Production of superheavy elements

Seminar: „Key experiments in particle physics“
26.06.09
Supervisor: Kai Schweda
Thorsten Heußer

Outline

1. Introduction

2. Nuclear shell model

3. Production of superheavy elements (SHE's)

4. Experiments at Helmholtz Center for Heavy-Ion Research (GSI), Darmstadt

5. Results on elements 111 and 112

6. Summary

- How many elements and nuclei (may) exist?
- What are their properties?

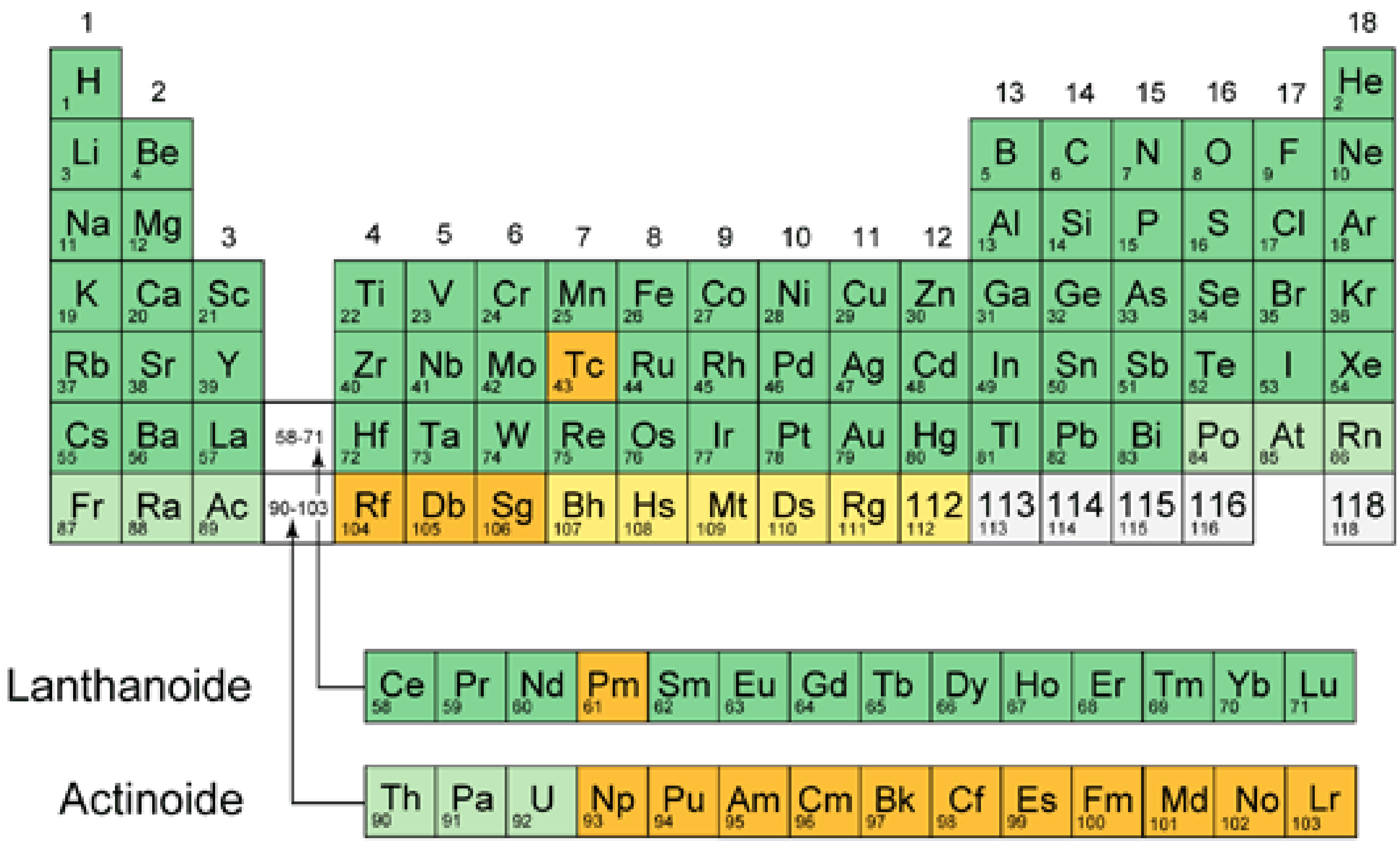
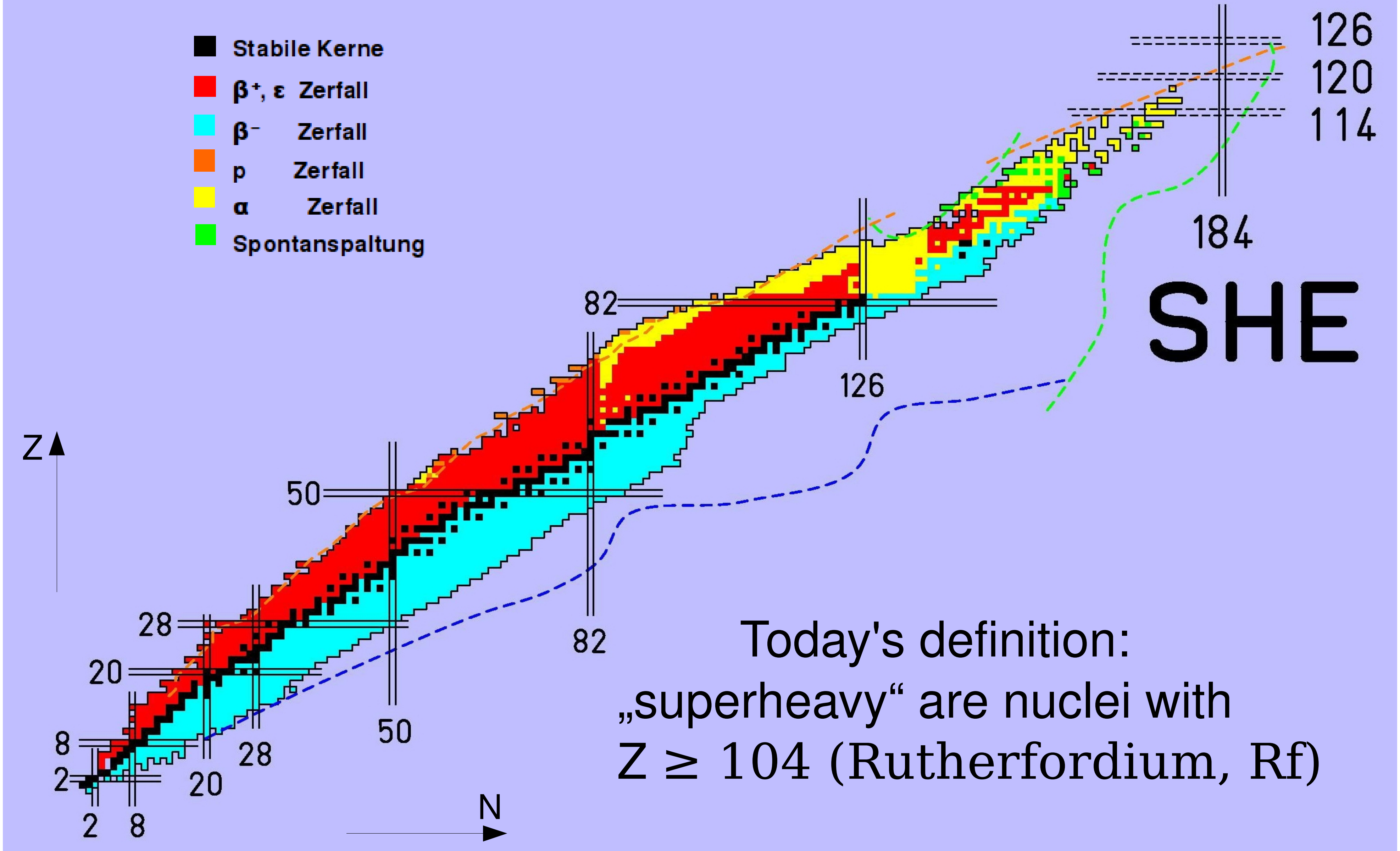


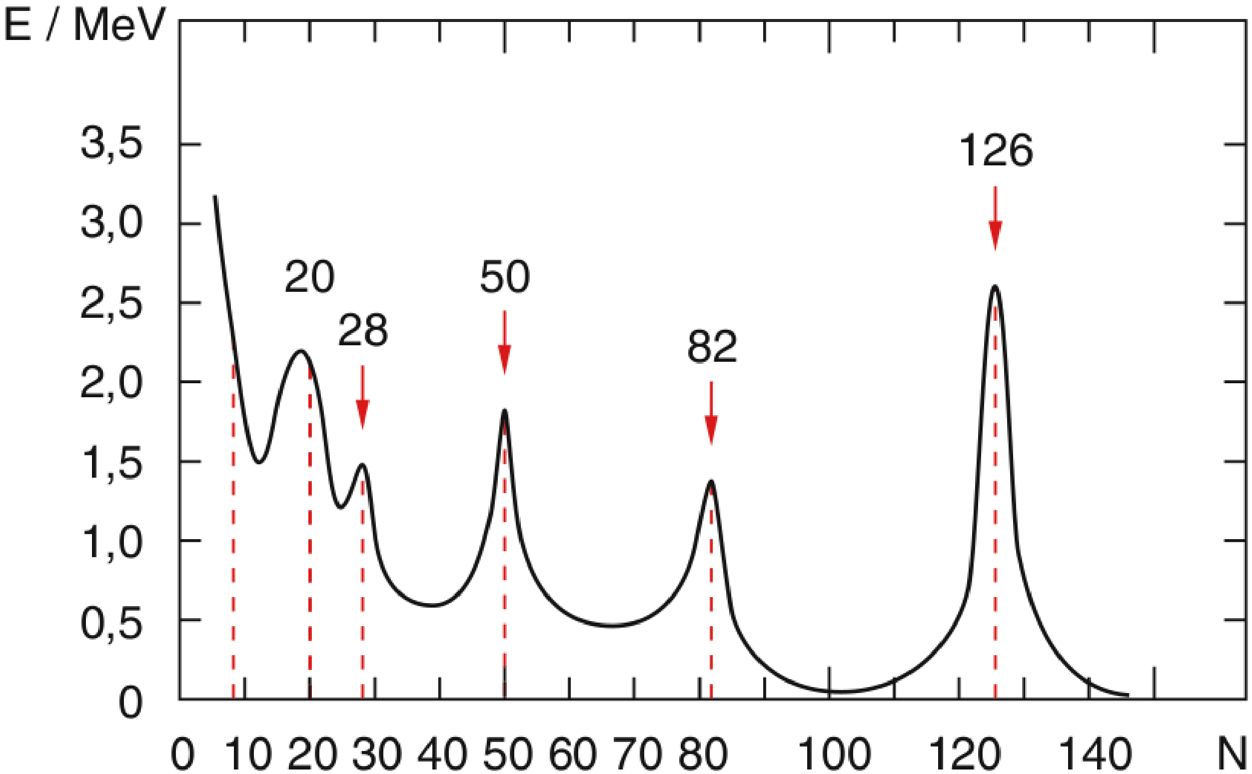
Table of nuclides



Today's definition:
„superheavy“ are nuclei with
$Z \geq 104$ (Rutherfordium, Rf)

2. Nuclear shell model

- Nuclei with certain proton and/or neutron numbers have remarkable properties:
  - · High excitation and separation energies for nucleons
  - · Large number of stable isotopes and isotones



Energy of the first excited level

- Magic numbers:
  Z = 2, 8, 20, 28, 50, 82
  N = 2, 8, 20, 28, 50, 82, 126

=> idea, that nucleons are arranged in shells

Single-particle shell-model

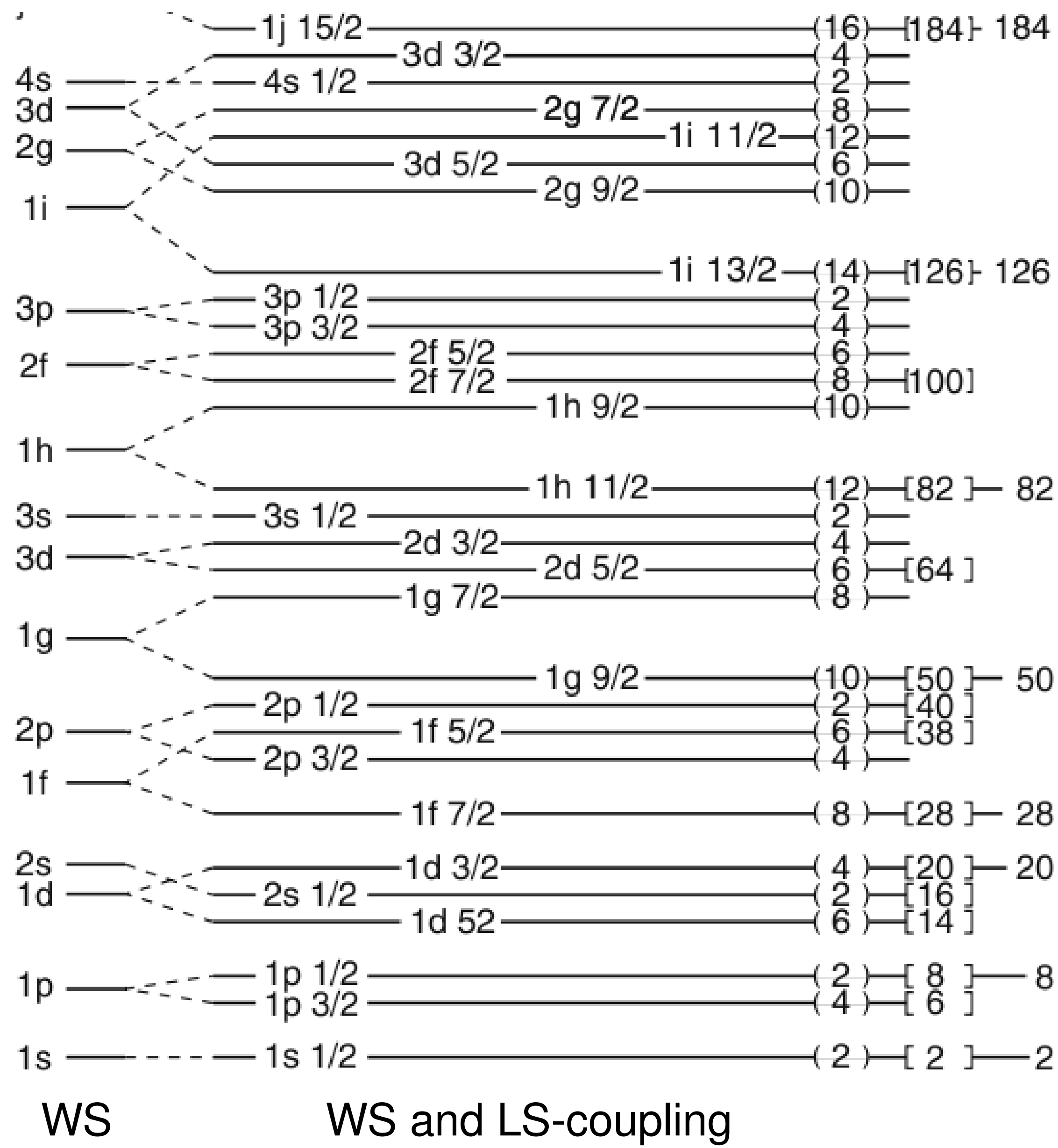
- Single-particle distribution

  Spherical potential (Woods-Saxon or harmonic oscillator), which is created by the other nucleons

- LS-coupling

  The correct magic numbers are received by taking into account the coupling of $\vec{L}$ and $\vec{S}$ due to the strong potential.

(Jensen and Haxel, Goeppert-Mayer; 1948)



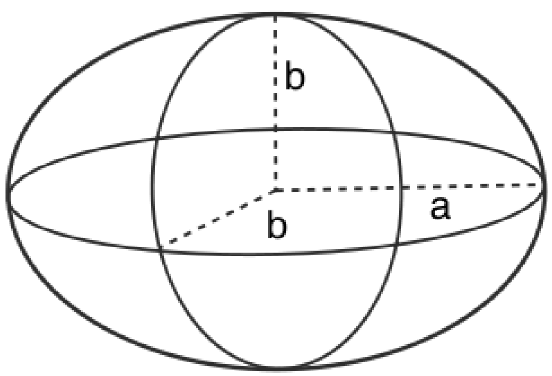
Nilsson-model

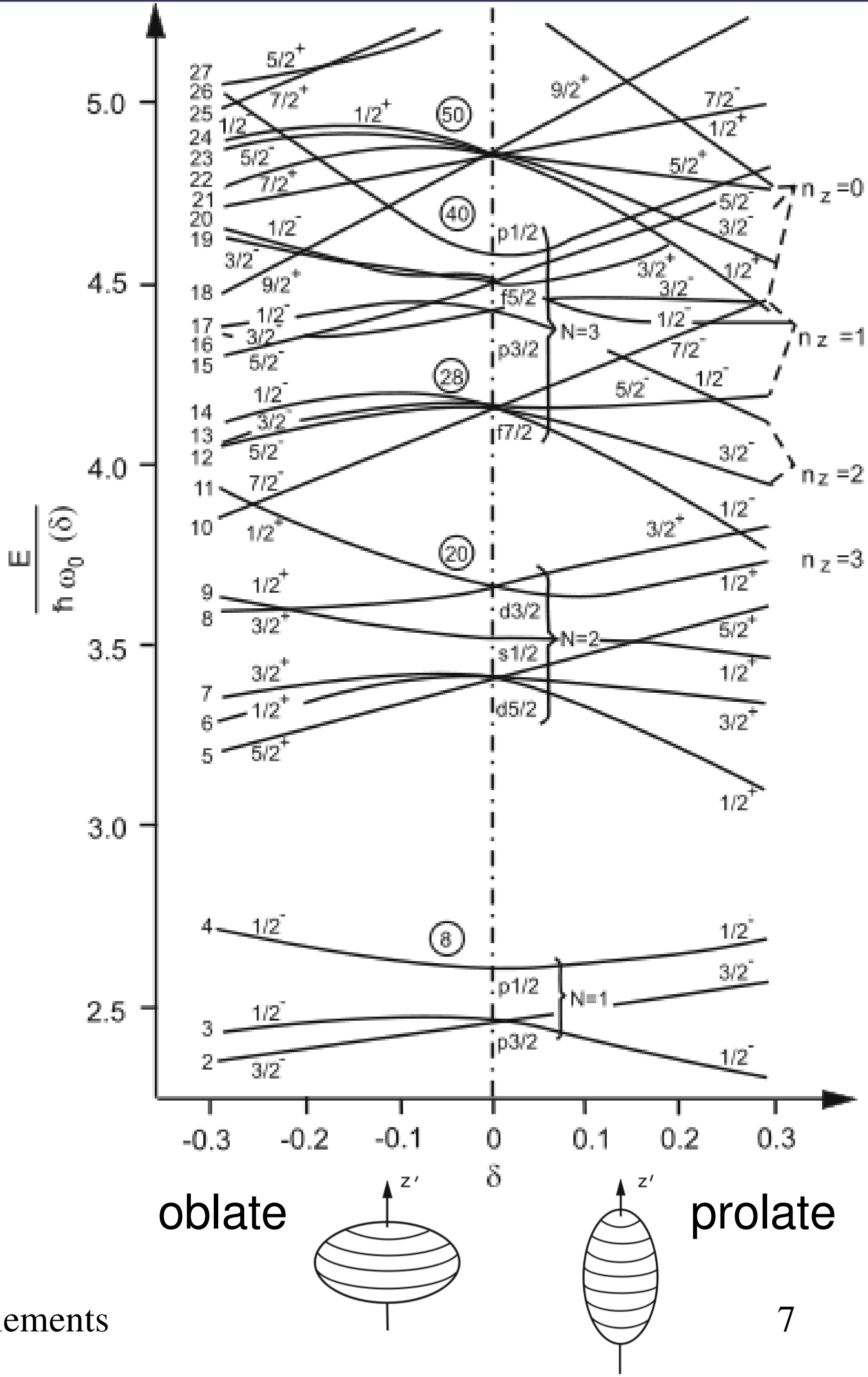
- Most heavy nuclei are not spherical, which is mainly due to the increasing coulomb-force between the protons.

=> spheroidal; deformation is described by

$$\delta = \frac{b-a}{R_0}$$

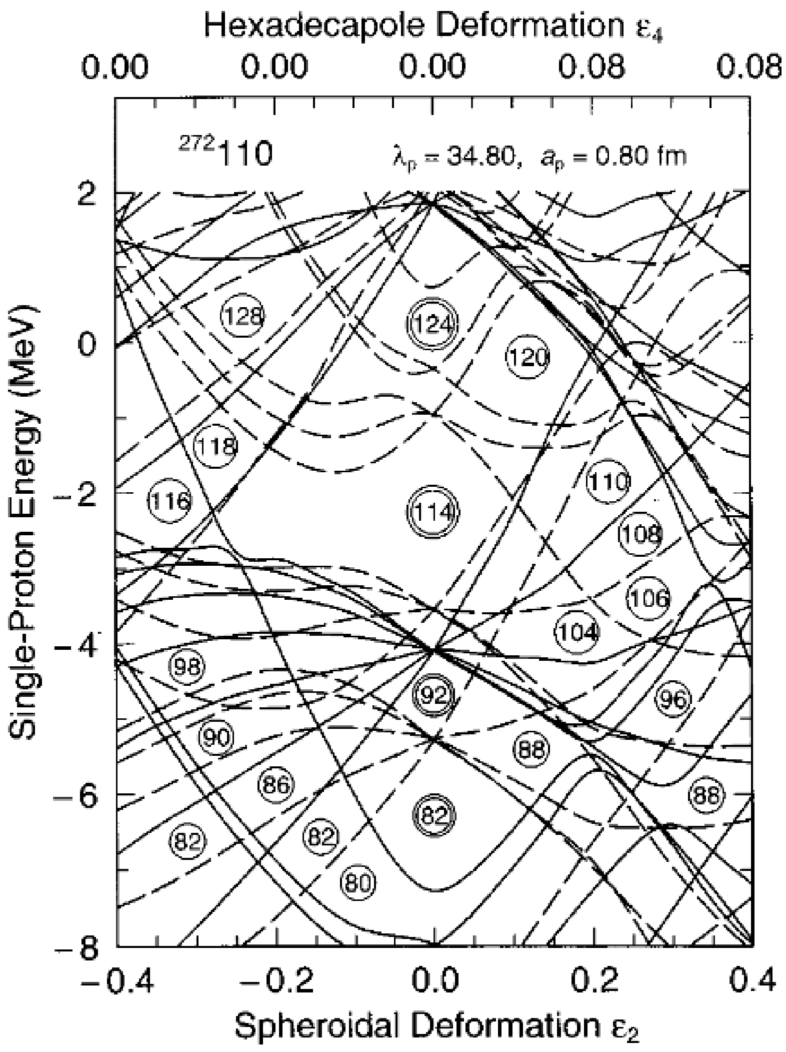
$$R_0 = \frac{a+b}{2}$$



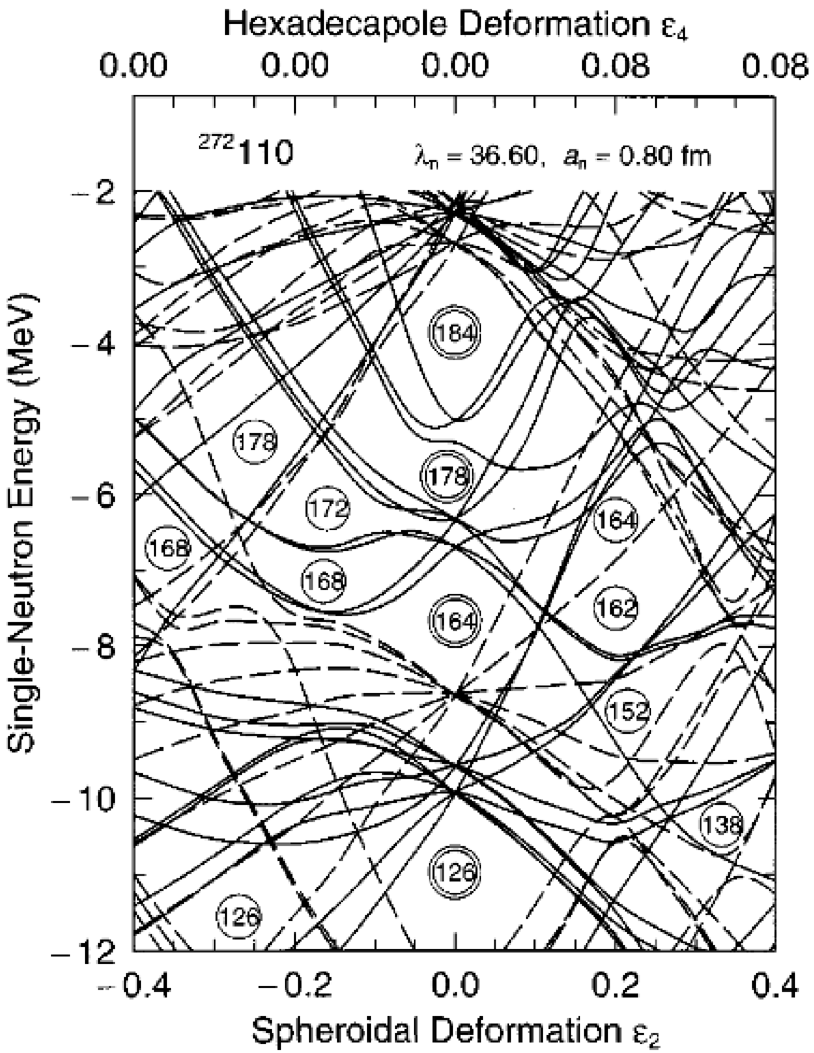


Nilsson-model (1955)

Nilsson-model



Calculated single nucleon energies dependent on deformation parameters ϵ_2 and ϵ_4 (multipole expansion)



Different theoretical methods agree with N = 184 for the next magic neutron number but the value for the next magic proton number is not as obvious (Z = 114, 120, 126).

3. Production of superheavy elements

- Heaviest (stable) natural element: Uranium (Z = 92)

- The next elements up to fermium (Z = 100) can be created by neutron capture and following β^-- decay.

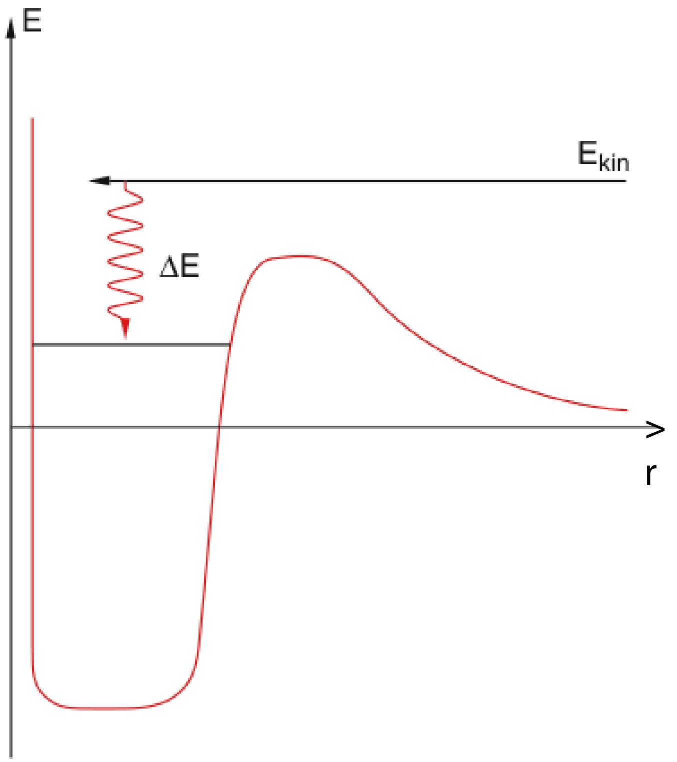
$$ {}^{238}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \longrightarrow {}^{239}_{92}\mathrm{U} \xrightarrow[23\ \mathrm{min}]{\beta^-} {}^{239}_{93}\mathrm{Np} \xrightarrow[2.355\ \mathrm{d}]{\beta^-} {}^{239}_{94}\mathrm{Pu} $$

- For elements with Z > 100 this process ends because of short lifetimes due fission and α - emission.

Nuclear fusion

Elements with Z > 100 can be obtained by fusion of heavy-ion projectiles and heavy-element targets.

General reaction: $a + A \rightarrow C^* \rightarrow B + b$

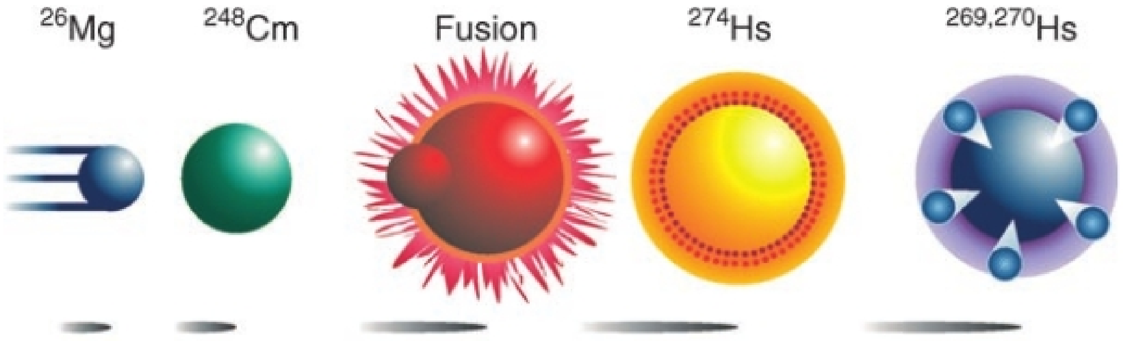


Two challenges:

- Coulomb-barrier between projectile and target has to be overcome
- Excitation energy of the Compound-nucleus has to be reduced (by evaporation of neutrons) to prevent spontaneous fission

Hot fusion

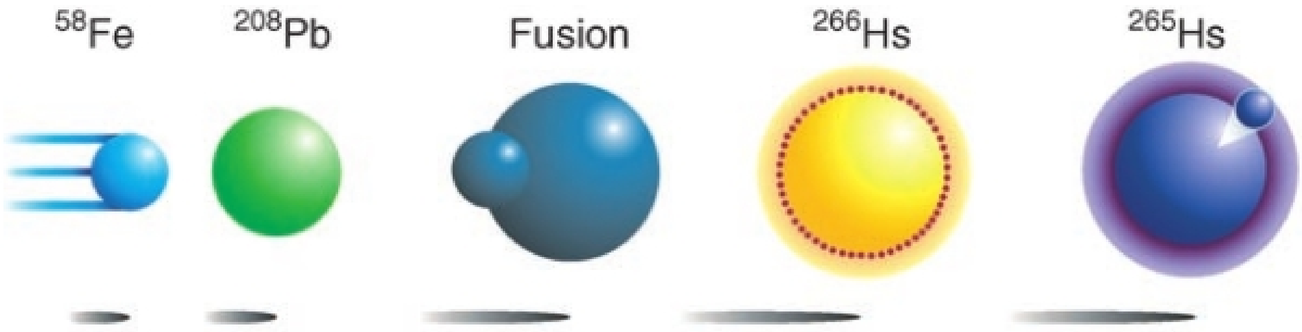
Hot fusion led to the discovery of the elements nobelium (Z = 102) to seaborgium (Z = 106) at the Lawrence Berkeley National Lab, California (Seaborg, Ghiorso).



- Light ions and actinoid targets (Z = 89 to Z = 99) are used
- Excitation energy of the Compound nucleus is about 40-50 MeV
- Evaporation of four or five neutrons reduces the excitation energy of the Compound nucleus below the fission barrier

Cold fusion

With the technique of the Cold fusion, the elements bohrium (Z = 107) to Z = 112 (not yet named) were produced at GSI, Darmstadt (Armbruster, Münzenberg, Hofmann).



- Medium heavy projectiles like isotopes of Fe, Ni or Zn are accelerated and shot on lead (Z = 82) or bismuth (Z = 83)

- Excitation energy of the Compound-nucleus is only 10-15 MeV

- Evaporation of one neutron is necessary to prevent the Compound-nucleus from spontaneous fission

Excitation energies

Estimation of the excitation energy:

$$E^* = E_{Beam} + \Delta mc^2$$

The beam energy can be approximated with the Coulomb energy

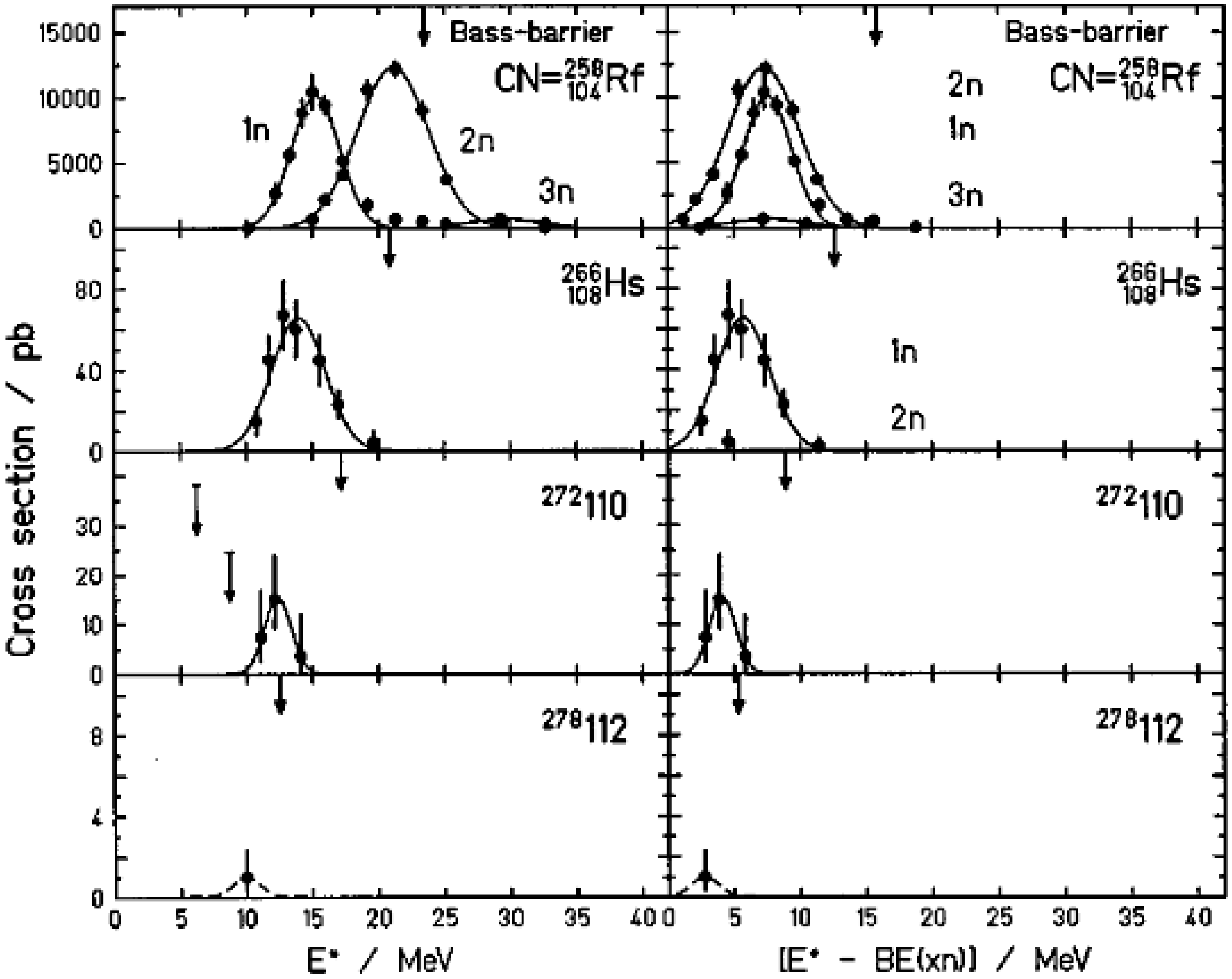
$$E_{Coul} = \frac{q_p q_t}{4\pi\epsilon_0 (R_p + R_t)}$$

The mass-difference before and after the fusion is

$$\Delta m = m_p + m_t - m_{RP}$$

=> for the hot fusion on slide 11: $E^* = 55{,}7\, MeV$

Excitation functions

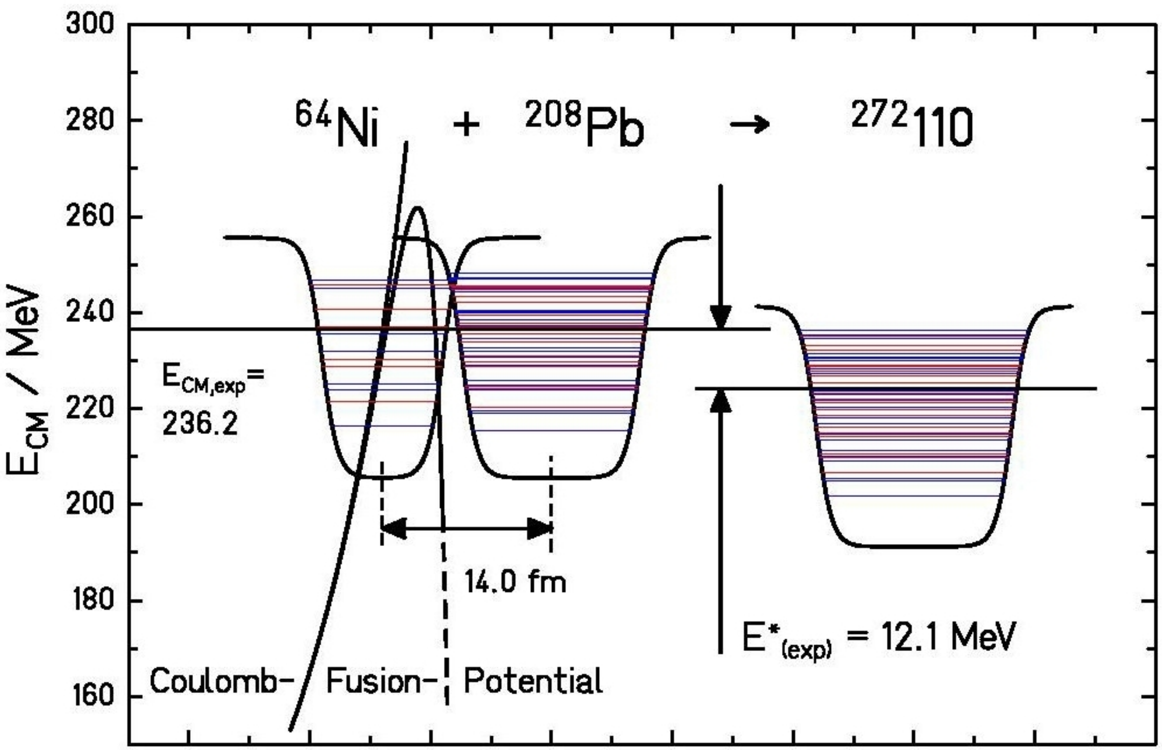


- The cross section is very low and decreases with higher Z (by a factor 10^4 from Z = 104 to Z = 112)
- For cold fusion, the highest cross section was measured for beam energies *below* the fusion-barrier.

Fusion initiated by transfer

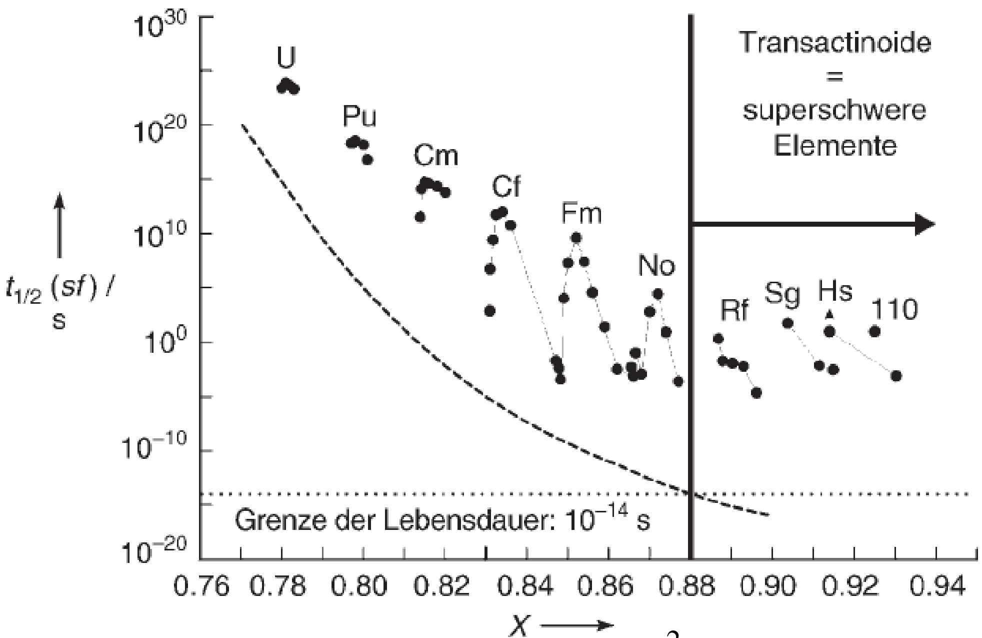
- Below the barrier, the kinetic energy (CMS) is converted into potential energy until the reaction partners come to rest in the CMS.
- At this touching configuration, only nucleons on the outer surface are in contact.

Fusion Initiated by Transfer (FIT)



- Transfer of some nucleons (usually pairs) reduces the Coulomb-barrier allowing the fusion.

Decay properties of SHE's

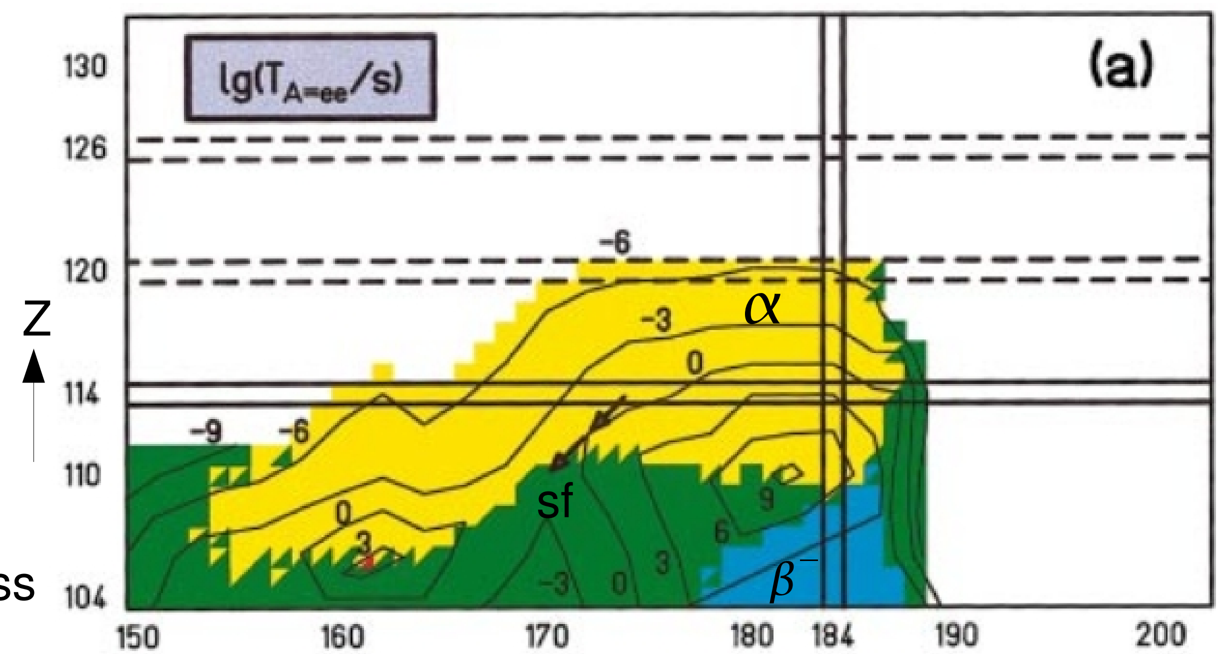


- Superheavy elements exist only because of nuclear shell- corrections to the Liquid-Drop- Model.

They are a lot more stable against fission than predicted by the LDM.

Fissility parameter $X \propto \dfrac{Z^2}{A}$

- In the region of superheavy elements, α - decay is the dominant decay process.



Calculated half-life and dominant decay-process

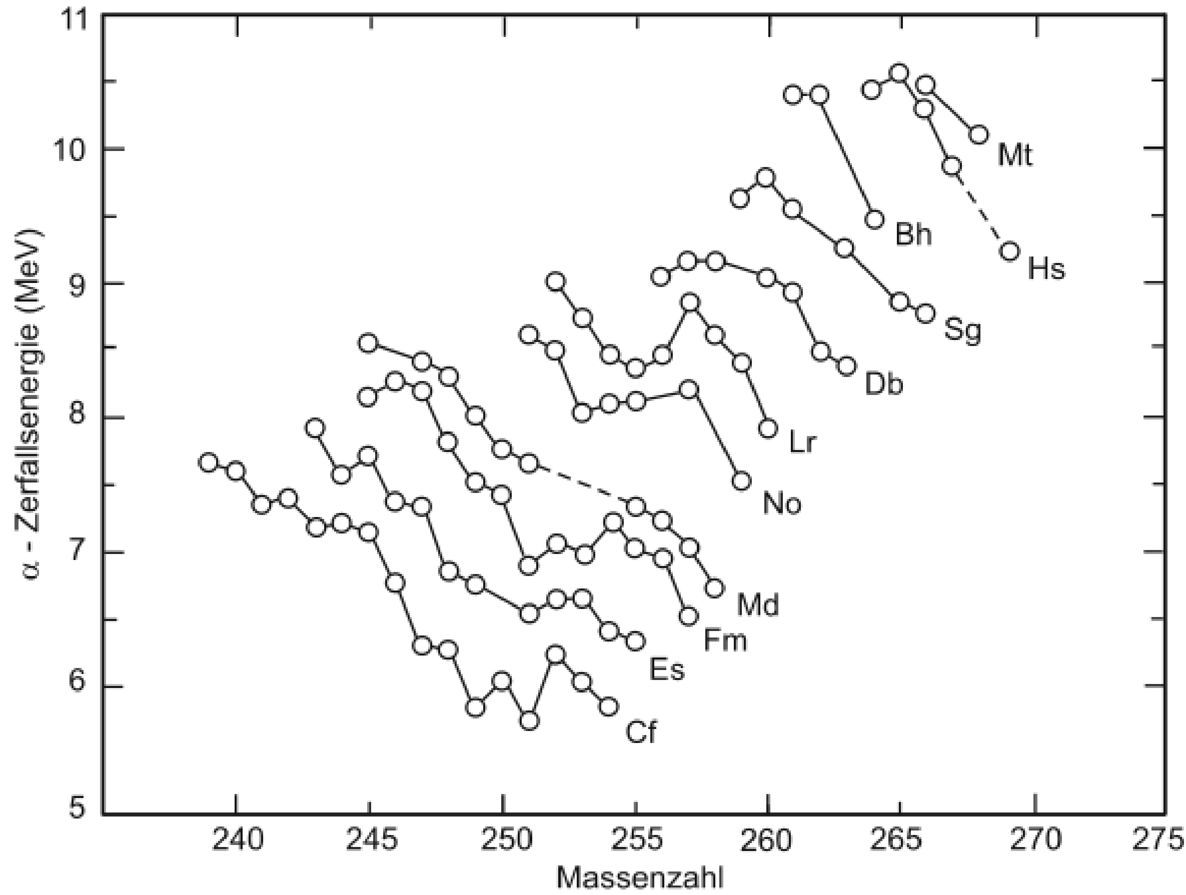
N

Alpha - decay

- Superheavy elements are α - emitter

- The energy of the α - particle is discrete and characteristic for each nuclei

=> Measurements of α - decay chains allow for the identification of the original nuclei



Next steps

- Creation of superheavy elements

  => ion source
  accelerator
  target

- Separation and detection of the reaction products

  => separation filter
  detector system for α- decay

4. Experiments at GSI

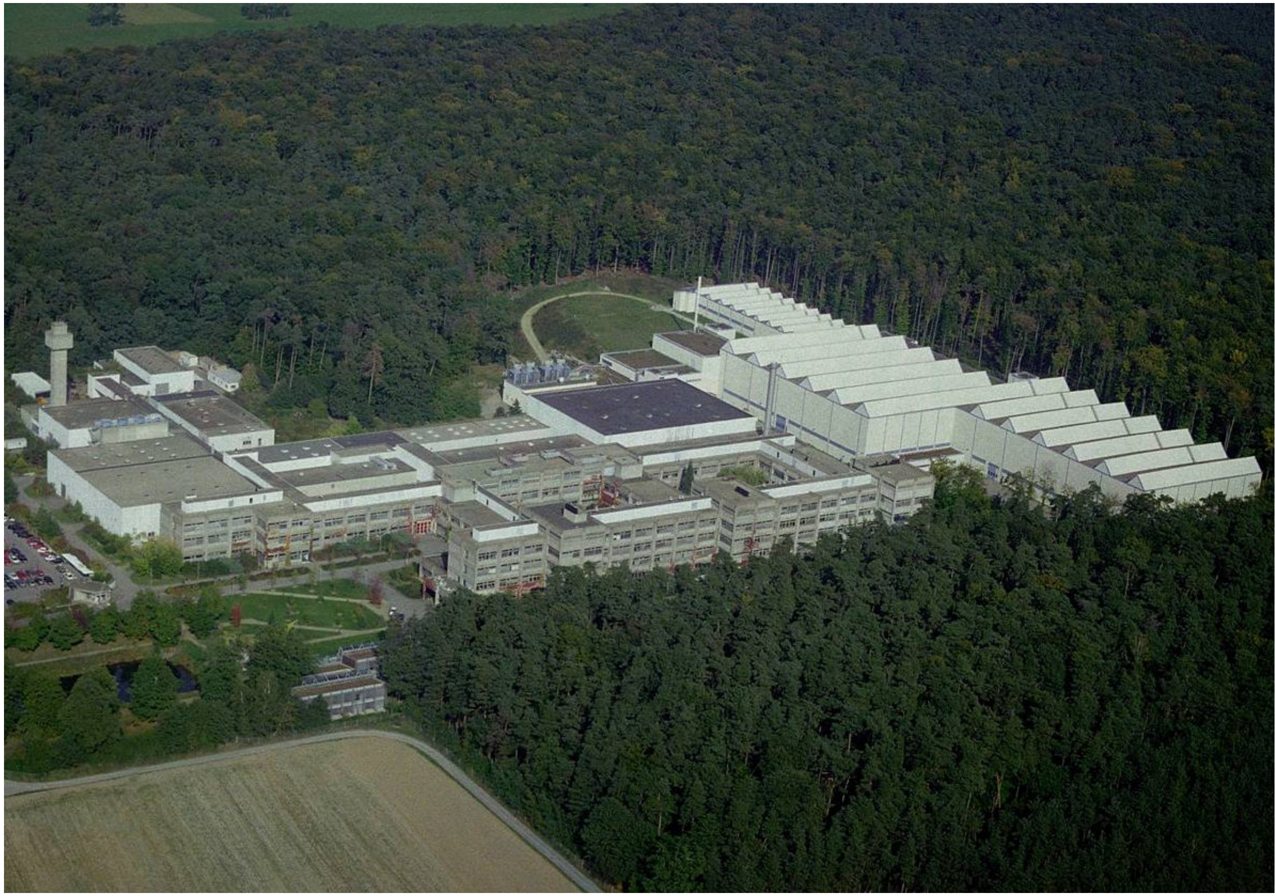
Helmholtz Center for Heavy-Ion Reasearch , Darmstadt

(Gesellschaft für Schwerionenforschung, GSI)

- One of the few laboratories in the world, where heavy ions can be accelerated

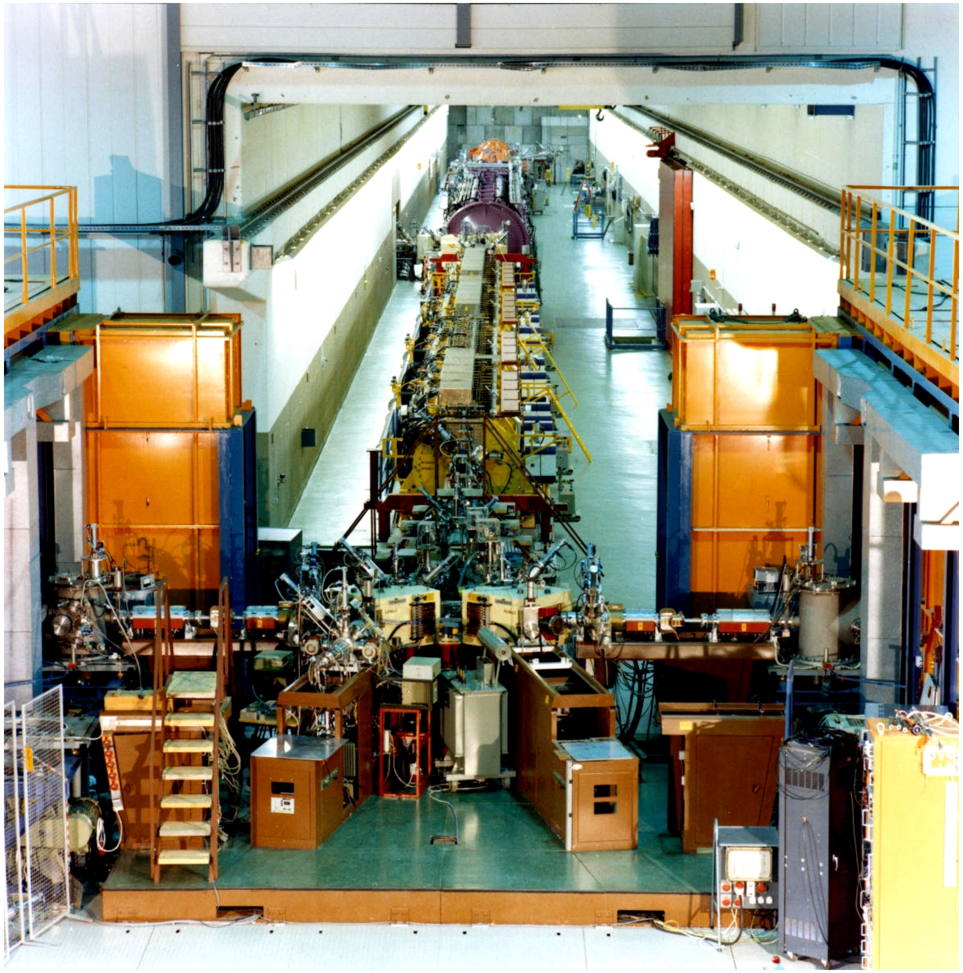
- research program:

  · Nuclear and atomic physics
  · Plasma and materials research
  · Medical and biophysics



UNILAC

Universal Linear Accelerator



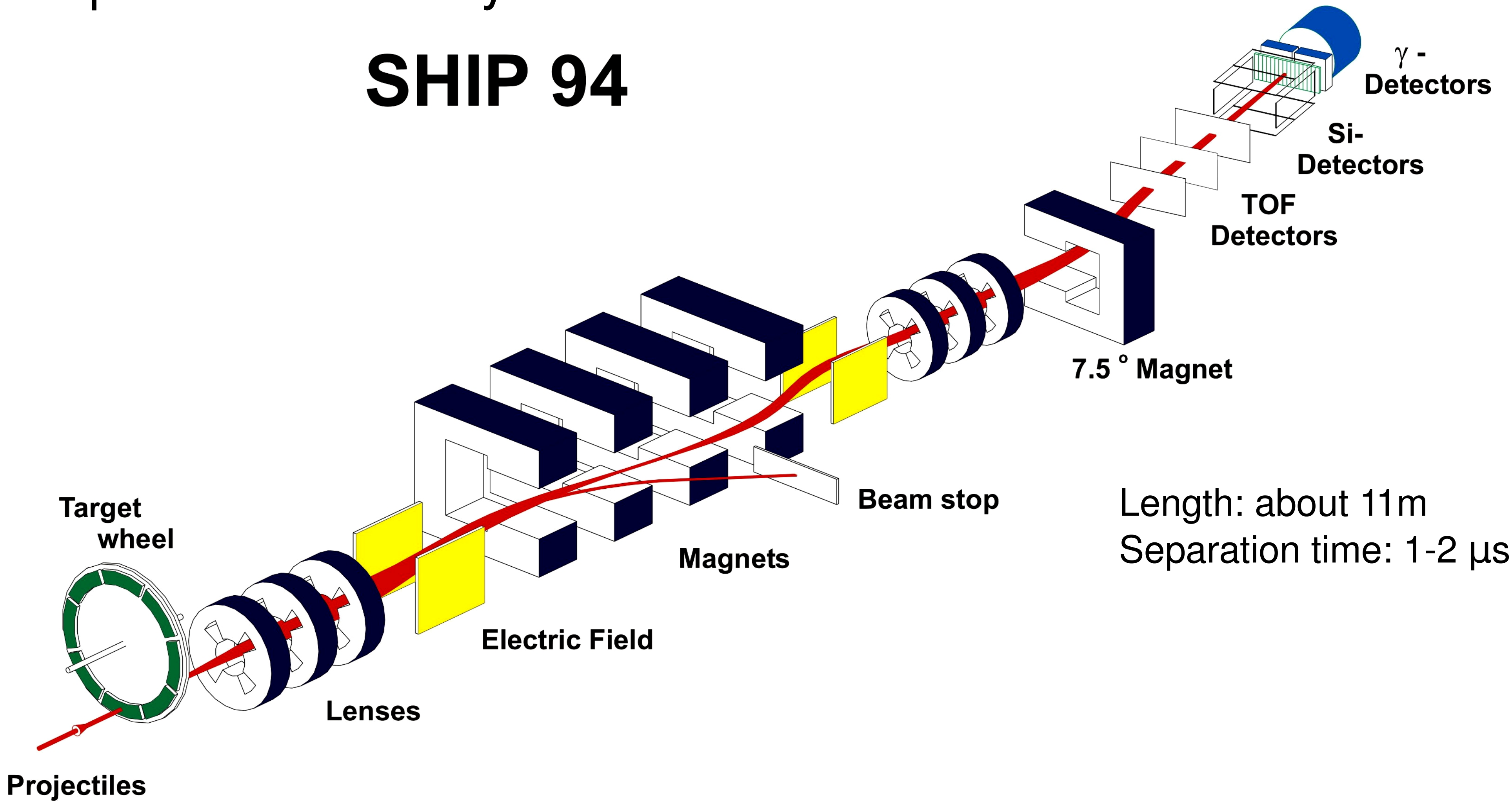
- Ion source: Electron cyclotron resonance (ECR) causes ionisation of atoms in a low pressure gas. Multiple ionisation is possible, e.g.

$$^{58}Fe^{8+},\ ^{70}Zn^{10+},\ ^{82}Se^{12+}$$

- Accelerator:
  - particles from protons to uranium with energies up to 11,4 MeV/u
  - about 10^{13} particles/s in the target area (for cold fusion)

SHIP

Separator for Heavy Ion reaction Products



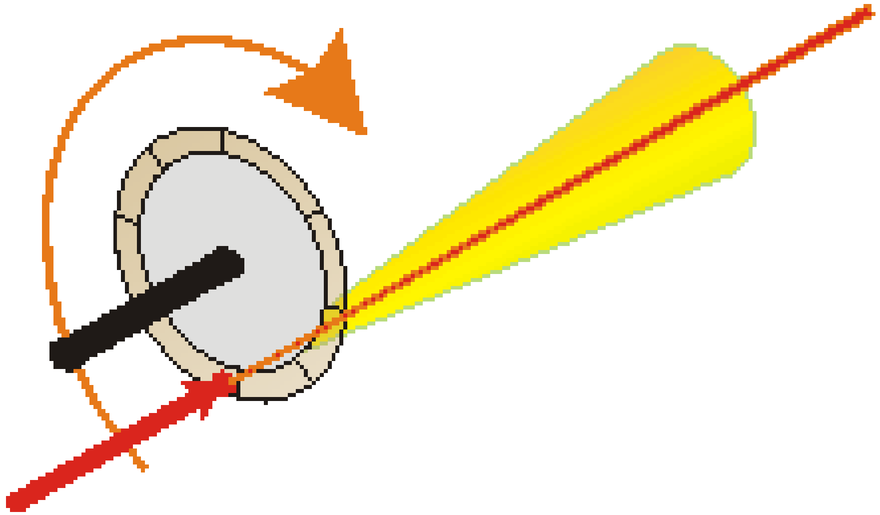
Length: about 11m
Separation time: 1-2 µs

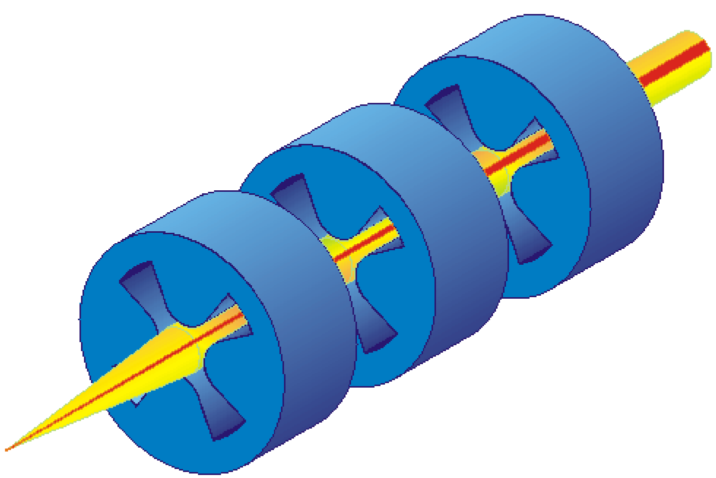
SHIP is a velocity filter, only particles with a certain velocity get through.

Target

- Thin foils of Pb (Z = 82) and Bi (Z = 83) targets are used (cold fusion)

- Low melting points of both materials
  => maximum beam intensity is limited to
  currently 2×10^{12} particles/s





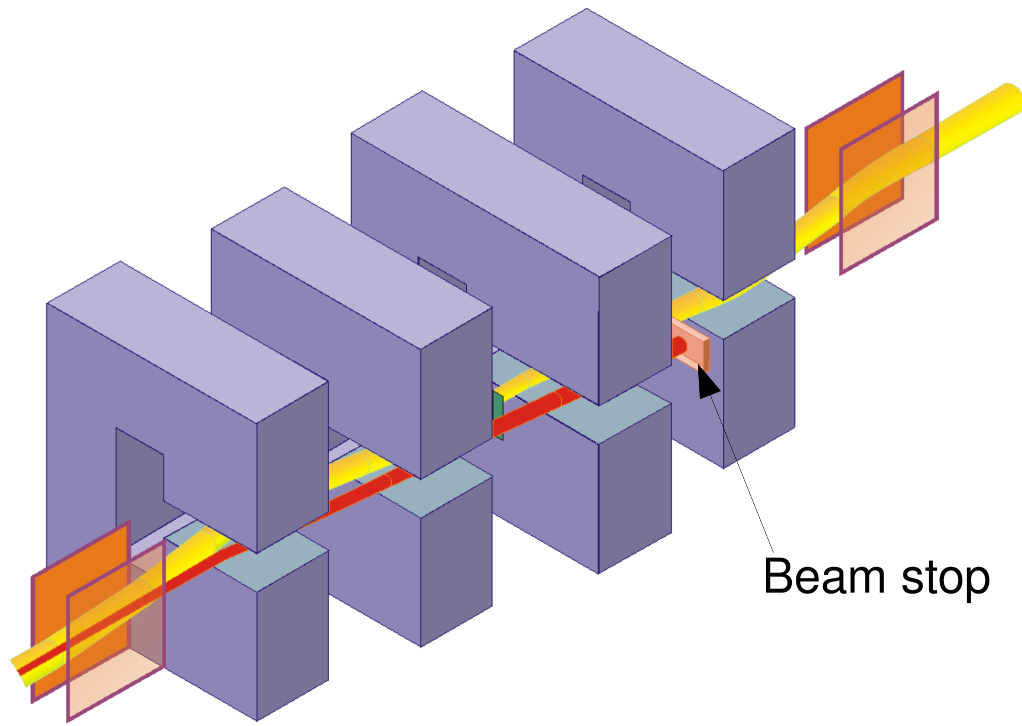
- The reaction products show an angular distribution caused by scattering in the target and neutron evaporation

- Quadrupole lenses focus the beam

Velocity filter

- Momentum conservation:

$$v_{RP} = \frac{m_p}{m_p + m_t} v_p$$



- A combination of electric and magnetic fields allow only particles with a certain velocity to pass.

$$F_{mag} = F_{el} \Leftrightarrow v = \frac{E}{B}$$

Electric deflectors: $\pm 330\ kV$
Dipole magnets: $0.7\ T$ max

- Independent of the electric charge and mass!

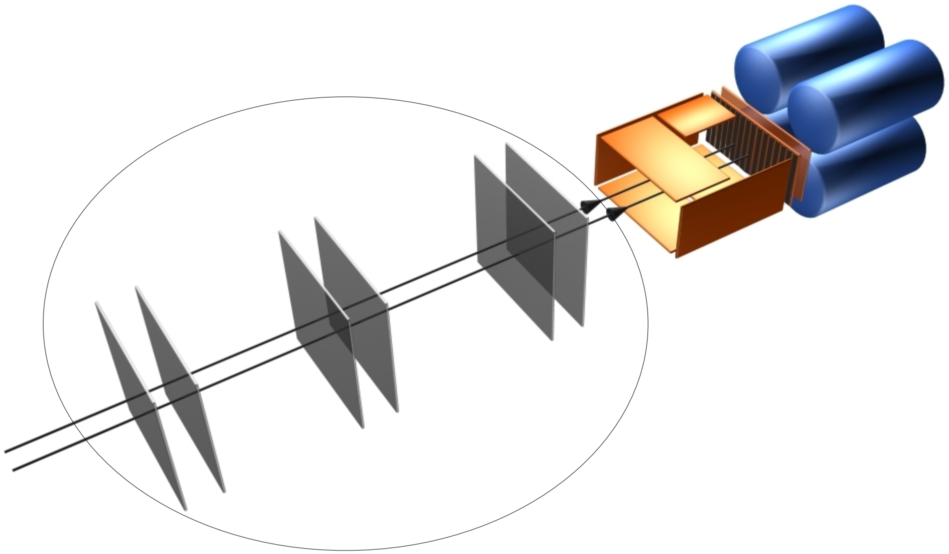
=> slow beam particles may pass the velocity filter

Detectors

Time-of-flight detector

- To distinguish between signals created by α - particles and signals from beam particles

=> only anticoincident signals between Si - and TOF - detector are taken into account

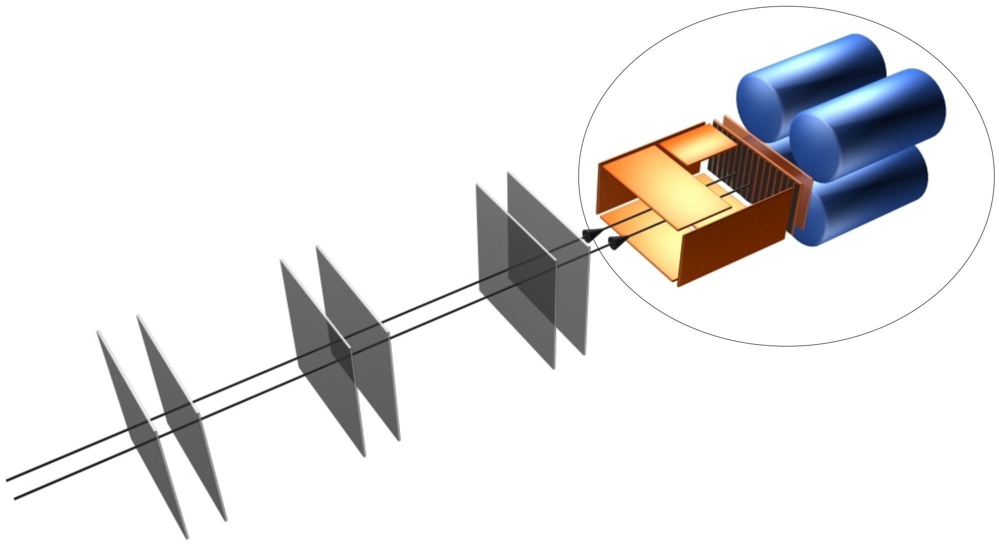


- Consists of three pairs of thin carbon foils
- Efficiency is nearly 100%

Detectors

Silicon detector

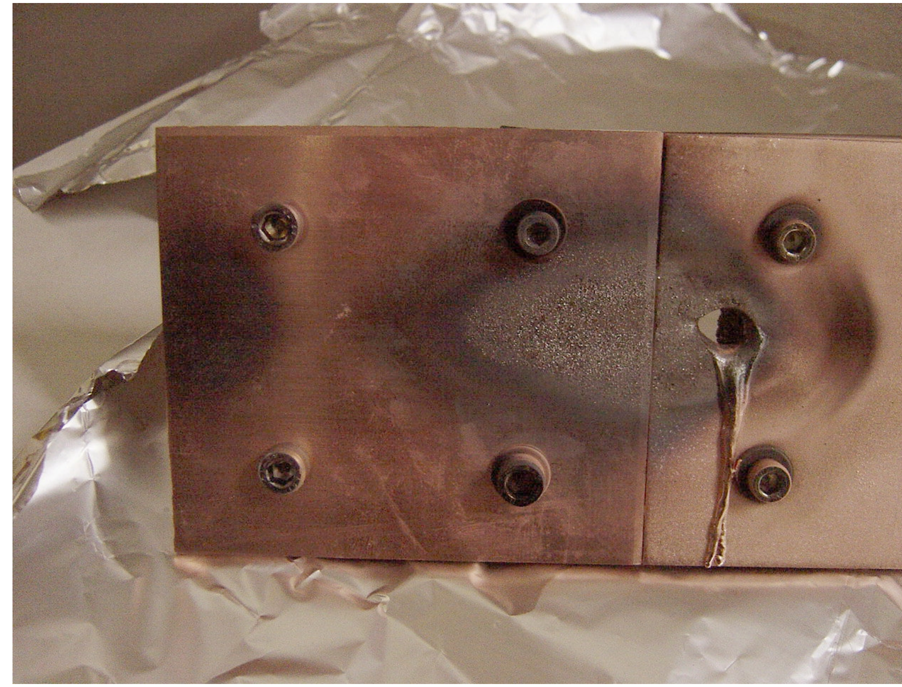
- Reaction products are stopped (Bethe-Bloch) in the detector
- α - energies are measured

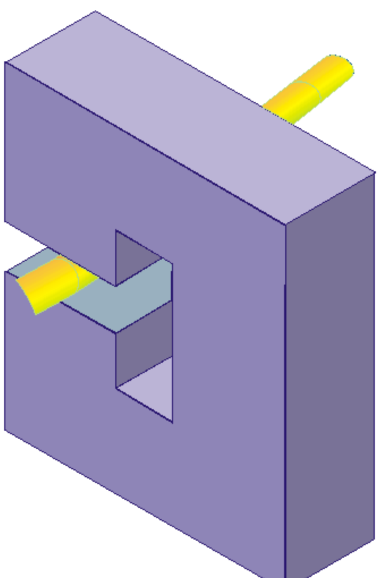


- Advantages of silicon:
  - · High energy resolution: $\Delta E = 40\, keV$ for α - particles
  - · Position senstive: $\Delta x = 150\, \mu m$

Background

- Up to ٢×١٠^{١٢} particles/s in target area
- Velocity filter suppresses the original beam intensity by a factor $10^{٧} - ١٠^{١١}$ (beam stop)



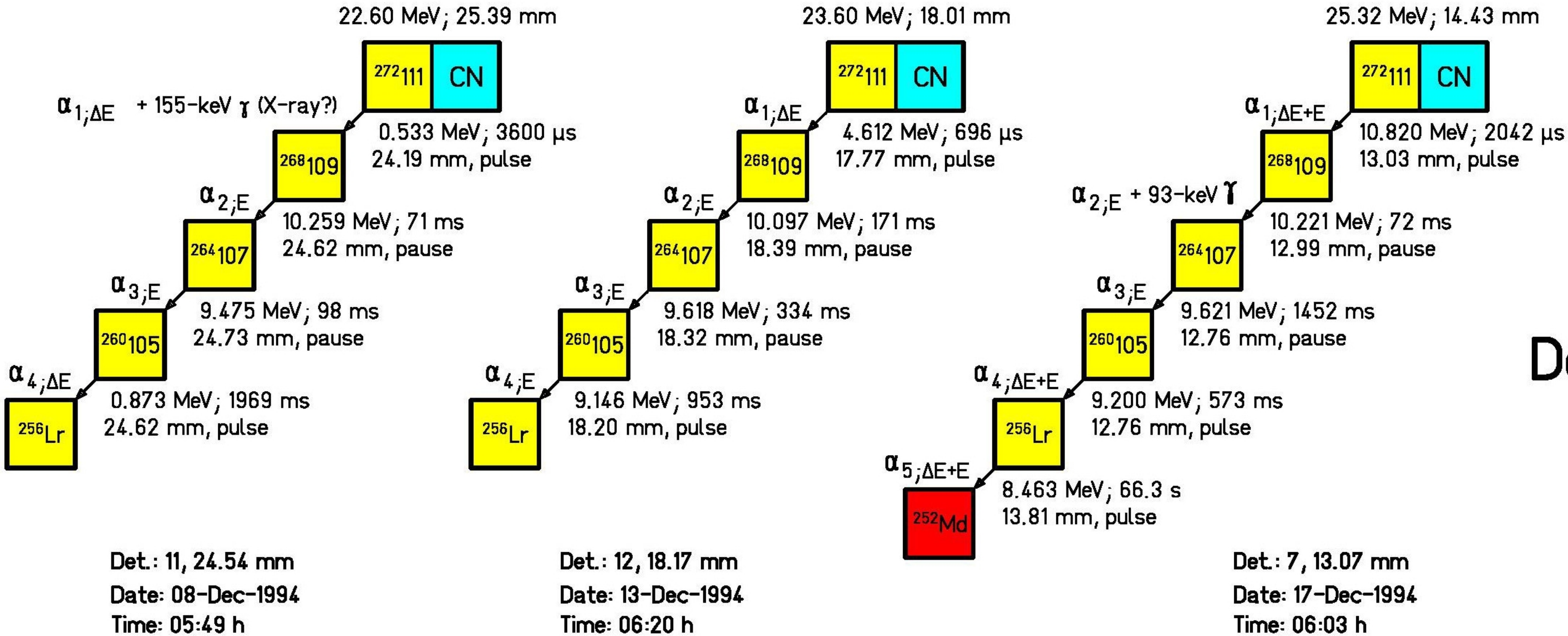


- Beam particles are deflected differently by an additional bending magnet than the reaction products

=> background of about 1 particle/min is left

5. Results on elements 111 and 112

$$^{64}\mathrm{Ni} + {}^{209}\mathrm{Bi} \rightarrow {}^{272}111 + 1n$$



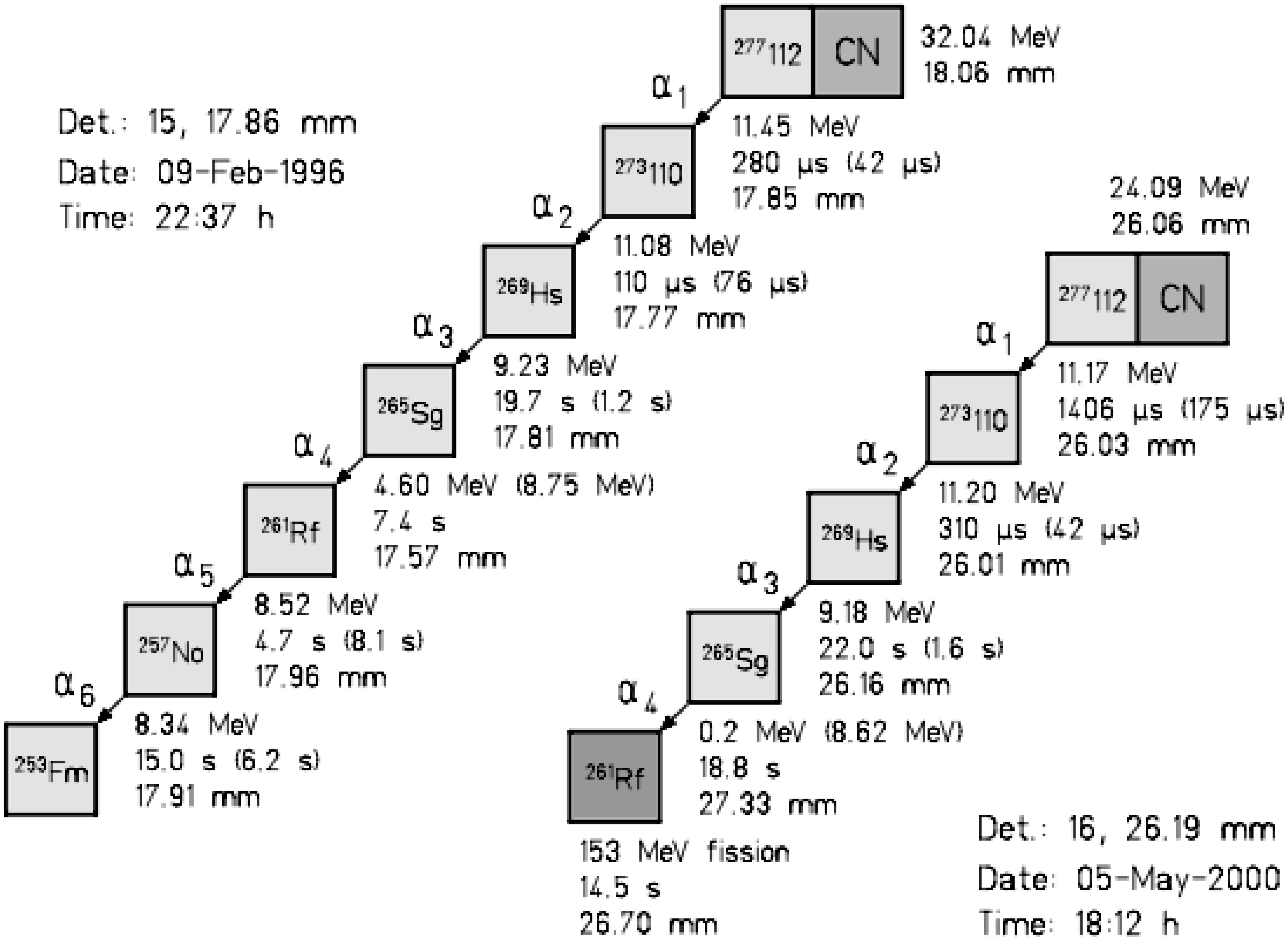
Dec. 1994

The irradiation time was 17 days => a total of only three decay-chains was measured

5. Results on elements 111 and 112

Date	Time (day)	Target isotope	Thickness ($\mu g/cm^2$)	Beam isotope	E_{proj} (MeV)	Compound nucleus	E^* (MeV)	Ion dose (10^{18})	Observed events	σ (pb)
01.12.–06.12.1994	5.0	^{209}Bi	450	^{64}Ni	316.1	$^{273}111$	9.4	1.0	0	< 2.9
06.12.–12.12.1994	5.8				318.1		11.0	1.1	1	$1.7^{+3.3}_{-1.4}$
12.12.–18.12.1994	5.9				320.0		12.5	1.1	2	$3.5^{+4.6}_{-2.3}$

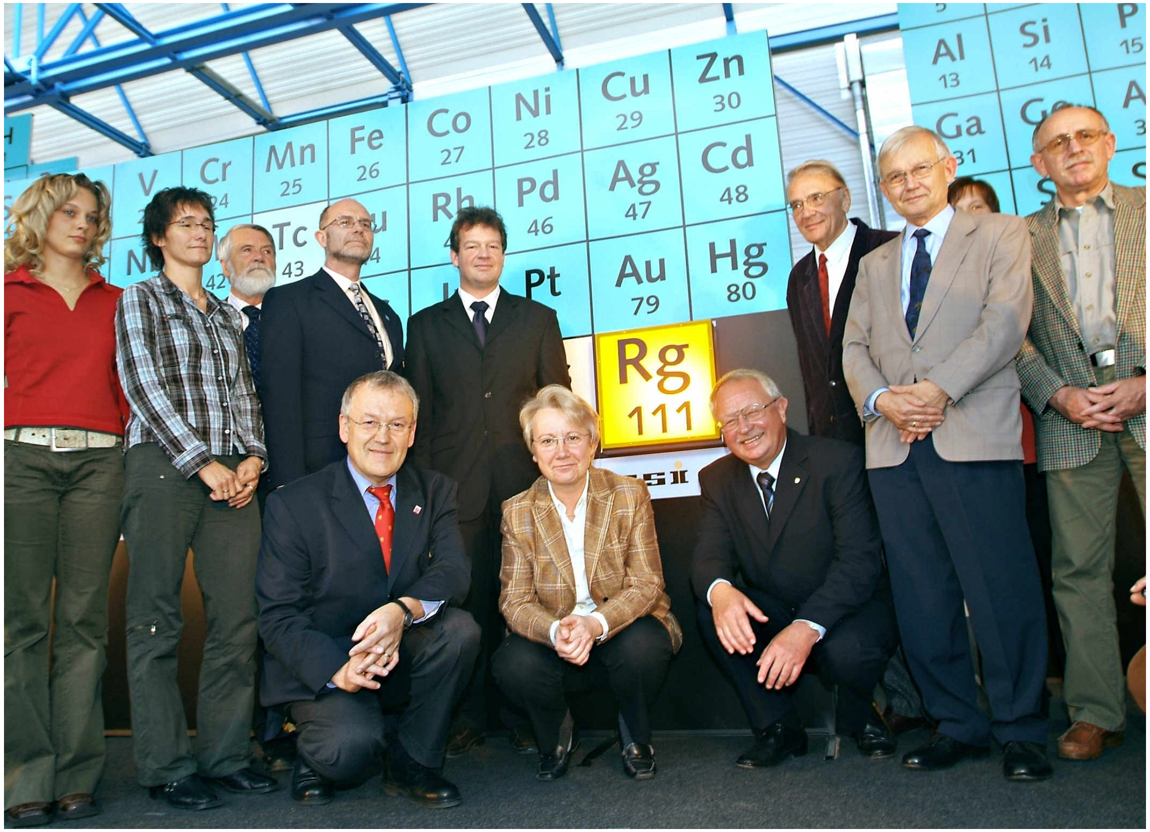
- The beam energy was varied to obtain higher cross sections.
- The measured half-life is $(1.5^{+2.0}_{-0.5})\ ms$.
- In a second experiment in 2000, the results were reproduced (again three decay-chains were measured) and officially confirmed.



The two measured decay chains of element 112 (not yet named) by using the reaction $^{70}Zn + ^{208}Pb \rightarrow ^{277}112 + 1\mathrm{n}$

5. Results on elements 111 and 112

Official naming of element 111 (roentgenium)



Darmstadt, June 10, 2009

A New Chemical Element in the Periodic Table

The element 112, discovered at the GSI Helmholtzzentrum für Schwerionenforschung (Centre for Heavy Ion Research) in Darmstadt, has been officially recognized as a new element by the International Union of Pure and Applied Chemistry (IUPAC).

(www.gsi.de/portrait/Pressemeldungen/10062009-2_e.html)

6. Summary

Elements made at GSI

Atomic number	Name	Symbol	Generation	Half-life of the longest-living Isotope
107	Bohrium	Bh	February 24, 1981	17 s
108	Hassium	Hs	March 14, 1984	25 s
109	Meitnerium	Mt	August 29, 1982	42 ms
110	Darmstadtium	Ds	November 9, 1994	56 ms
111	Roentgenium	Rg	December 8, 1994	6.4 ms
112	prel. Ununbium	Uub	February 9, 1996	0.6 ms

(status: June 2009)

- Experiments have shown that the cross section for the synthesis of superheavy elements decreases almost continuously with higher Z

  => Improvements on beam, target and separator required to create heavier elements

References

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