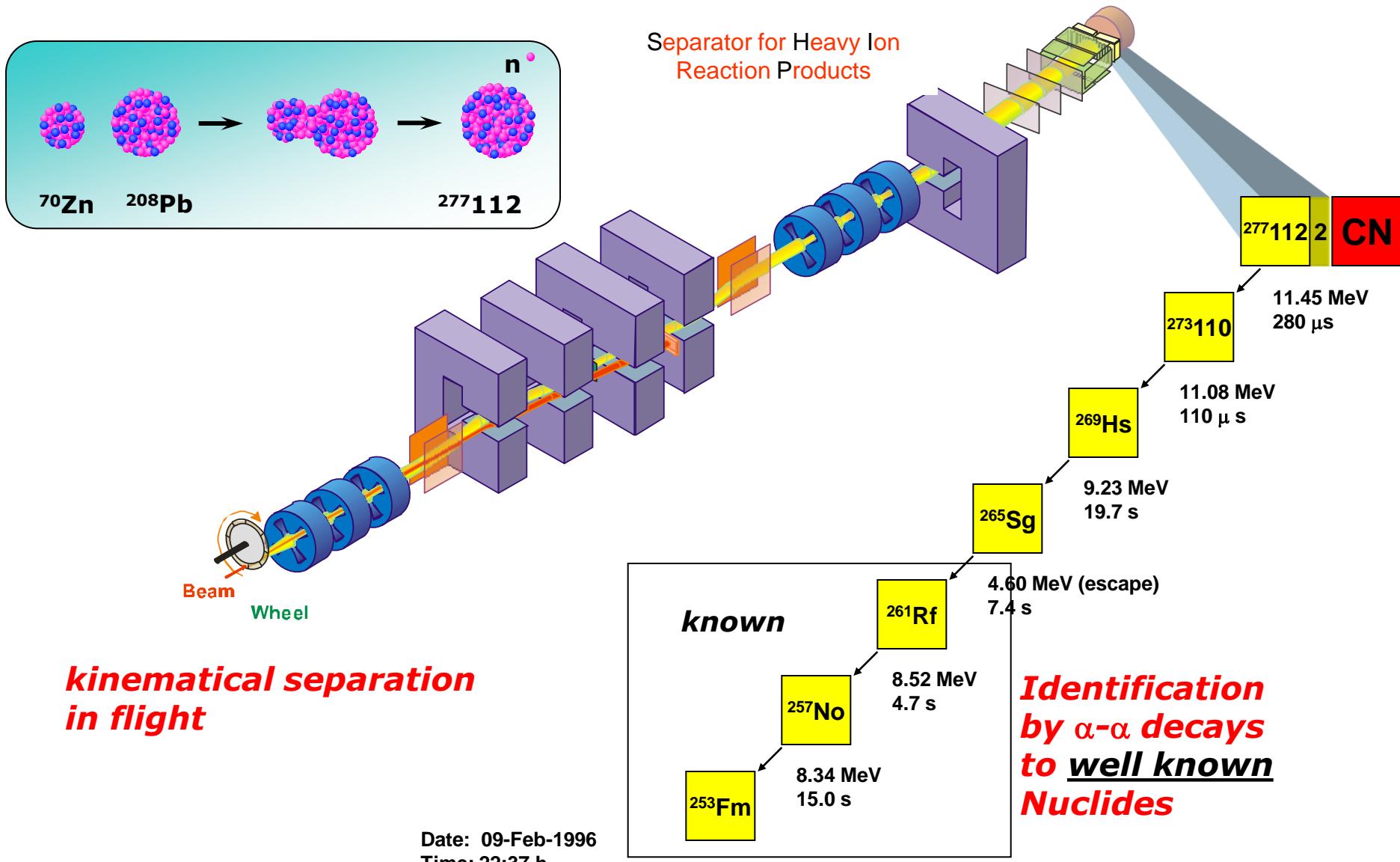


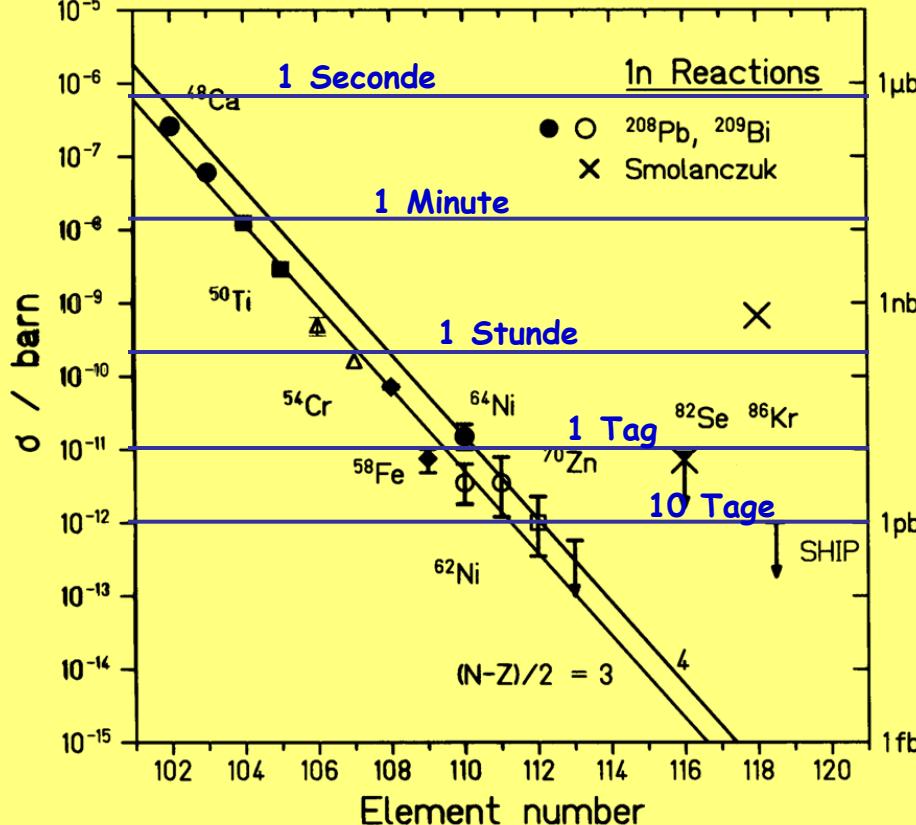
Foto: Achim Zschau, GSI

A look into the interior of the linear accelerator

# *Synthesis of Super-heavy Elements at SHIP*



# Systematics of cross sections ( $1n$ reaktions)



time for 1 event (on the average)

→ present sensitivity:

limit  $\approx 1 \text{ pbarn}$

→ Radiation-dosis:

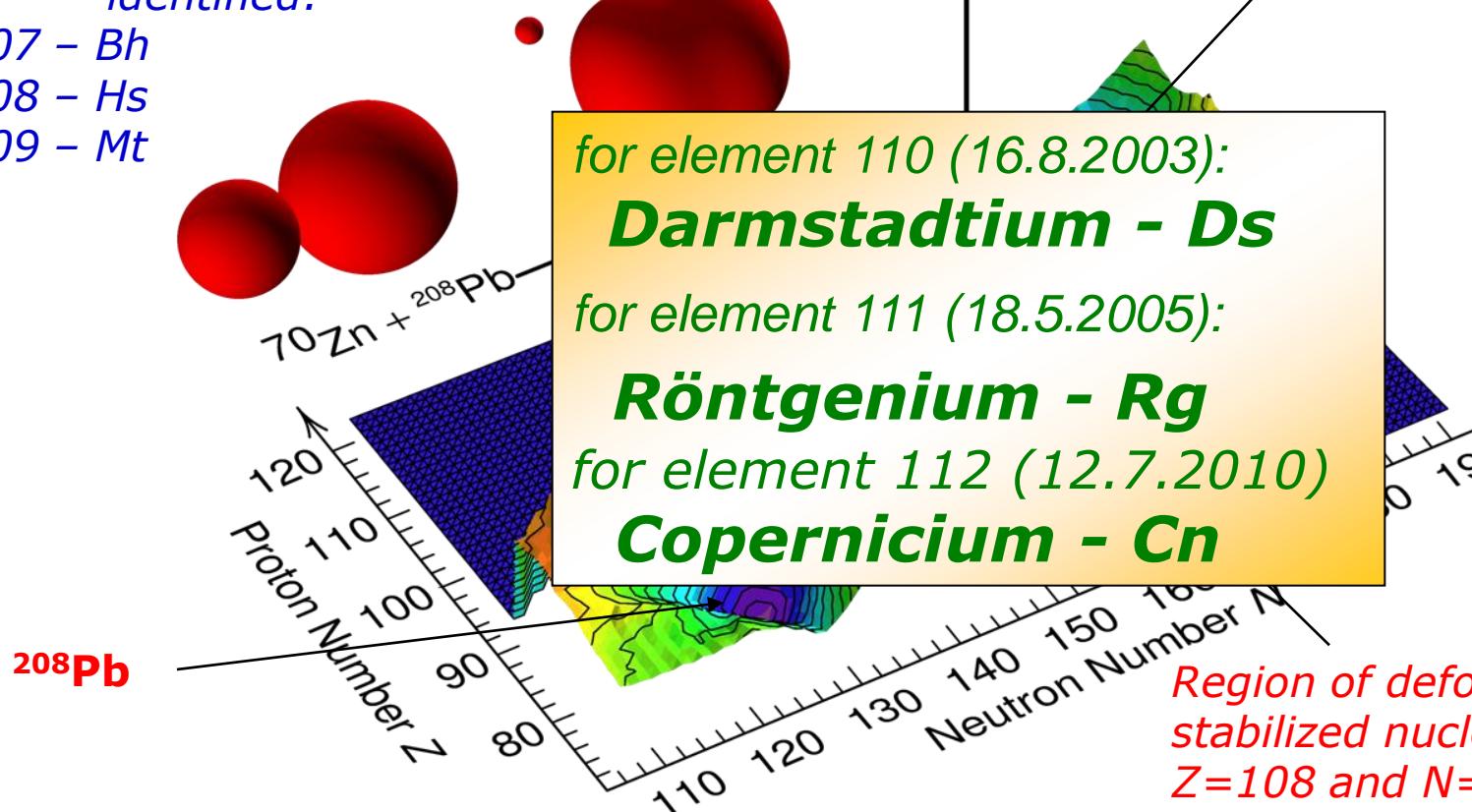
$1.5 \times 10^{18} \text{ projectile}$

# **Shell correction $E_{shell}$ in the region of superheavy elements**

P. Möller et al.

**GSI:** Elemente 107-112 first synthesised and uniquely identified:

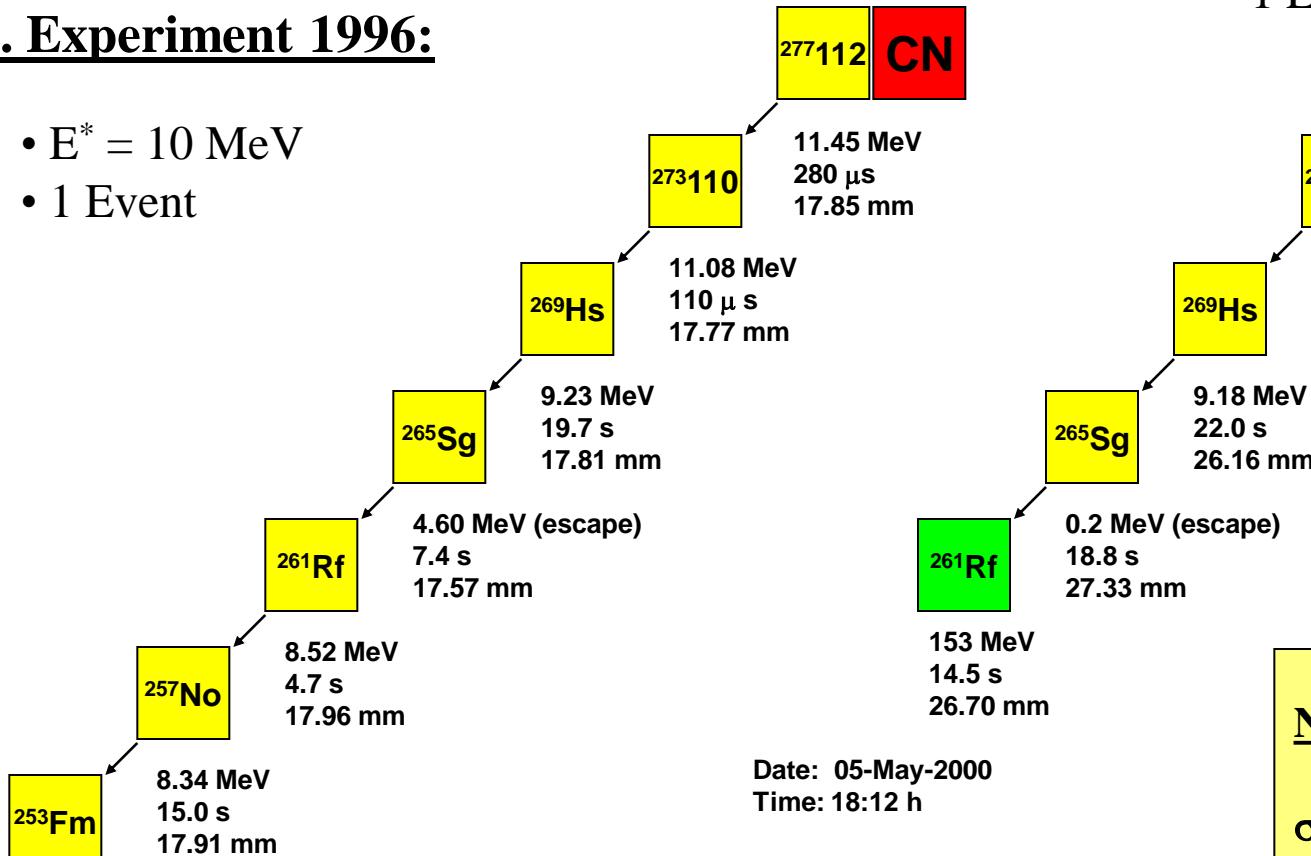
107 - Bh  
108 - Hs  
109 - Mt



# ***Confirmation of Element 112***

## **1. Experiment 1996:**

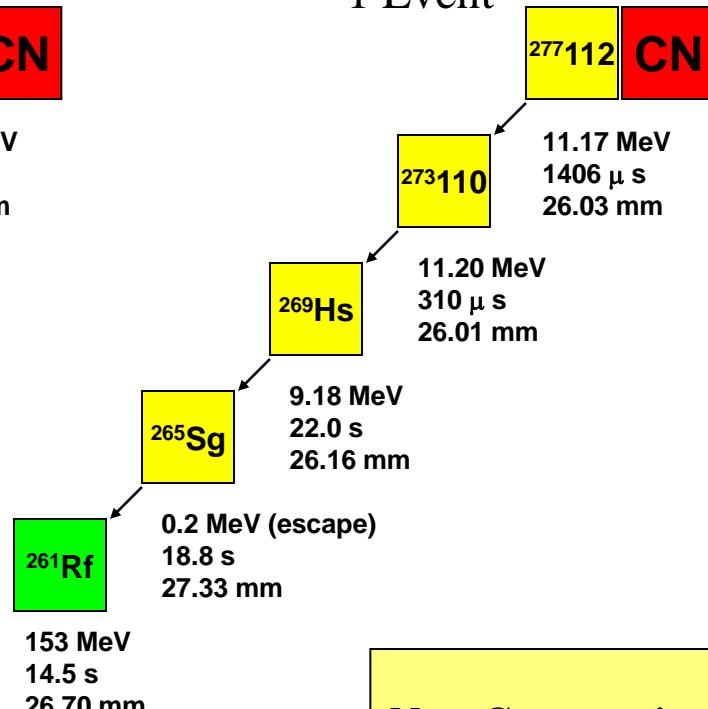
- $E^* = 10 \text{ MeV}$
- 1 Event



Date: 09-Feb-1996  
Time: 22:37 h

## **2. Exp. in Mai 2000:**

- $E^* = 10 \text{ MeV}$  und  $12 \text{ MeV}$
- 1 Event



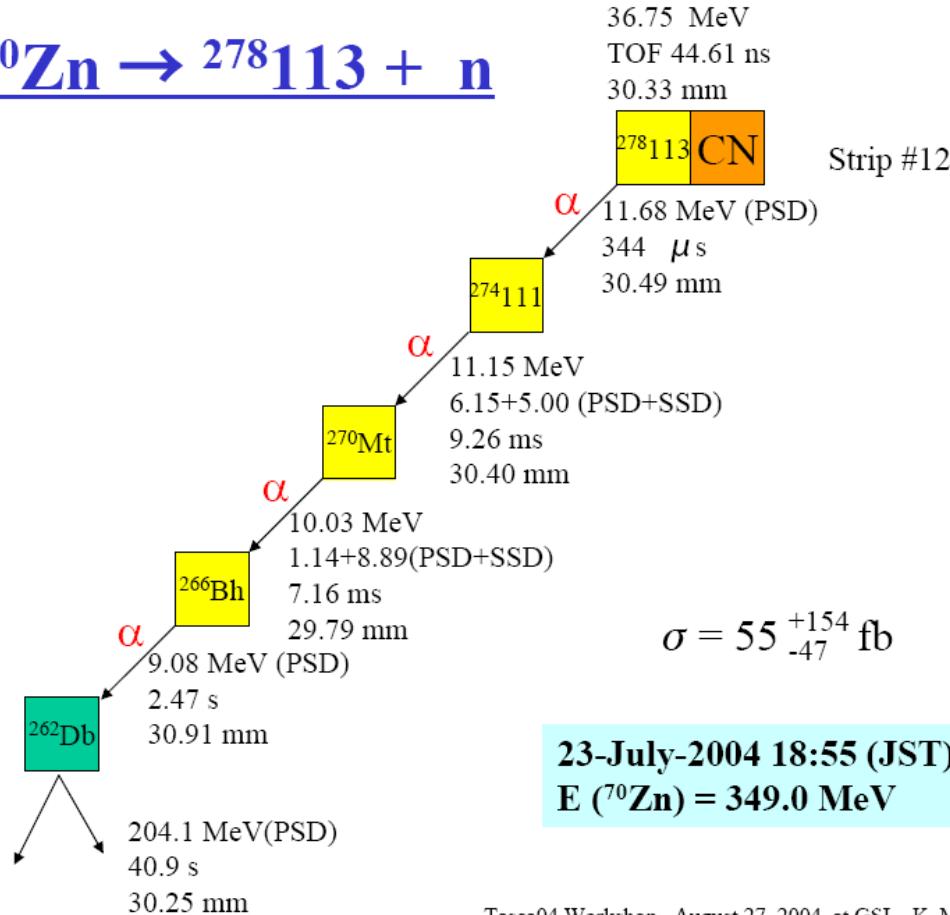
## **New Crosssections:**

$$\sigma(E^*=10 \text{ MeV}) = 0.4^{+0.9}_{-0.3} \text{ pb}$$

$$\sigma(E^*=12 \text{ MeV}) = 0.5^{+1.1}_{-0.4} \text{ pb}$$

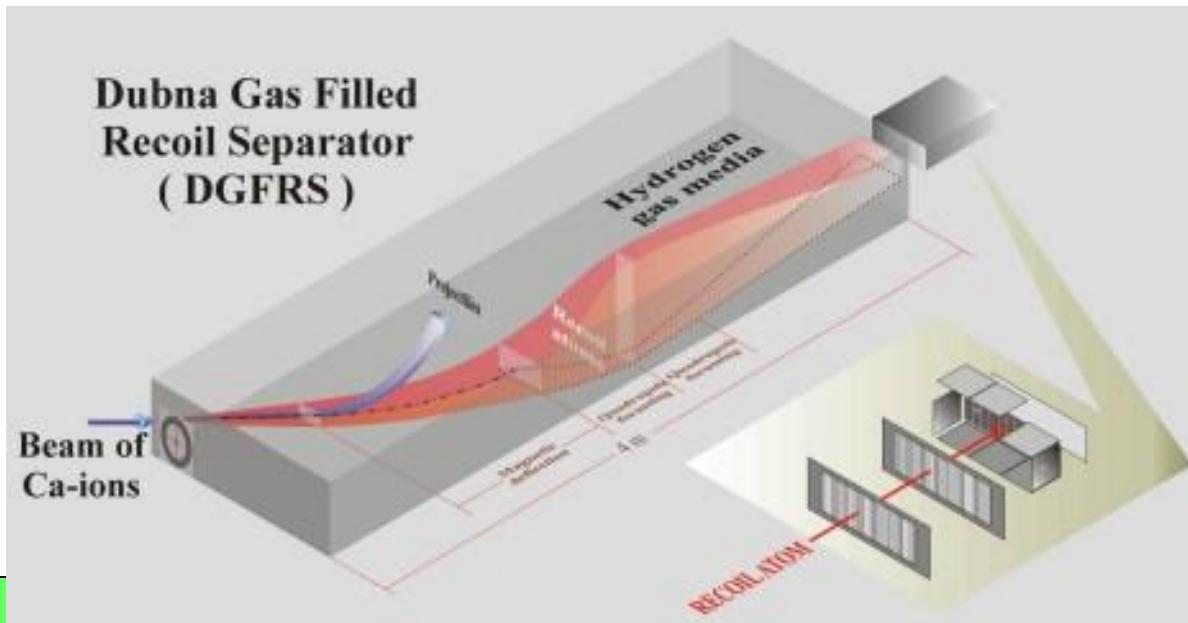
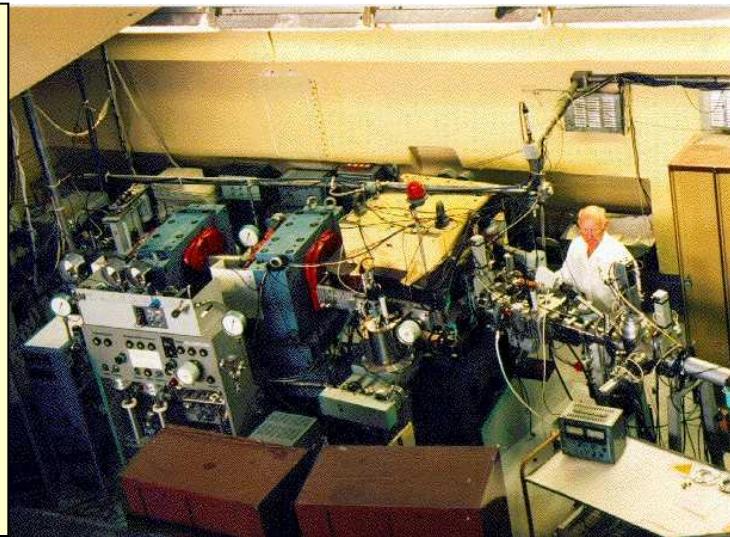
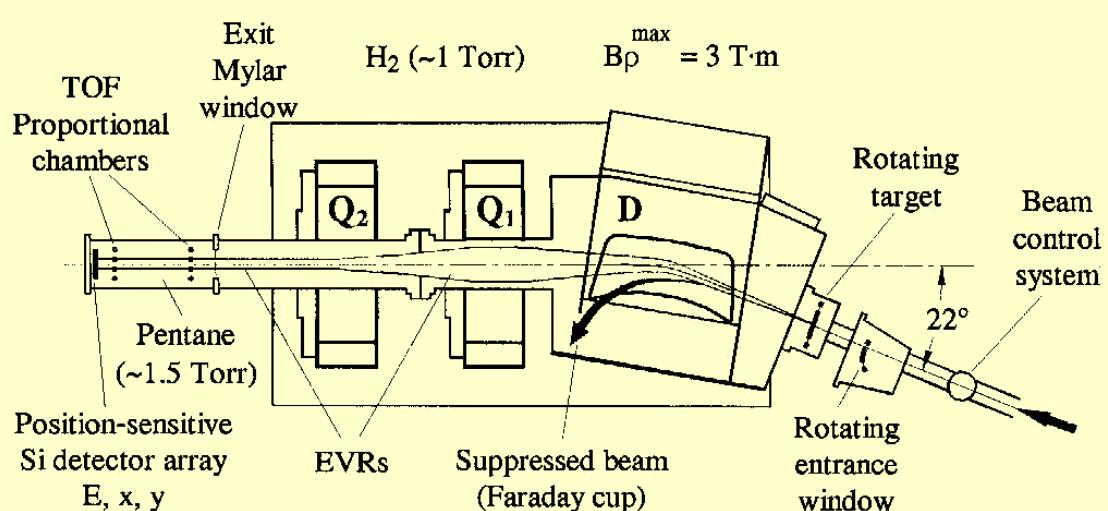
# **First observation of $^{278}\text{113}$ by cold fusion in Japan**

**K. Morita et al., JPSJ (J. Phys. Soc. Japan) Vol. 73 (2004)**



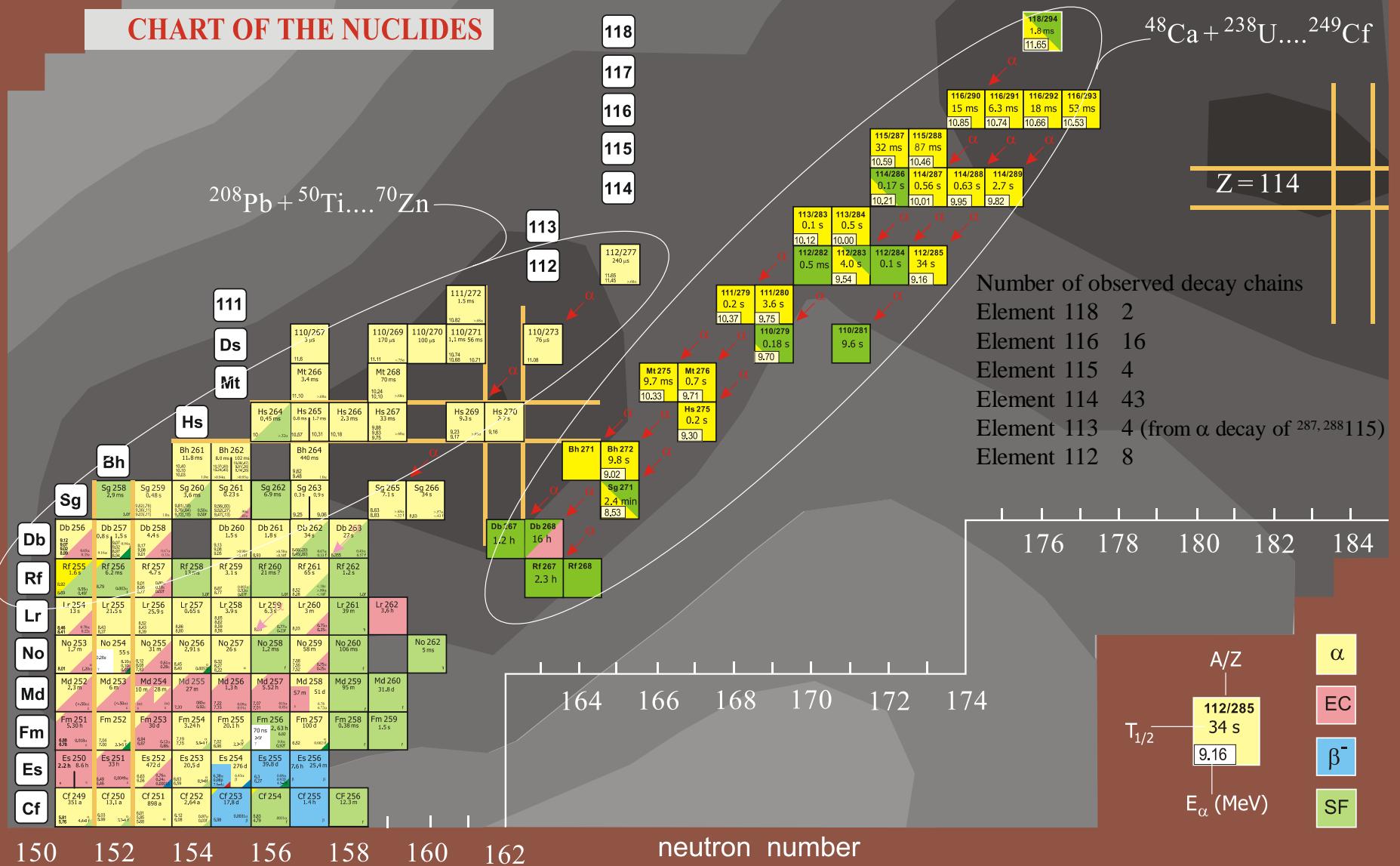
# The elements 114-120 at JINR-FLNR in Dubna

Yu.Ts. Oganessian, V.K. Utyonkov et al.

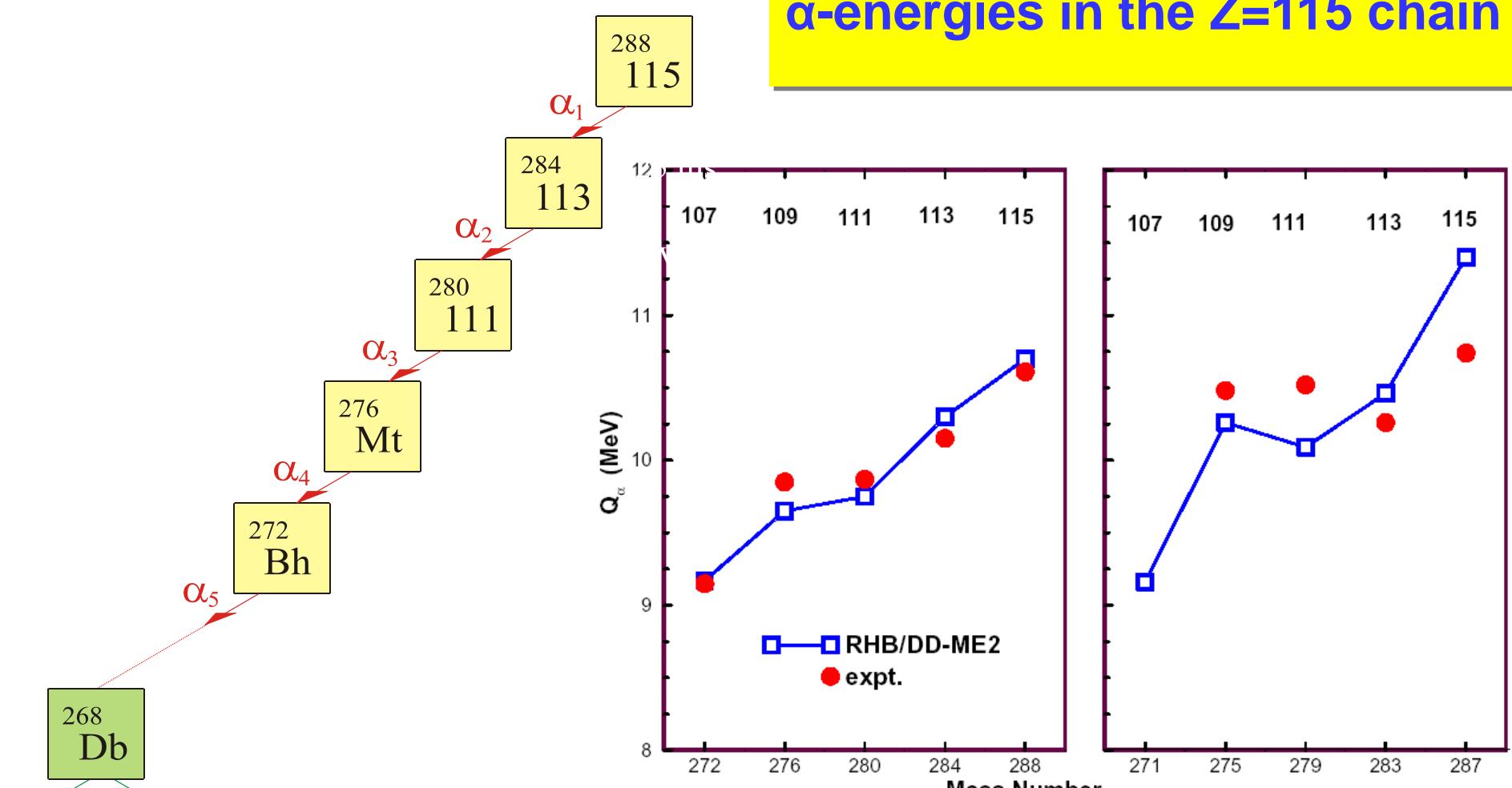


# CHART OF THE NUCLIDES

proton number



## Calculations : $\alpha$ -energies in the Z=115 chain



● Exp: Oganessian *et al*, PRC 69, 021601(R) (2004)

■ RHB: Lalazissis *et al*, PRC 71, 024312 (2005)

# Conclusions:

Important facts for the stability of atomic nuclei:

- surface tension (nuclear force)
- electric repulsion of the protons
- quantenmechanical shell effects

There are still new elements:

- where is the next major shell, Z=114, 120, 126 ?
- besides, there are deformed subshells.

Properties:

- very small life time (milliseconds – seconds)
- so far one could synthesize only single atoms
- one hopes longer life times at the major shells

Why is this interesting?

- Chemistry: Extreme strong fields in the electron
- Physics: Is our understanding of the nuclear force o.k.?
- Perhaps there are surprises !

# Bubble nucleus: $^{500}\text{Zn}$

