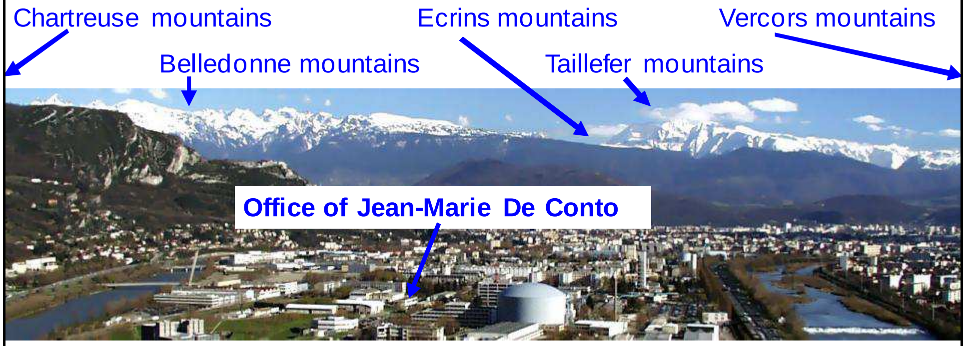
Electromagnetic separators

Ulli Köster

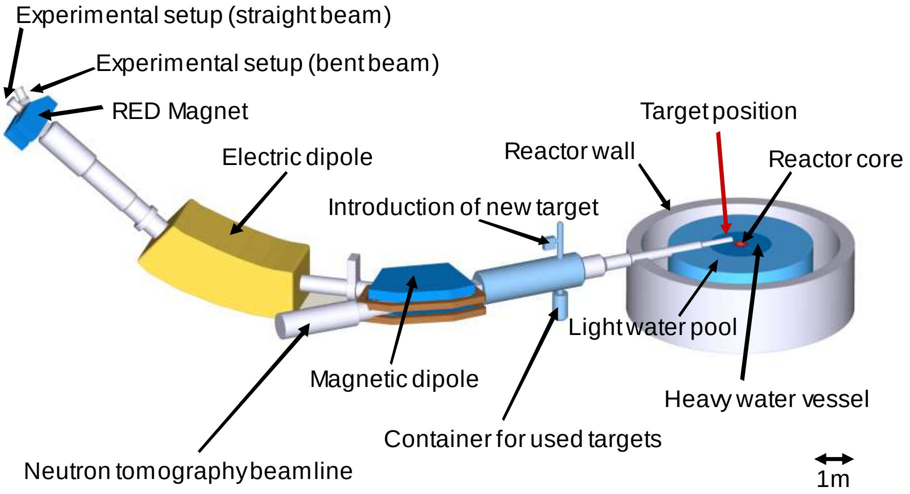
Institut Laue-Langevin
Grenoble, France

Institut Laue-Langevin

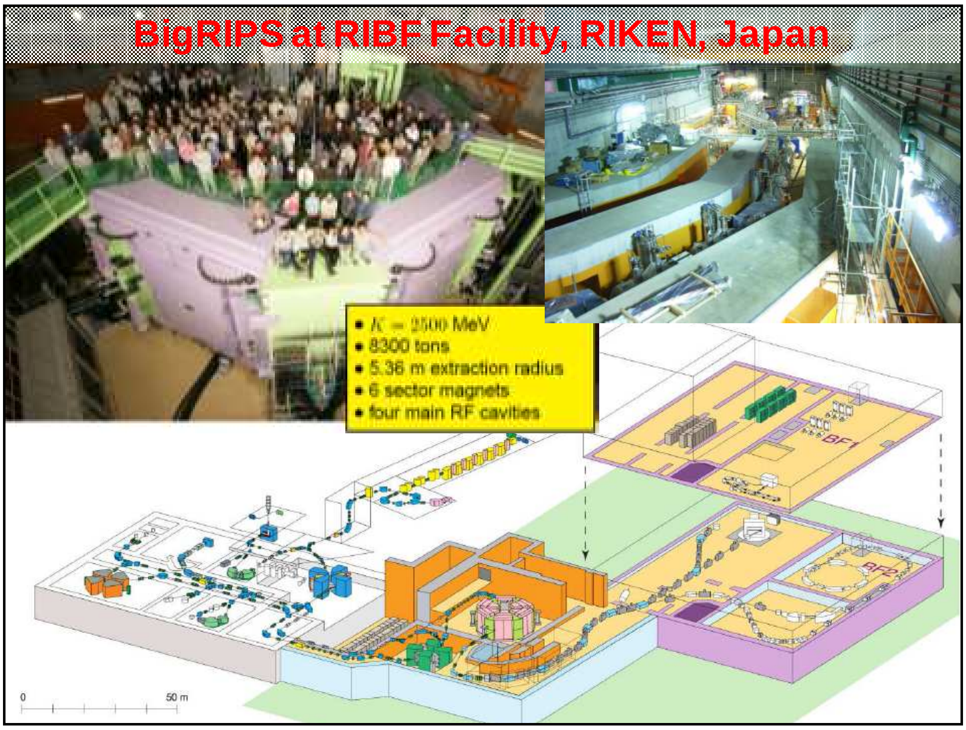


- **founded 1967**
- **today 13 member states**
- **operates most powerful neutron source of the world:**
  58 MW high flux reactor, 1.5·10^{15} n./cm^2/s maximum neutron flux
- **over 40 instruments, mainly for neutron scattering**
- **user facility: 2000 scientific visitors from 45 countries per year**
- **Nuclear physics instruments: LOHENGRIN, GAMS, (PF1B)**

LOHENGRIN: an electromagnetic separator

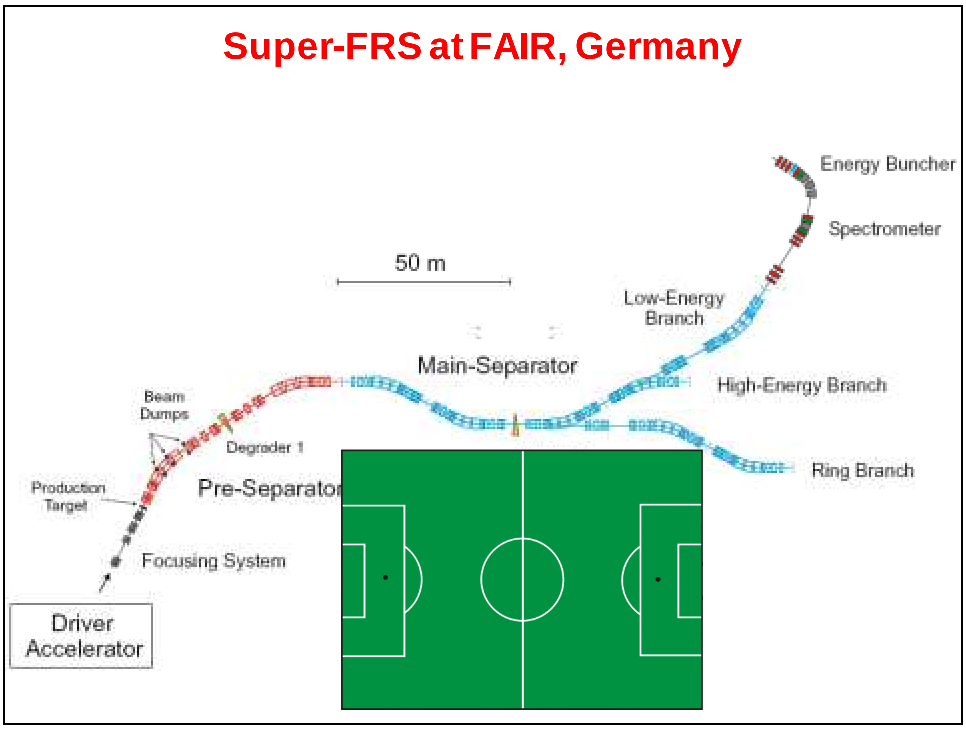


Electromagnetic separators at GANIL



BigRIPS at RIBF Facility, RIKEN, Japan

- $K = 2500$ MeV
- 8300 tons
- 5.36 m extraction radius
- 6 sector magnets
- four main RF cavities



Super-FRS at FAIR, Germany

Importance of electromagnetic spectrometers

Outline

1. **Definitions and history**
2. **Basics of ion optics and dispersive elements**
3. **Static fields**
    a) deflection spectrometer
    b) retardation spectrometer
4. **Dynamic fields/separation**
    a) Time-of-Flight spectrometer
    b) Radiofrequency spectrometer
    c) Traps
5. **Technical realization (ion sources, etc.)**
6. **“Real examples” for nuclear physics applications**
    a) ISOL
    b) Recoil separators
    c) Fragment separators
    d) Spectrometer

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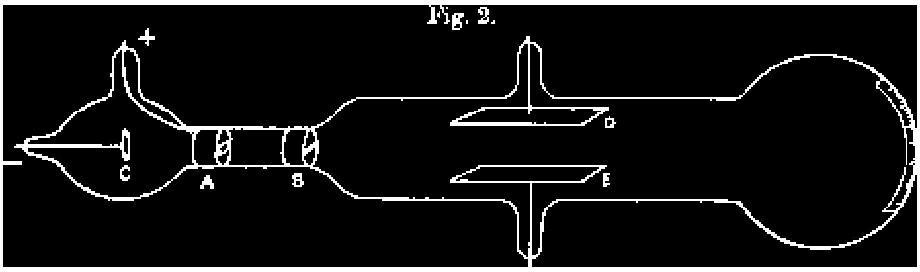
Definitions

- spectrometer: electrical detection
- spectrograph: photographic or other non-electrical detection
- also used: spectroscope

- mass / energy / isotope separator: assures a physical separation of different masses / energies / isotopes

Thomson 1897: cathode rays



“Cathode rays”, J.J. Thompson, Phil. Mag. 44 (1897) 293.

Noble prize in physics 1906 for discovery of the electron and the determination of its m/q ratio.

Goldstein 1886: *Kanalstrahlen*

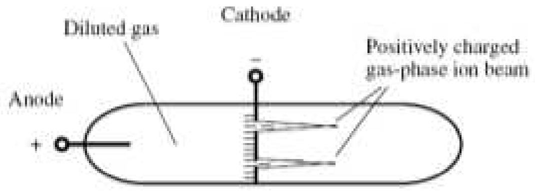
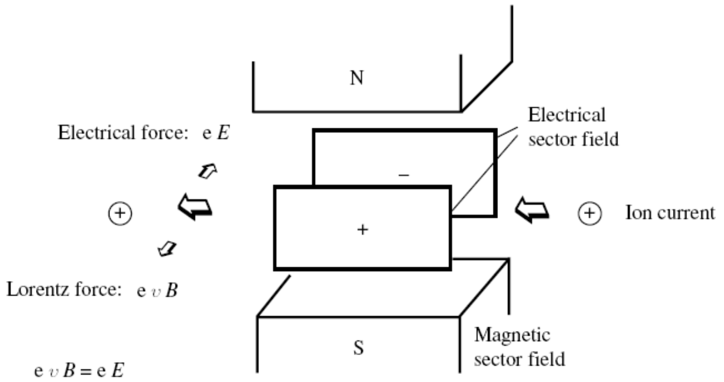


Figure 1.3 Goldstein's glow discharge tube (1886) for generation of positively charged ions. (C. Brunnée, Int. J. Mass. Spectrom. Ion Proc. 76, 125 (1987). Reproduced by permission of Elsevier.)

First fluorescent lamp and ion source.

Wien 1902: Wien filter



$$e\,\upsilon B = e\,E$$

$$\upsilon = \frac{E}{B}$$

Electric field perpendicular to magnetic field

Figure 1.4 Schematic of a Wien velocity filter with EB configuration: combination of electric (E) and magnetic (B) field (Wien,1898). (C. Brunnée, Int. J. Mass. Spectrom. Ion Proc. 76, 125 (1987). Reproduced by permission of Elsevier.)

Wien: Nobel price in physics 1911 for discovery that "Kanalstrahlen" carry positive charge

Thomson 1910: parabola mass spectrograph

Electric field parallel to magnetic field

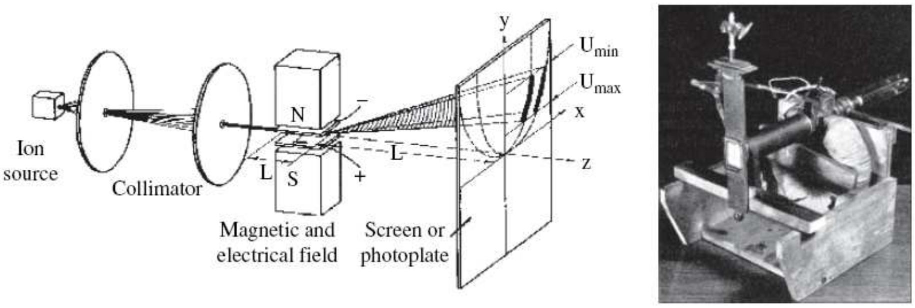


Figure 1.5 *Parabola mass spectrograph constructed by J. J. Thomson (1910) with a discharge tube as ion source, a superimposed electrical field and a magnetic field oriented parallel to it for ion separation, and a photoplate for ion detection. (H. Kienitz (ed.), Massenspektrometrie (1968), Verlag Chemie, Weinheim. Reproduced by permission of Wiley-VCH.)*

Neon consists of two isotopes with mass 20 and 22

Thomson 1913: mass spectrum of neon

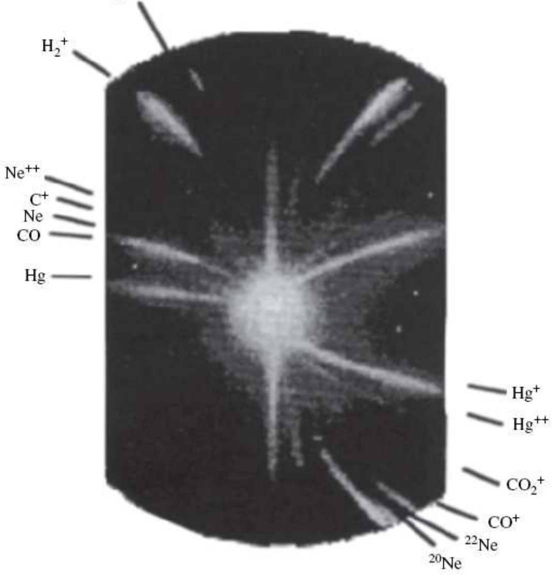
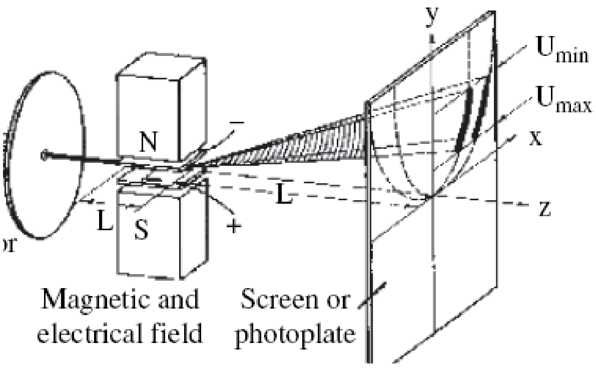


Figure 1.6 *Mass spectrum of neon with masses 20 and 22 u measured by J. J. Thomson (1913) using his parabola mass spectrograph is shown in Figure 1.5. (H. Kienitz (ed.), Massenspektrometrie (1968), Verlag Chemie, Weinheim. Reproduced by permission of Wiley-VCH.)*

Parabola spectrograph



transit time through field: $t = L/v$

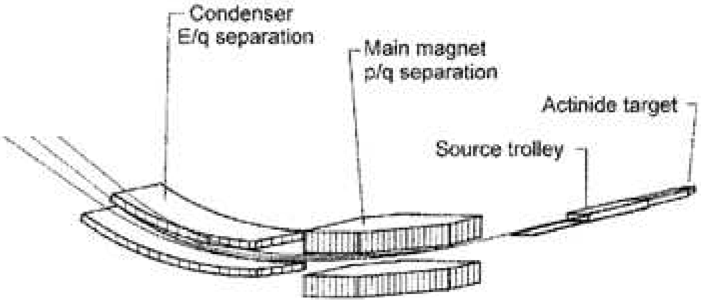
vertical displacement: $y = \frac{1}{2}\, U/d\ q/m\ (L/v)^2$

horizontal displacement: $x = \frac{1}{2}\, B\ q/m\ L^2/v$

$y = k\ m/q\ x^2$; $k = 2\ U/(d\ B^2\ L^2)$

The LOHENGRIN fission fragment separator

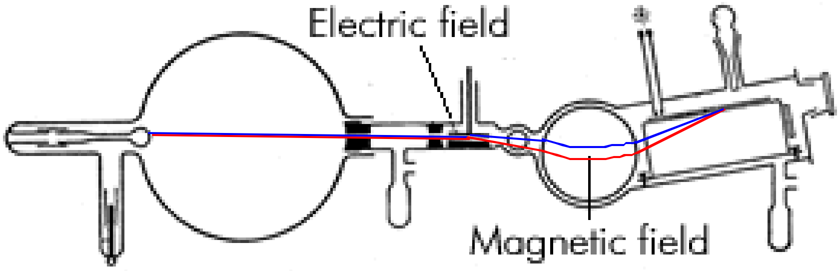
Angular focusing in x and y direction.



$m\, v^2 / r_{el} = q\, E$ $m\, v^2 / r_{magn} = q\, v\, B$

$E_{kin} / q = E / 2\, r_{el}$ $m\, v / q = B\, r_{magn}$

Aston 1919: velocity focusing spectrograph



Aston's design for the mass spectrograph.

Aston: velocity focusing gives factor 10 improvement in mass resolution ($\Delta m/m = 1/130$)

Noble prize in chemistry 1922 for the discovery that elements may have isotopes of different mass (^{20}Ne, ^{21}Ne and ^{22}Ne).

Dempster 1918: 180 degree spectrometer

- **electron bombardment ion source for monoenergetic ions**
- **180 degree magnetic field provides angular focusing**
- **scan of magnetic field to measure mass spectra**

1920: discovery of isotopes in Mg, Li, K, Ca, Zn

$$q/m = 2\,U / (B^2\, r^2)$$

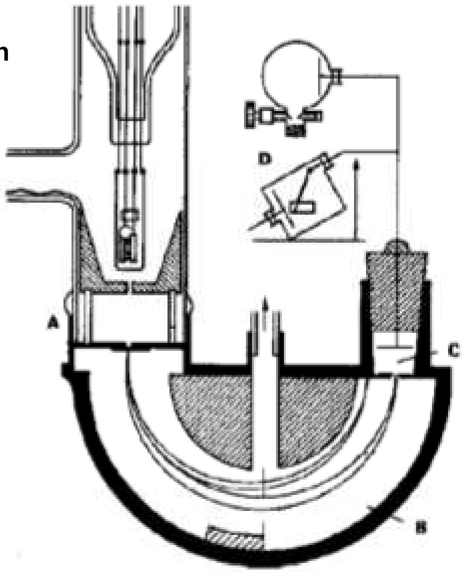
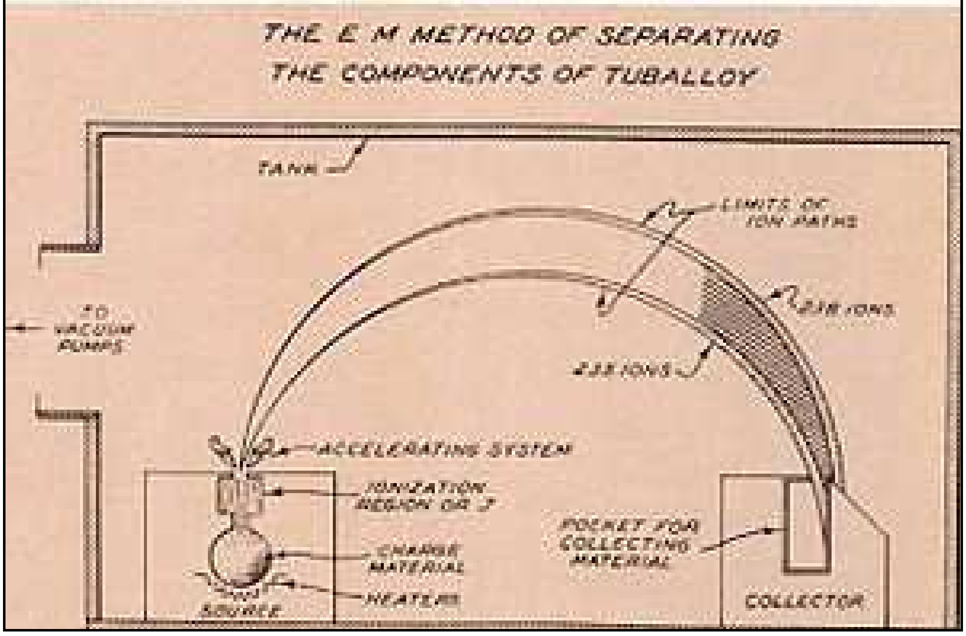
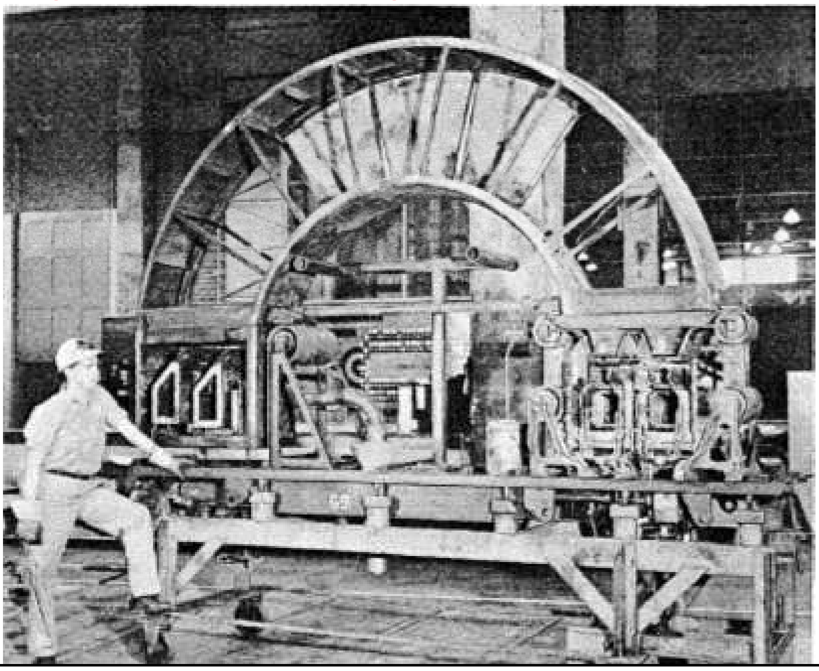


Figure 1.7 Mass spectrometer from A.J. Dempster (1918). A – ion source; B – electromagnet; C – Faraday cup; D – electrometer. (H. Kienitz (ed.), Massenspektrometrie (1968), Verlag Chemie, Weinheim. Reproduced by permission of Wiley-VCH.)

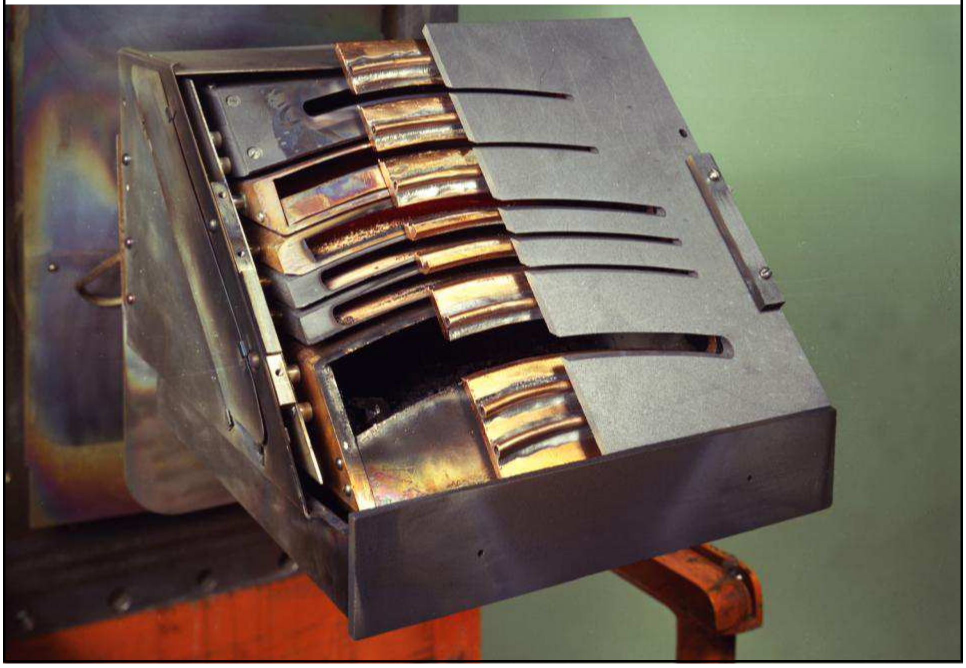
Calutron 1942: electromagnetic isotope separation



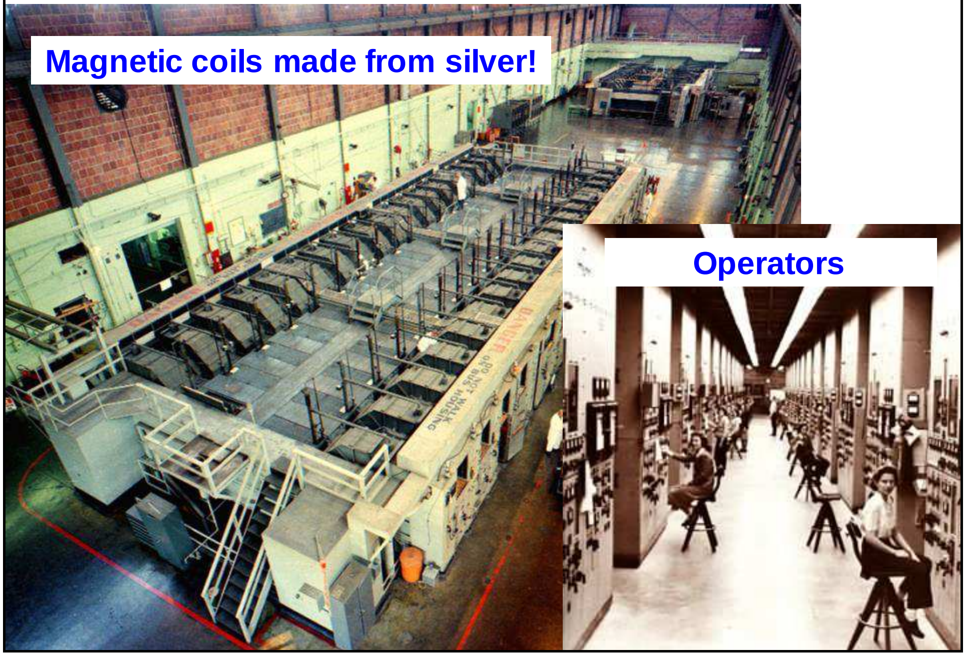
Large scale electromagnetic isotope separation



Collector plates of a Calutron



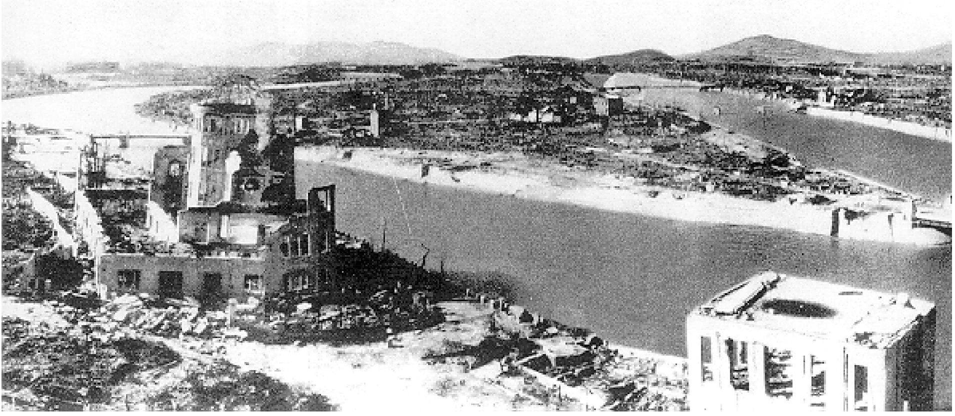
1945: large scale electromagnetic isotope separation



Magnetic coils made from silver!

Operators

1945: “Impact” of electromagnetic isotope separation

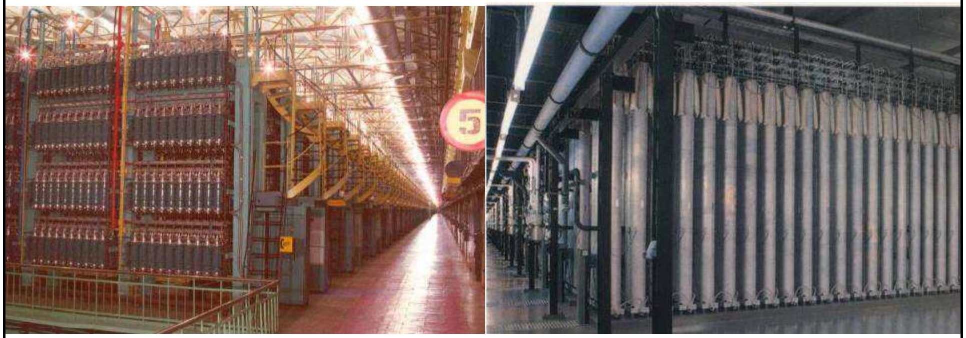


Hiroshima: 60 kg of isotopically enriched ^{235}U

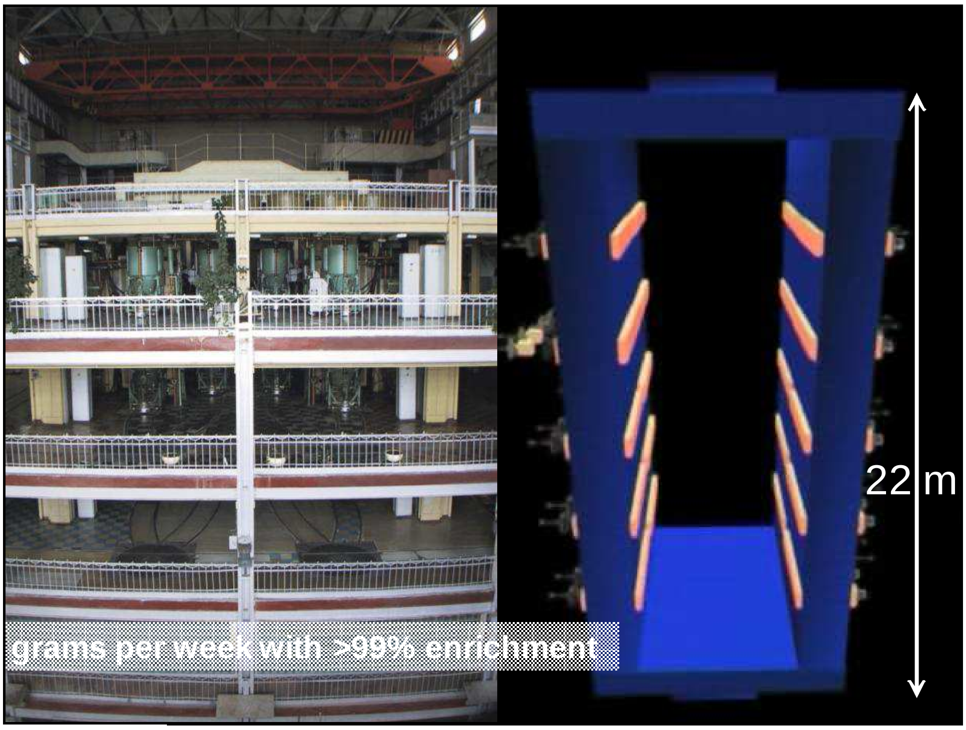
Present enrichment technology for ^{235}U

boiling point: UF_6 56 °C

⇒ centrifuges



Today: very high enrichment of stable isotopes



grams per week with >99% enrichment

Cancer and efficiency of treatments

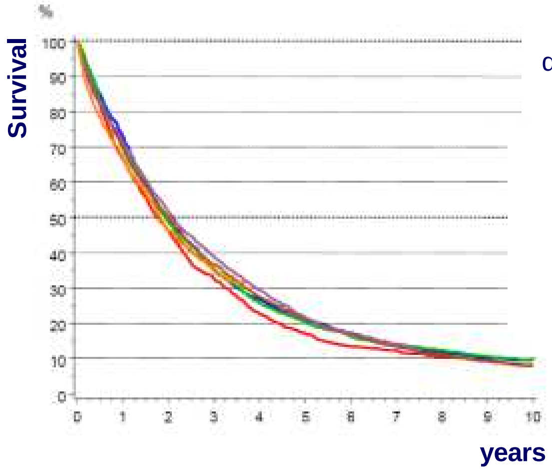
At time of diagnosis	Primary tumor	With metastases	Total
Diagnosed	**58%**	**42%**	**100%**
Cured by:			
Surgery	22%		
Radiation therapy	12%		
Surgery+radiation therapy	6%		
All other treatments and combinations incl. chemotherapy		5%	
Total cured	40%	5%	45%
Fraction cured	**69%**	**12%**	**45%**

Per year over one million cancer deaths in the EU.

⇒ improve early diagnosis

⇒ improve systemic treatments

Mammary Carcinoma
Survival time since diagnosis of metastases

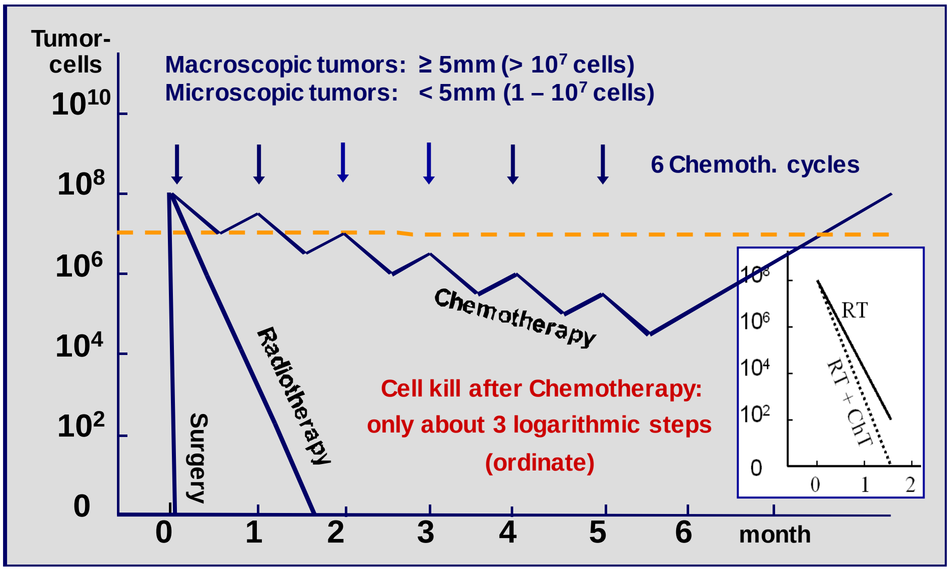


Results for 6 time periods
data from tumor centre Munich
n = 9228

1980-1984
1985-1989
1990-1994
1995-1999
2000-2003
since 2004

Little/no improvement with (modern) chemotherapies!

Comparison of Therapies



Macroscopic tumors: ≥ 5mm (> 10^7 cells)
Microscopic tumors: < 5mm (1 – 10^7 cells)

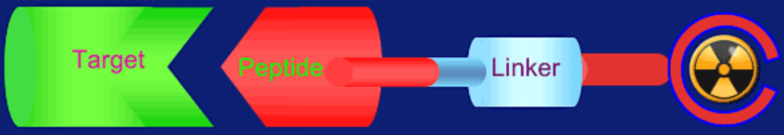
Cell kill after Chemotherapy: only about 3 logarithmic steps (ordinate)

(Molls, TU München; according to Tannock: Lancet 1998, Nature 2006)

Klinik und Poliklinik für Strahlentherapie und Radiologische Onkologie

Prof. Molls

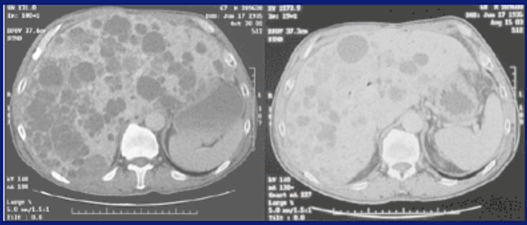
Somatostatin analogues: Peptide Receptor Radionuclide Therapy (PRRT)



Peptide receptor

Peptide analog

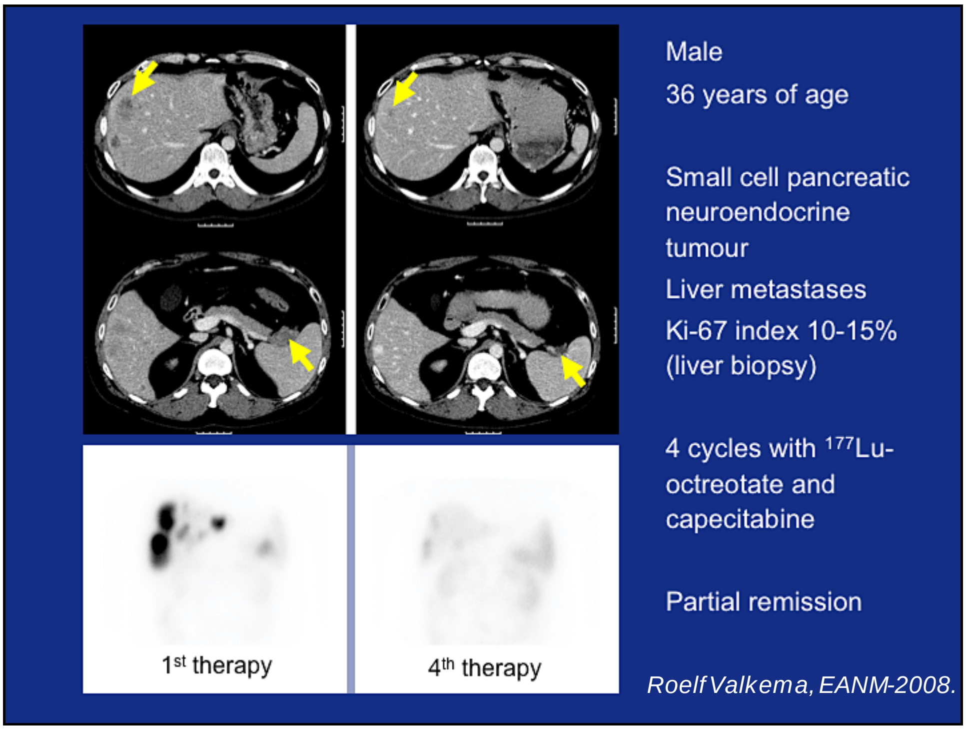
Radionuclide
with Chelator



[^{177}Lu-DOTA,Tyr^3]octreotate

Roelf Valkema, EANM-2008.

Erasmus MC



Male

36 years of age

Small cell pancreatic neuroendocrine tumour

Liver metastases

Ki-67 index 10-15% (liver biopsy)

4 cycles with ^{177}Lu-octreotate and capecitabine

Partial remission

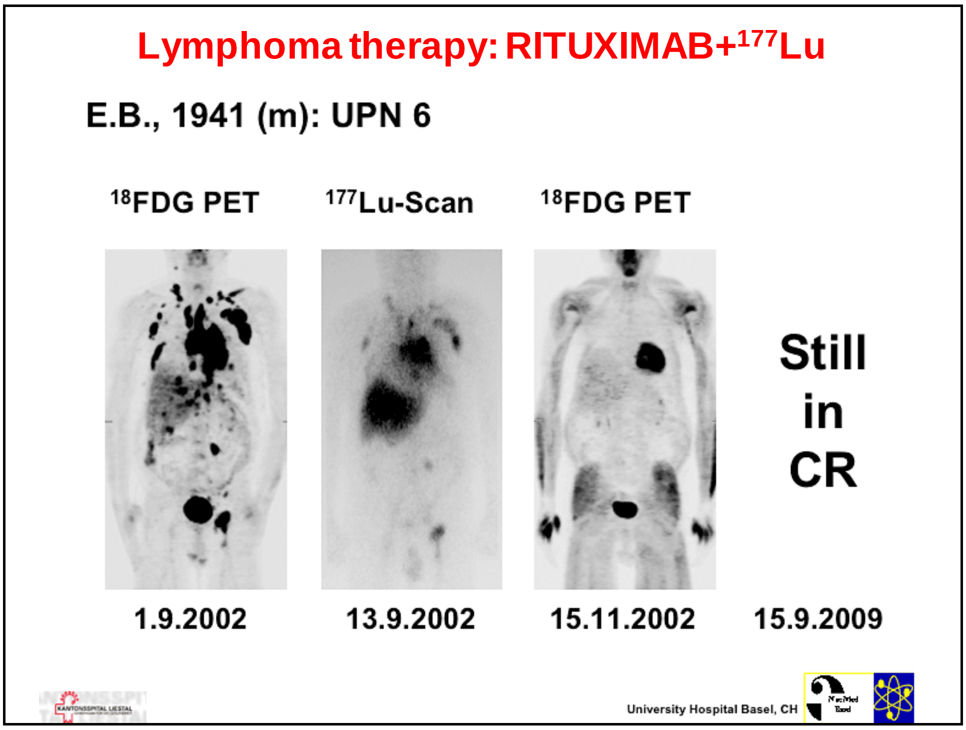
Roelf Valkema, EANM-2008.

What success does PRRT offer?

- ✓ CR+ PR + MR in about 50% of patients: YES
- ✓ Reduce symptoms and improve quality of life: YES
- ✓ Increase survival time: YES
- ✓ Safety and tolerability: YES

Roelf Valkema, EANM-2008.

Erasmus MC

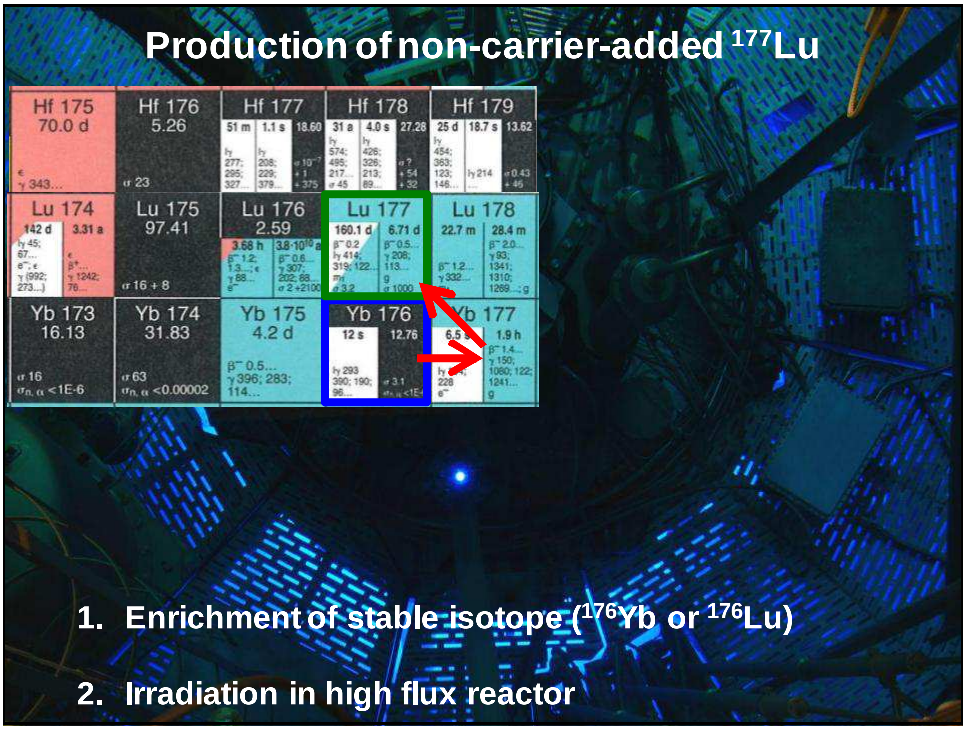


Lymphoma therapy: RITUXIMAB+^{177}Lu

E.B., 1941 (m): UPN 6

^{18}FDG PET	^{177}Lu-Scan	^{18}FDG PET	Still in CR
1.9.2002	13.9.2002	15.11.2002	15.9.2009

University Hospital Basel, CH



Production of non-carrier-added ^{177}Lu

Hf 175 70.0 d	Hf 176 5.26	Hf 177 51 m · 1.1 s · 18.60	Hf 178 31 a · 4.0 s · 27.28	Hf 179 25 d · 18.7 s · 13.62
Lu 174 142 d · 3.31 a	Lu 175 97.41	Lu 176 2.59 3.68 h · 3.8·10^{10} a	Lu 177 160.1 d · 6.71 d	Lu 178 22.7 m · 28.4 m
Yb 173 16.13	Yb 174 31.83	Yb 175 4.2 d	Yb 176 12 s · 12.76	Yb 177 6.5 s · 1.9 h

1. Enrichment of stable isotope (^{176}Yb or ^{176}Lu)
2. Irradiation in high flux reactor

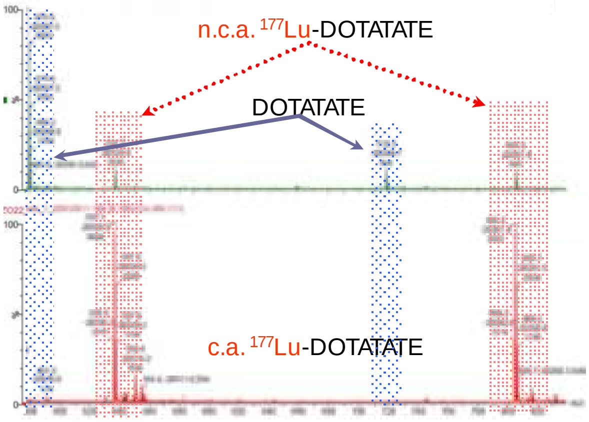
The rising star for targeted therapy

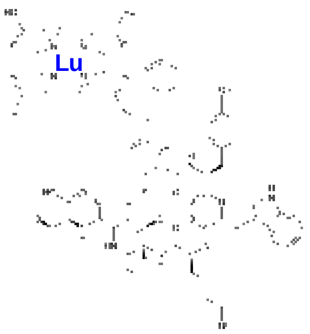
ESI-TOF-MS for DOTA-peptides analysis

Electrospray ionization/TOF-MS positive ion mode

1:4 ^{177}Lu to ligand
10 MBq ^{177}Lu-DOTATATE
0.014 nmol

Identification of radiometallated species





K. Zhernosekov et al., ICTR-PHE 2012.

back to electromagnetic separators…

Aston 1925: improved mass spectrograph

Improved version gives mass resolution: $\Delta m/m = 1/600$

Accuracy of mass determination: 10^{-4}

Used to study deviations of atomic masses m from A.

Introduced: “packing fraction” = $m/A - 1$

Systematic investigation of nuclear binding energies

Carbon isotopes

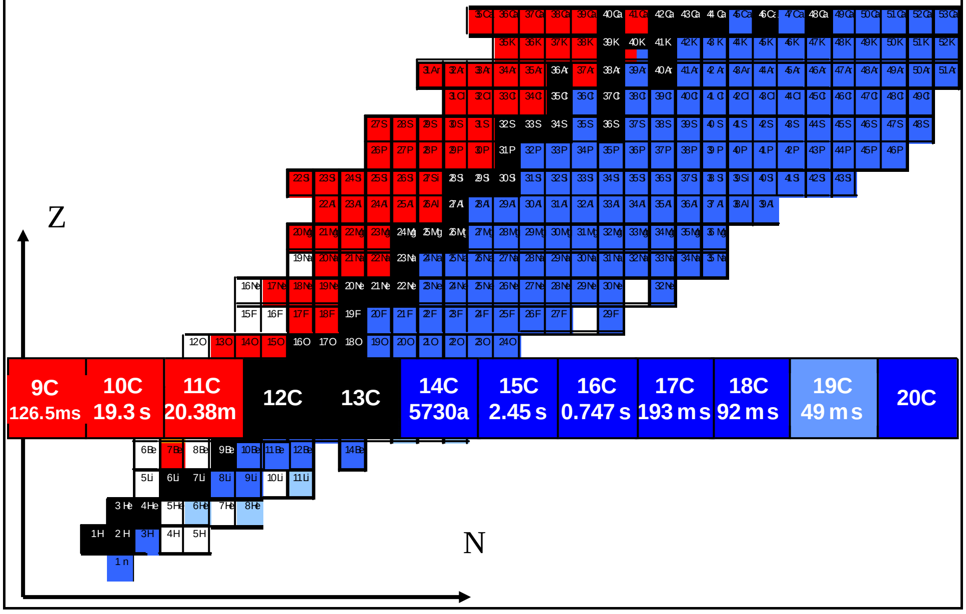
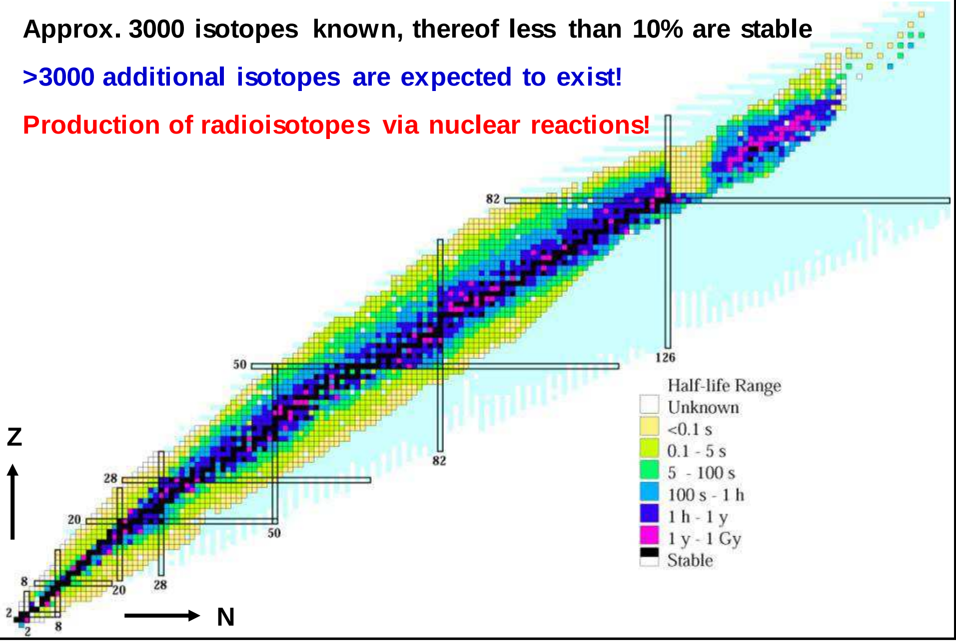


Chart of the nuclides

Approx. 3000 isotopes known, thereof less than 10% are stable

>3000 additional isotopes are expected to exist!

Production of radioisotopes via nuclear reactions!



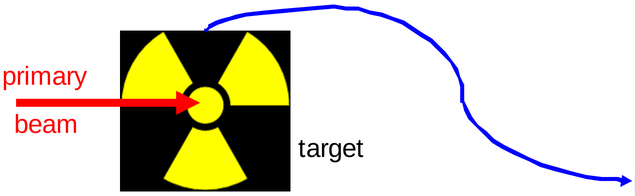
Why "ion beams"?

Production:

high radiation environment

Detection:

low radiation background

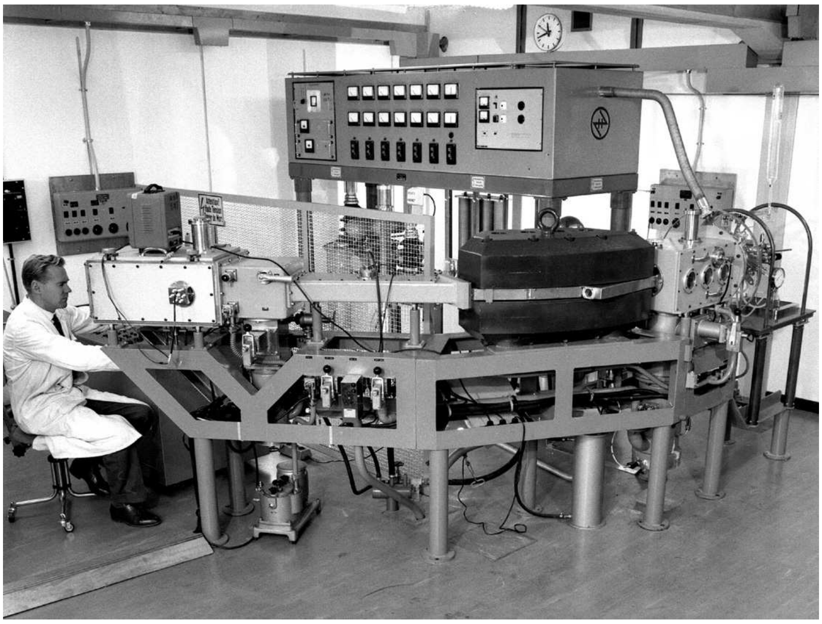


Transport methods:

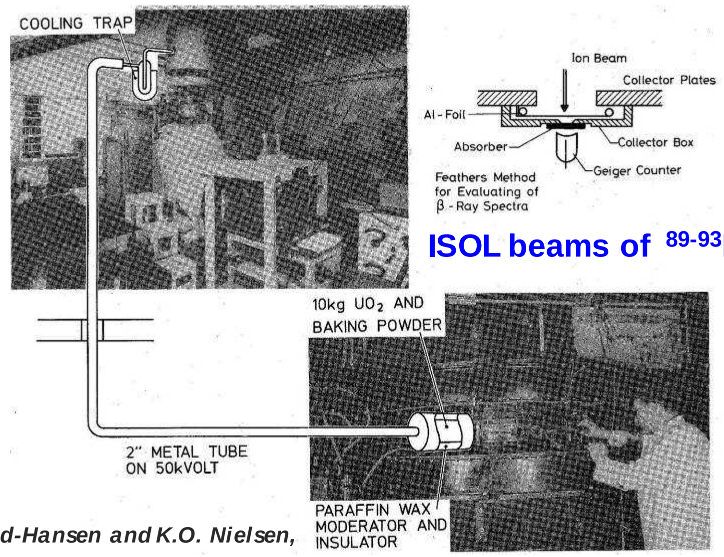
- carry ("SRAFAP")
- drive (*G.T. Seaborg and W.D. Loveland, The Elements beyond Uranium, John Wiley & Sons, 1990*)
- transport shuttle with pressurized air
- transport in gas-jet
- pump through vacuum system
- send as ion beam

Irradiations of targets

Off-line mass separator



1951: first ISOL experiment at Niels Bohr Institute

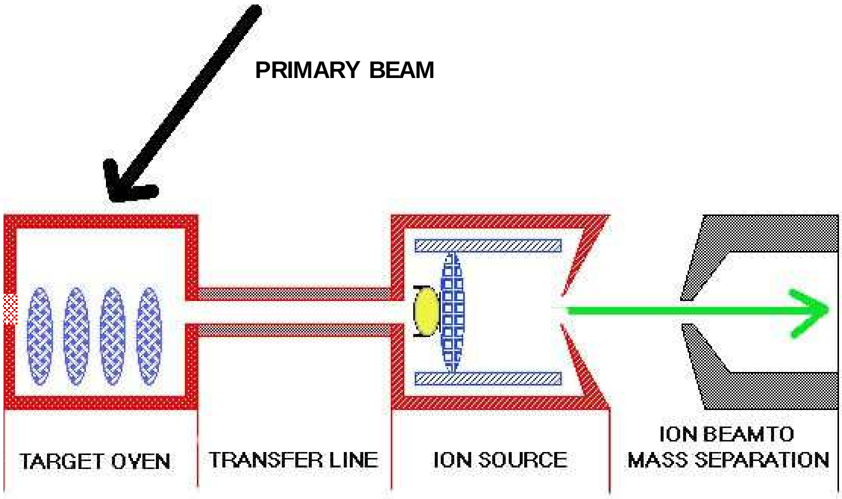


ISOL beams of $^{89\text{-}93}$Kr

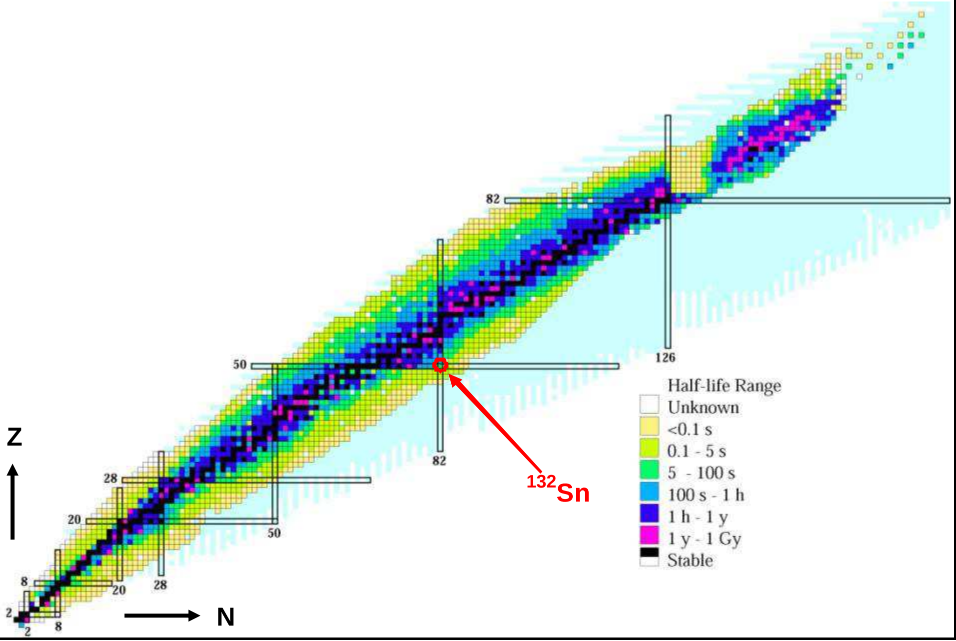
O. Kofoed-Hansen and K.O. Nielsen,

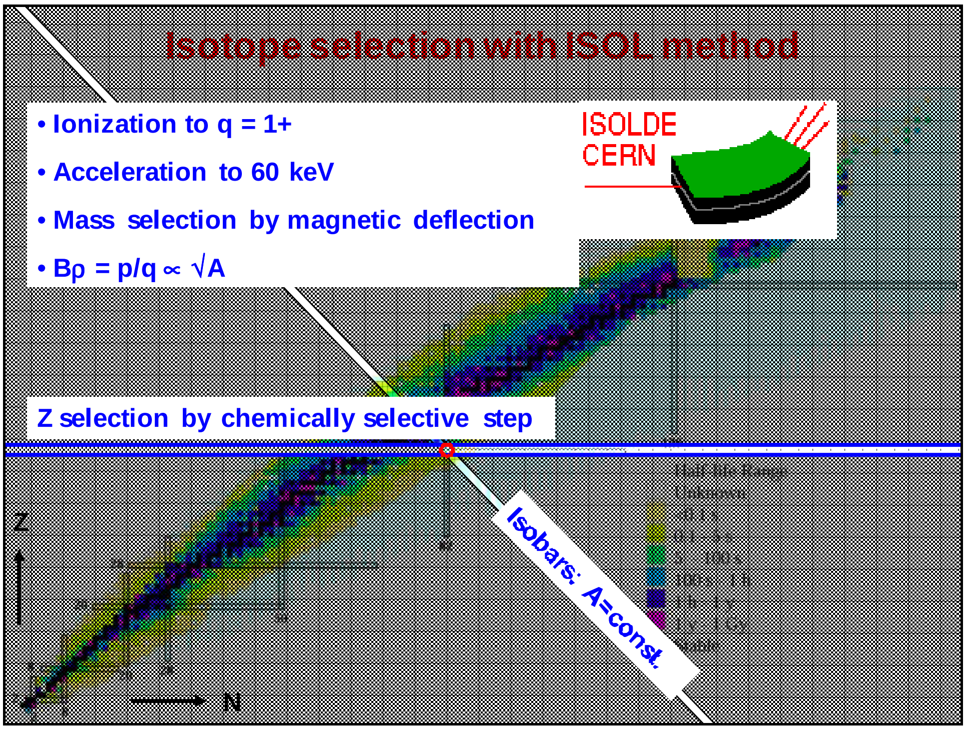
Mat. Fys. Medd. Dan. Vid. Selsk. 26, Nr. 7 (1951).

*I*sotope *S*eparation *O*n-*L*ine



Isotope selection

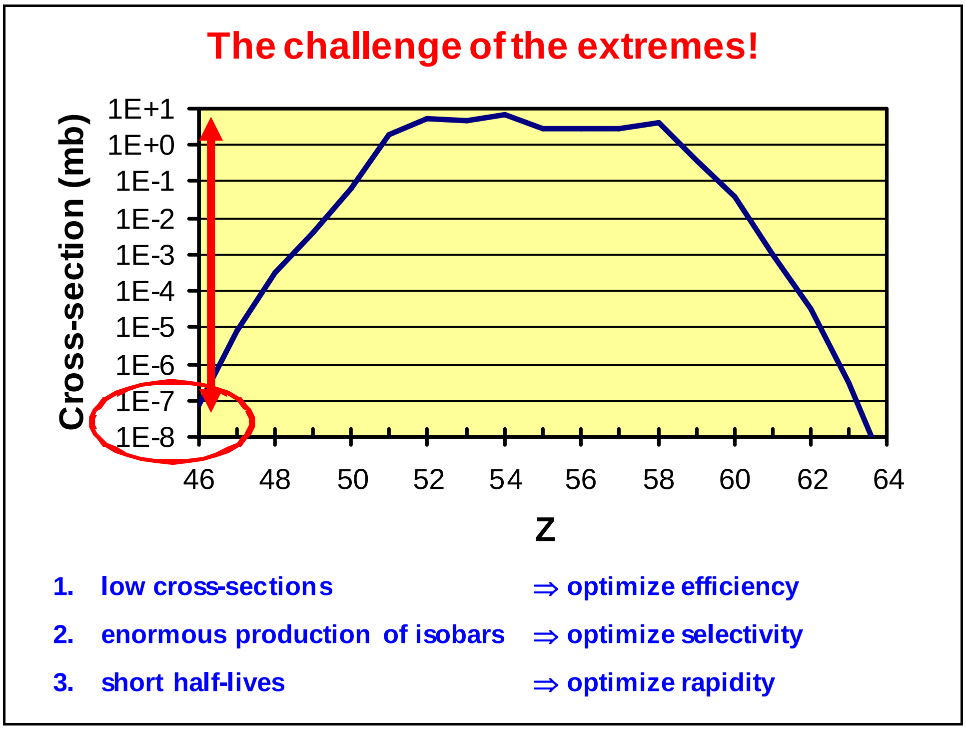




Isotope selection with ISOL method

- Ionization to q = 1+
- Acceleration to 60 keV
- Mass selection by magnetic deflection
- $B\rho = p/q \propto \sqrt{A}$

Z selection by chemically selective step



The challenge of the extremes!

1. low cross-sections ⇒ optimize efficiency
2. enormous production of isobars ⇒ optimize selectivity
3. short half-lives ⇒ optimize rapidity

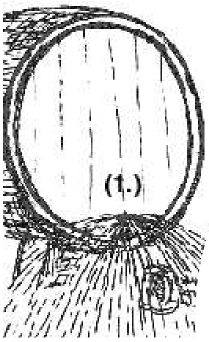
Optimize event rate

All steps of the separation chain need to be optimized!

$$r = \underbrace{\Phi \cdot \sigma \cdot N}_{\text{In-target production}} \cdot \underbrace{\varepsilon_{target} \cdot \varepsilon_{source} \cdot \varepsilon_{transp} \cdot \varepsilon_{det}}_{\text{Efficiency}}$$

Optimize RIB intensity

All steps of the separation chain need to be optimized!



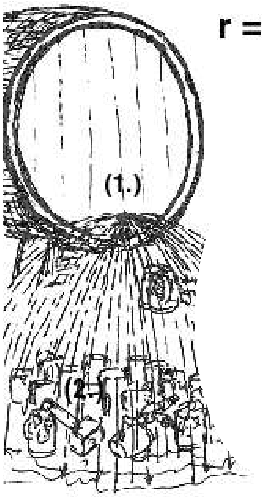
$$r = \Phi \cdot \sigma \cdot N \cdot \varepsilon_{target} \cdot \varepsilon_{source} \cdot \varepsilon_{transp} \cdot \varepsilon_{det}$$

powerful accelerator

⇒ accelerator technology

Optimize RIB intensity

All steps of the separation chain need to be optimized!



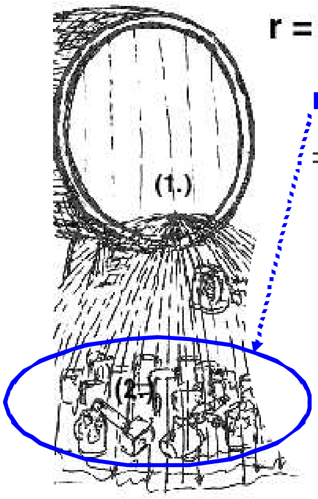
$r = \Phi \cdot \sigma \cdot N \cdot \varepsilon_{target} \cdot \varepsilon_{source} \cdot \varepsilon_{transp} \cdot \varepsilon_{det}$

high production cross-sections

⇒ nuclear physics

Optimize RIB intensity

All steps of the separation chain need to be optimized!



$r = \Phi \cdot \sigma \cdot N \cdot \varepsilon_{target} \cdot \varepsilon_{source} \cdot \varepsilon_{transp} \cdot \varepsilon_{det}$

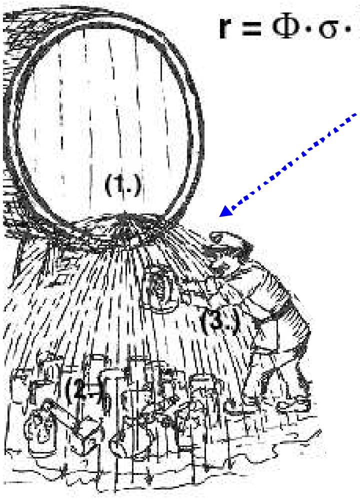
reliable “thick” targets

⇒ materials science

Optimize RIB intensity

All steps of the separation chain need to be optimized!

$$r = \Phi \cdot \sigma \cdot N \cdot \varepsilon_{target} \cdot \varepsilon_{source} \cdot \varepsilon_{transp} \cdot \varepsilon_{det}$$



Extraction efficiency from target determined by:

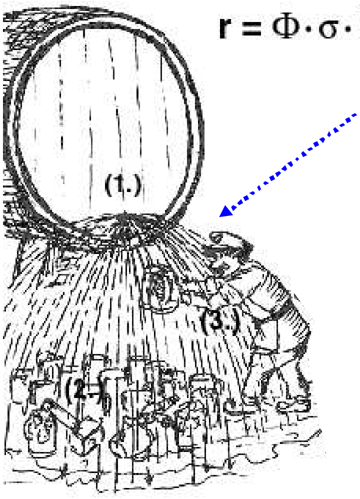
- bulk diffusion
  ⇒ solid state physics
- surface desorption
  ⇒ surface chemistry
- effusion
  ⇒ gas phase chemistry

strongly element dependent!

Optimize RIB intensity

All steps of the separation chain need to be optimized!

$$r = \Phi \cdot \sigma \cdot N \cdot \varepsilon_{target} \cdot \varepsilon_{source} \cdot \varepsilon_{transp} \cdot \varepsilon_{det}$$



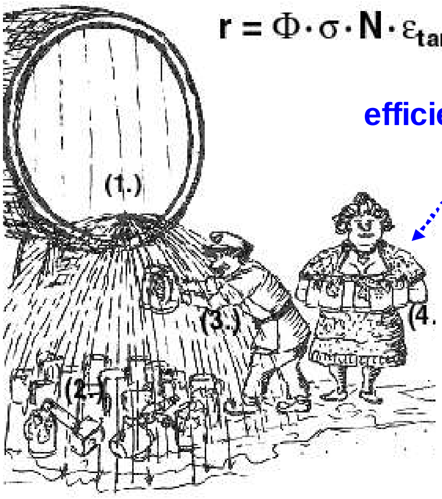
high ionization and extraction efficiency

⇒ ion source technology

Optimize RIB intensity

All steps of the separation chain need to be optimized!

$$r = \Phi \cdot \sigma \cdot N \cdot \varepsilon_{target} \cdot \varepsilon_{source} \cdot \varepsilon_{transp} \cdot \varepsilon_{det}$$



efficient transport of RIB

⇒ ion optics

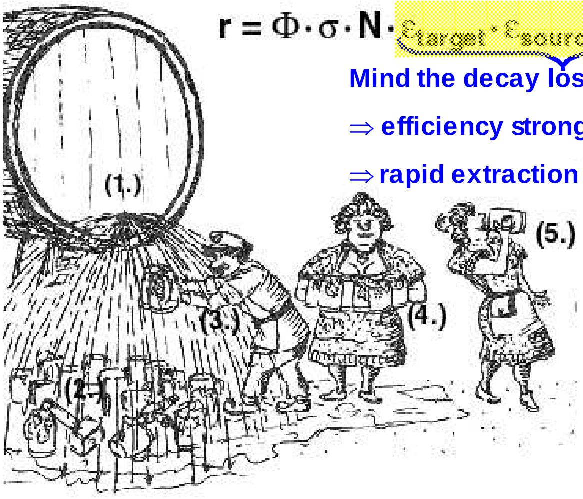
Optimize RIB intensity

All steps of the separation chain need to be optimized!

$$r = \Phi \cdot \sigma \cdot N \cdot \underbrace{\varepsilon_{target} \cdot \varepsilon_{source} \cdot \varepsilon_{transp}}_{\text{Mind the decay losses during delays}} \cdot \varepsilon_{det}$$

⇒ efficiency strongly half-life dependent

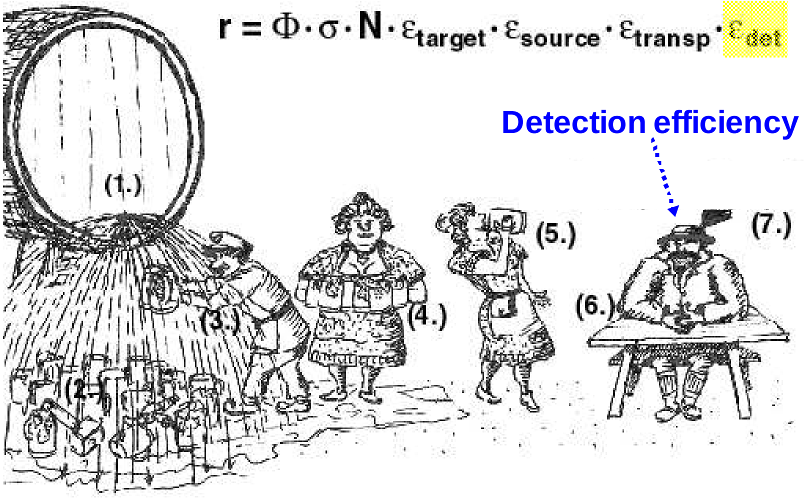
⇒ rapid extraction required!



Optimize RIB intensity

All steps of the separation chain need to be optimized!

$r = \Phi \cdot \sigma \cdot N \cdot \varepsilon_{target} \cdot \varepsilon_{source} \cdot \varepsilon_{transp} \cdot \varepsilon_{det}$



Detection efficiency

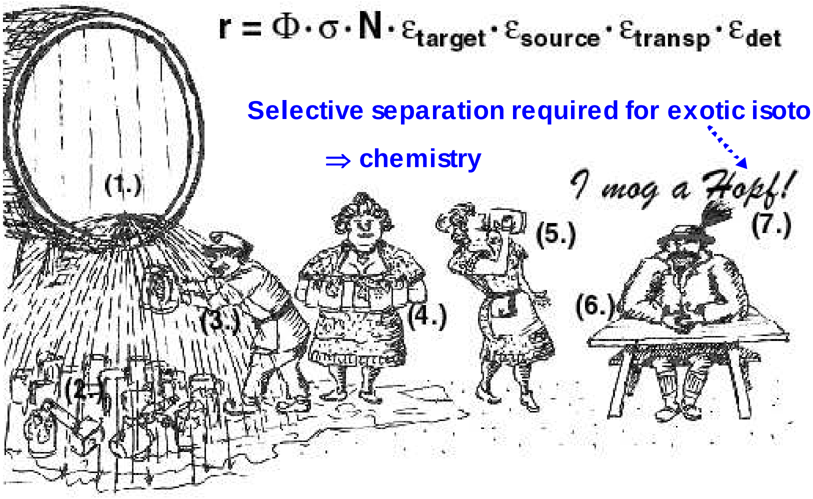
Optimize RIB intensity and purity

All steps of the separation chain need to be optimized!

$r = \Phi \cdot \sigma \cdot N \cdot \varepsilon_{target} \cdot \varepsilon_{source} \cdot \varepsilon_{transp} \cdot \varepsilon_{det}$

Selective separation required for exotic isotopes!

⇒ chemistry

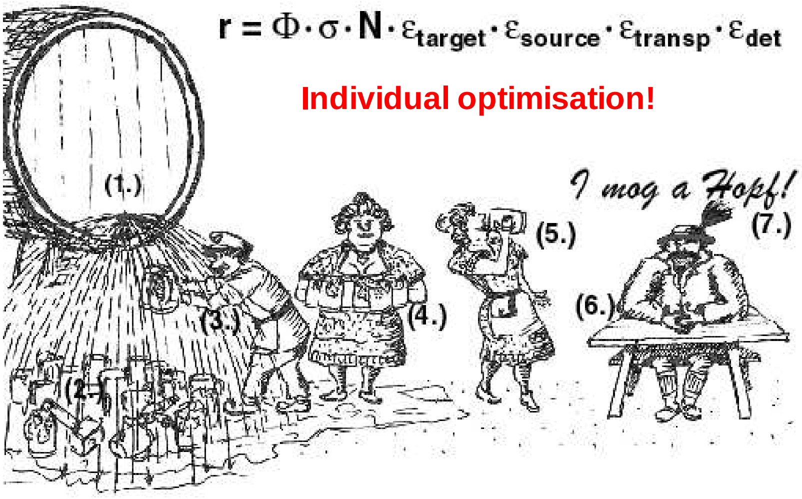


Optimize RIB intensity

Factors are highly correlated and isotope dependent!

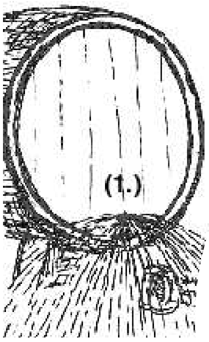
$$r = \Phi \cdot \sigma \cdot N \cdot \varepsilon_{target} \cdot \varepsilon_{source} \cdot \varepsilon_{transp} \cdot \varepsilon_{det}$$

Individual optimisation!



Prog. Part. Nucl. Phys. 46 (2001) 411.

Particle accelerators



$$r = \Phi \cdot \sigma \cdot N \cdot \varepsilon_{target} \cdot \varepsilon_{source} \cdot \varepsilon_{transp} \cdot \varepsilon_{det}$$

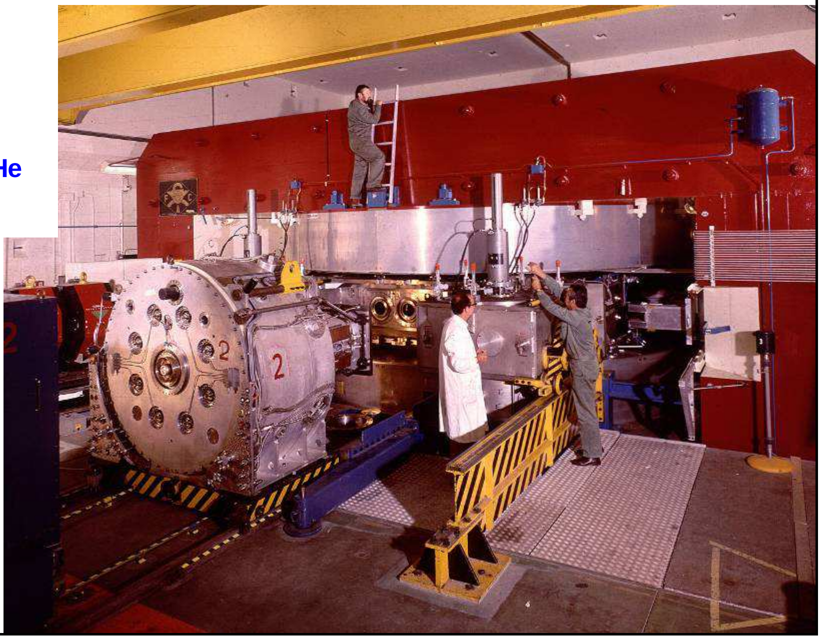
CERN synchrocyclotron 1957-1990

600 MeV p

up to 4 µA

910 MeV ^{3}He

1 GeV ^{12}C



CERN accelerator structure

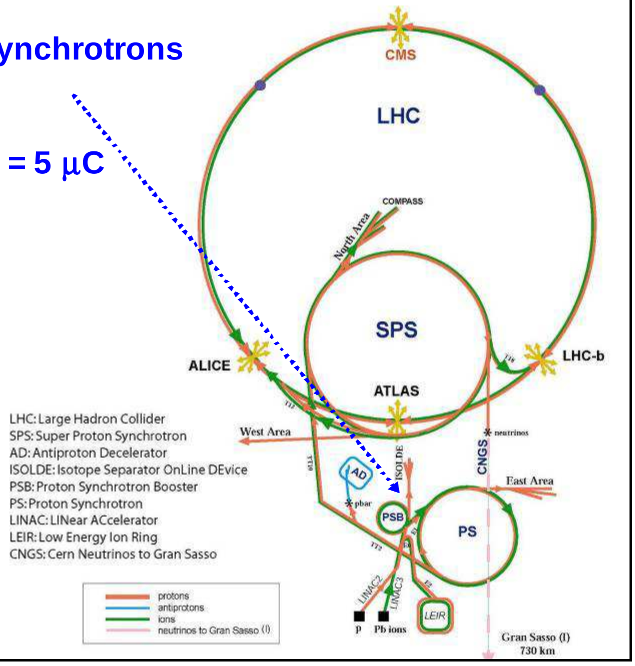
CERN-PS Booster Synchrotrons

E_p = 1.4 GeV

$3 \cdot 10^{13}$ protons/pulse = 5 µC

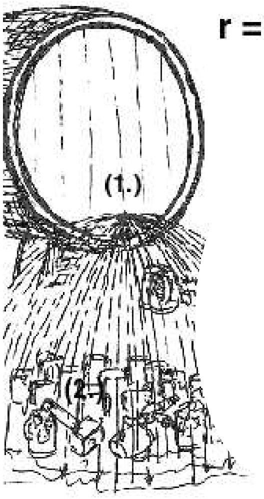
$I_{average}$ = 4 µA

$p_{average}$ = 6 kW



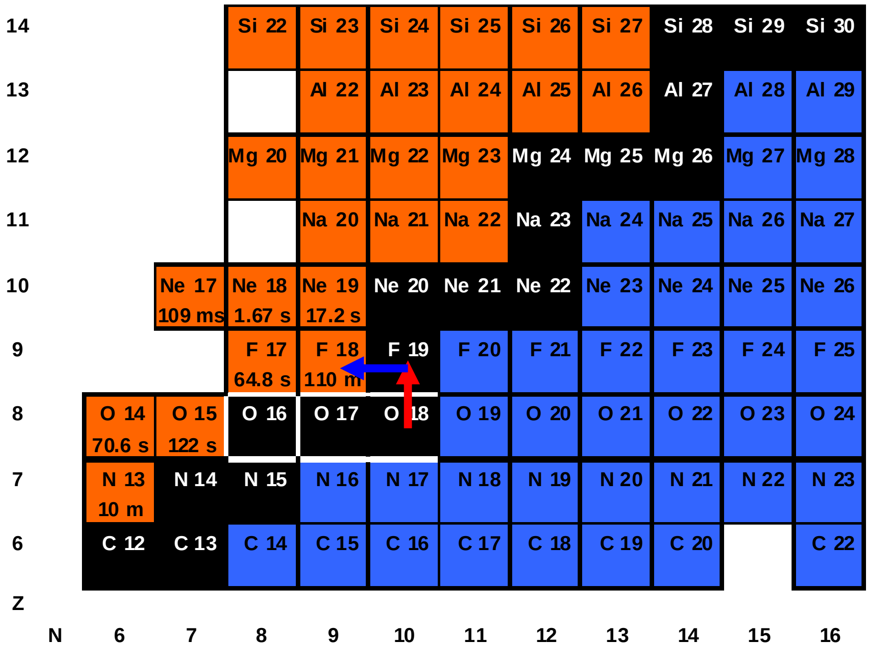
LHC: Large Hadron Collider
SPS: Super Proton Synchrotron
AD: Antiproton Decelerator
ISOLDE: Isotope Separator OnLine DEvice
PSB: Proton Synchrotron Booster
PS: Proton Synchrotron
LINAC: LINear ACcelerator
LEIR: Low Energy Ion Ring
CNGS: Cern Neutrinos to Gran Sasso

Nuclear reactions



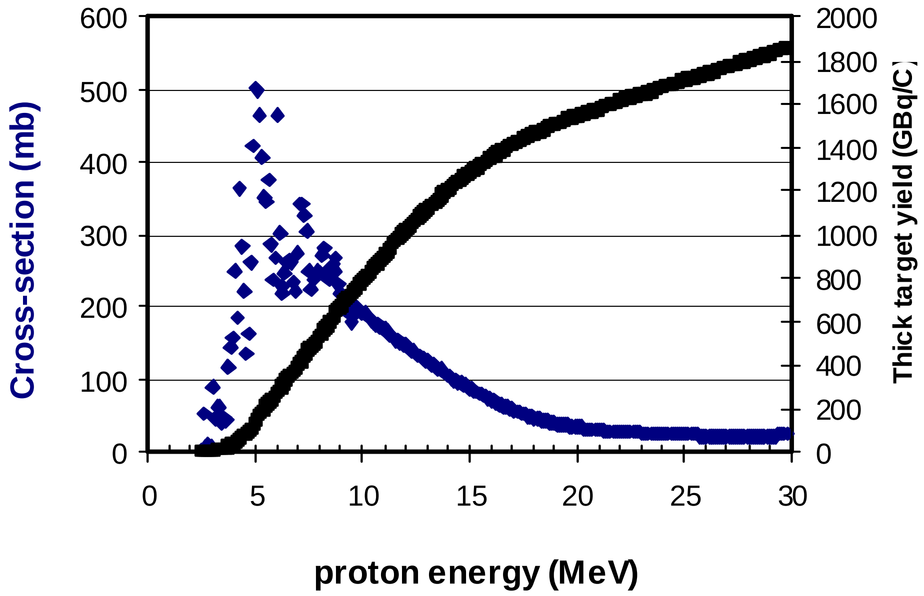
$$r = \Phi \cdot \sigma \cdot N \cdot \varepsilon_{target} \cdot \varepsilon_{source} \cdot \varepsilon_{transp} \cdot \varepsilon_{det}$$

Direct reactions



14				Si 22	Si 23	Si 24	Si 25	Si 26	Si 27	Si 28	Si 29	Si 30
13					Al 22	Al 23	Al 24	Al 25	Al 26	Al 27	Al 28	Al 29
12				Mg 20	Mg 21	Mg 22	Mg 23	Mg 24	Mg 25	Mg 26	Mg 27	Mg 28
11					Na 20	Na 21	Na 22	Na 23	Na 24	Na 25	Na 26	Na 27
10			Ne 17 109 ms	Ne 18 1.67 s	Ne 19 17.2 s	Ne 20	Ne 21	Ne 22	Ne 23	Ne 24	Ne 25	Ne 26
9				F 17 64.8 s	F 18 110 m	F 19	F 20	F 21	F 22	F 23	F 24	F 25
8		O 14 70.6 s	O 15 122 s	O 16	O 17	O 18	O 19	O 20	O 21	O 22	O 23	O 24
7		N 13 10 m	N 14	N 15	N 16	N 17	N 18	N 19	N 20	N 21	N 22	N 23
6		C 12	C 13	C 14	C 15	C 16	C 17	C 18	C 19	C 20		C 22
Z												
	N	6	7	8	9	10	11	12	13	14	15	16

$^{18}O(p,n)^{18}F$ cross-sections



Nuclear reactions

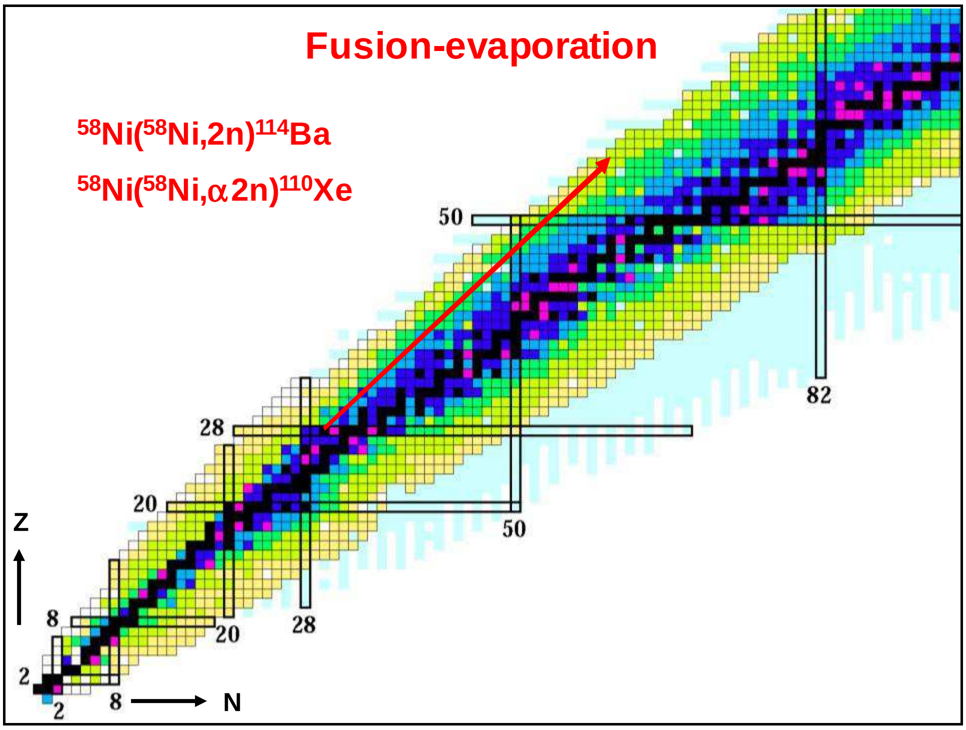
1. Direct reactions

- (p,n), (^{3}He,n), (α,n), (n,α),...
- high cross-sections, products relatively close to stability
- driver beams from (low-cost) cyclotrons

Fusion-evaporation

$^{58}\mathrm{Ni}(^{58}\mathrm{Ni},2n)^{114}\mathrm{Ba}$

$^{58}\mathrm{Ni}(^{58}\mathrm{Ni},\alpha 2n)^{110}\mathrm{Xe}$



Nuclear reactions

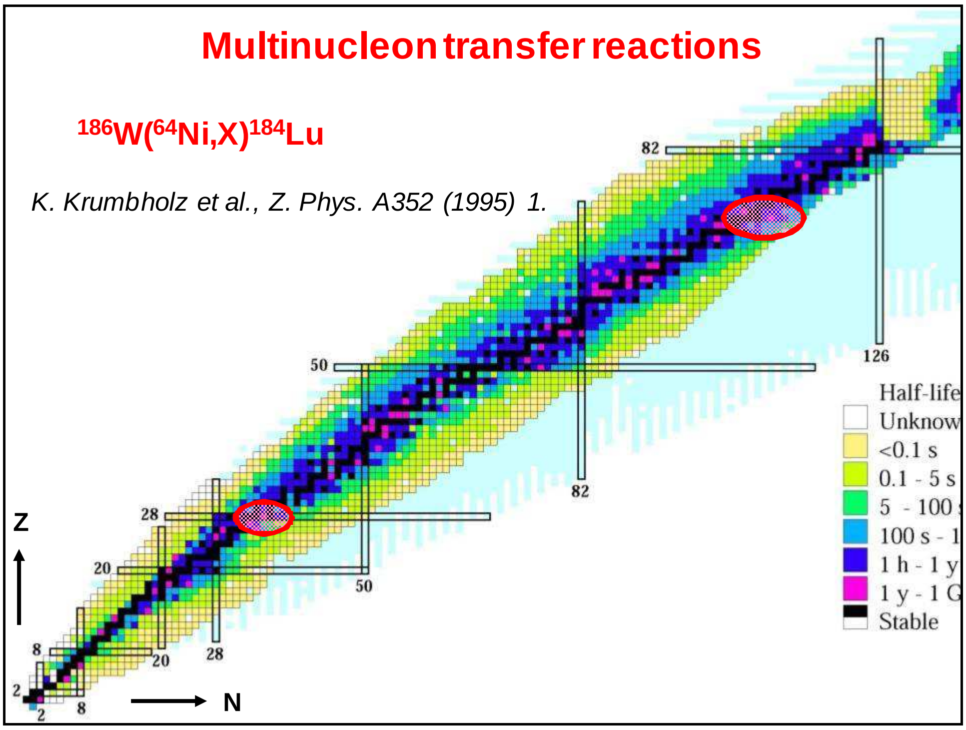
1. Direct reactions
- (p,n), (^{3}He,n), (α,n), (n,α),…
- high cross-sections, products relatively close to stability
- driver beams from (low-cost) cyclotrons

2. Heavy-ion fusion-evaporation
- produces neutron-deficient heavier isotopes
- small energy window in vicinity of Coulomb barrier (some MeV/nucl.)
- requires heavy ion beams ⇒ bigger cyclotrons or LINACs

Multinucleon transfer reactions

$^{186}W(^{64}Ni,X)^{184}Lu$

K. Krumbholz et al., Z. Phys. A352 (1995) 1.



Nuclear reactions

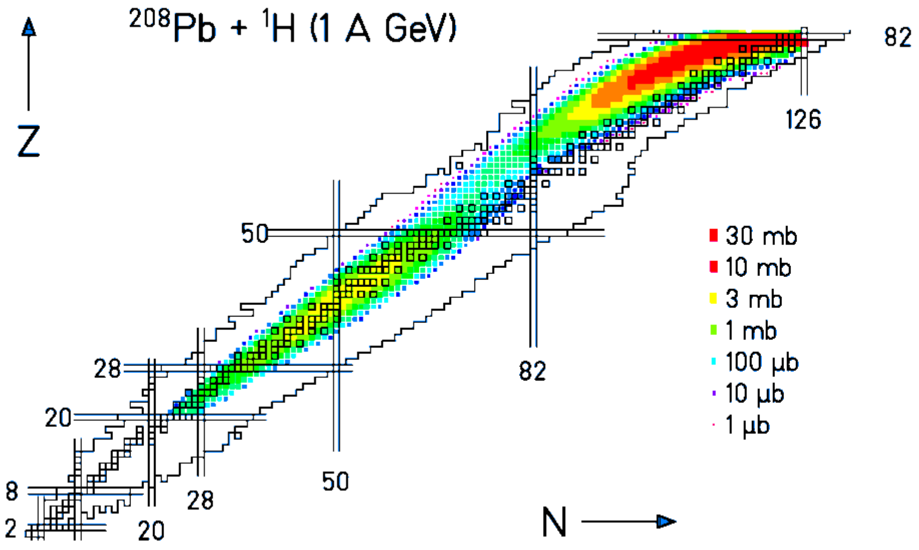
1. Direct reactions
- high cross-sections, products relatively close to stability
- driver beams from (low-cost) cyclotrons

2. Heavy-ion fusion-evaporation
- produces neutron-deficient heavier isotopes
- small energy window in vicinity of Coulomb barrier (some MeV/nucleon)
- requires heavy ion beams ⇒ bigger cyclotrons or LINACs

3. Deep inelastic collisions (multi-nucleon transfer)
- products close to target, mass-flow towards stability
- light to heavy ion beams (tens of MeV/nucleon)
- only method to reach neutron-rich isotopes with $N_{product} > N_{target} + 1$

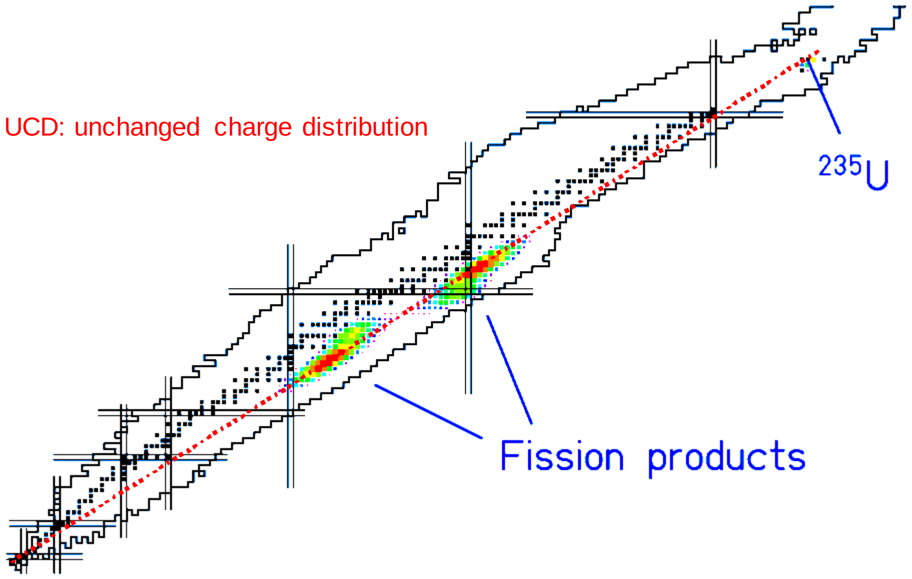
4. Spallation
- intranuclear cascade heats nucleus
- evaporation of preferentially neutrons ⇒ neutron-deficient products
- high cross-sections for products close to target
- requires protons of >100 MeV ⇒ big p cyclotron, synchrotron or LINAC

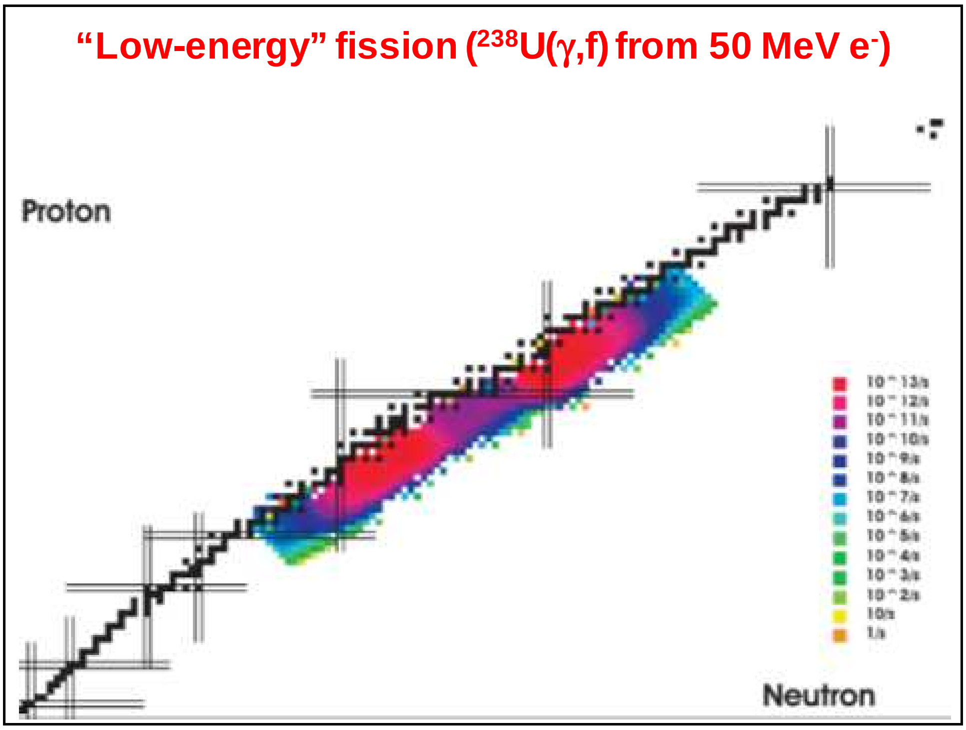
Spallation + Fragmentation + Fission



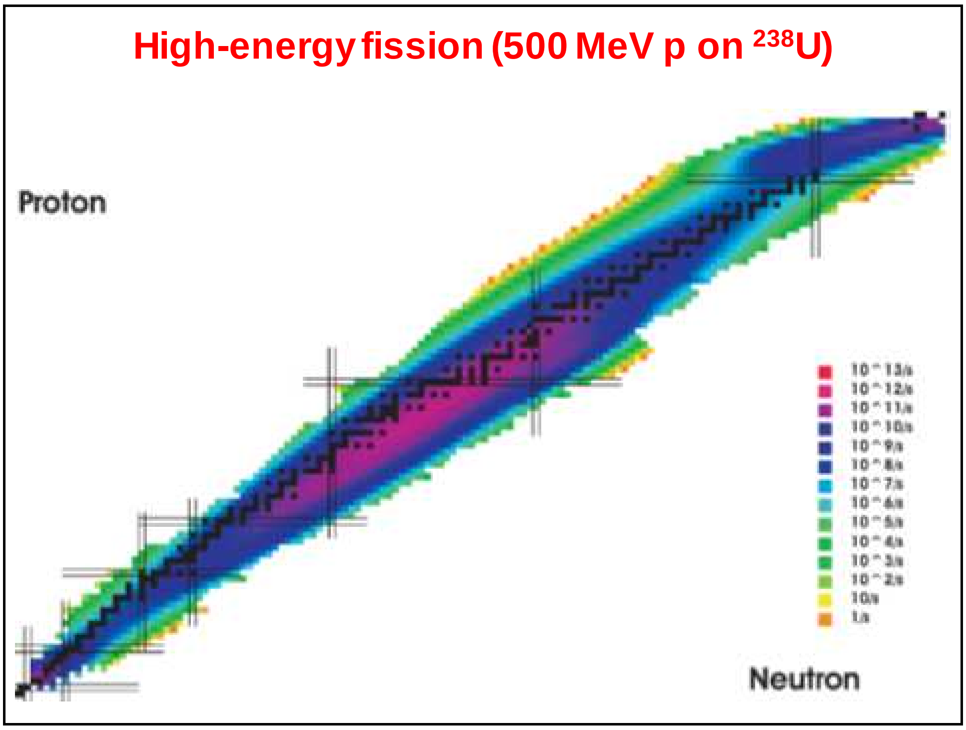
T. Enqvist et al., Nucl. Phys. A686 (2001) 481.

Low-energy fission





“Low-energy” fission (^{238}U(γ,f) from 50 MeV e$^-$)



High-energy fission (500 MeV p on ^{238}U)

Nuclear reactions

5. Fragmentation

- many cross-sections show little energy dependence in the region
  40-2000 MeV/nucleon
- target fragmentation needs high energy protons (see spallation)
- projectile fragmentation needs high energy heavy ions
  ⇒ huge cyclotron, synchrotron or LINAC

6. Fission

- induced by: “time” (**spontaneous**), **neutrons**, **photons**, **protons**, **heavy ions**, antiprotons, pions, post fusion-evaporation, beta-decay/EC
- highest cross-sections for thermal neutrons
- with increasing excitation energy symmetric and far asymmetric fission is favored, but the products get in average less neutron-rich!
- driver accelerators: reactors, medium-energy (some MeV to tens MeV) deuterons from cyclotron or LINAC, microtron or LINAC for electron beams,…