Electromagnetic separators

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- founded 1967
- today 13 member states
- operates most powerful neutron source of the world: 58 MW high flux reactor, \(1.5 \times 10^{15} \text{n./cm}^2/\text{s}\) 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)
LOHENGREN: an electromagnetic separator

Electromagnetic separators at GANIL
BigRIPS at RIBF Facility, RIKEN, Japan

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
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*

*First fluorescent lamp and ion source.*

Wien 1902: *Wien filter*

*Electric field perpendicular to magnetic field*

*Wien: Nobel price in physics 1911 for discovery that “Kanalstrahlen” carry positive charge*
Neon consists of two isotopes with mass 20 and 22

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 Willey-VCH.)

Figure 1.6  Mass spectrum of neon with masses 20 and 22 as 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: \( t = \frac{L}{v} \)
vertical displacement: \( y = \frac{1}{2} \frac{U}{d} \frac{q}{m} \left(\frac{L}{v}\right)^2 \)
horizontal displacement: \( x = \frac{1}{2} B \frac{q}{m} L^2/v \)
\( y = k \frac{m}{q} x^2; \quad k = 2 \frac{U}{(d B^2 L^2)} \)

The LOHENGRIN fission fragment separator

Angular focusing in x and y direction.

\[ m \frac{v^2}{r_{el}} = q \ E \]
\[ E_{kin} / q = \frac{E}{2} r_{el} \]
\[ m \frac{v^2}{r_{magn}} = q \ v \ B \]
\[ m \frac{v}{q} = B \ r_{magn} \]
Aston 1919: velocity focusing 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 ($^{20}\text{Ne}$, $^{21}\text{Ne}$ and $^{22}\text{Ne}$).

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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

$q/m = 2U/(B^2r^2)$
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: $\text{UF}_6 \ 56 \degree \text{C} \Rightarrow \text{centrifuges}$
Today: very high enrichment of stable isotopes

gram per week with 99% enrichment
Cancer and efficiency of treatments

<table>
<thead>
<tr>
<th>At time of diagnosis</th>
<th>Primary tumor</th>
<th>With metastases</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diagnosed</td>
<td>58%</td>
<td>42%</td>
<td>100%</td>
</tr>
<tr>
<td>Cured by:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surgery</td>
<td>22%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiation therapy</td>
<td>12%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surgery+radiation therapy</td>
<td>6%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>All other treatments and combinations incl. chemotherapy</td>
<td>5%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total cured</td>
<td>40%</td>
<td>5%</td>
<td>45%</td>
</tr>
<tr>
<td>Fraction cured</td>
<td>69%</td>
<td>12%</td>
<td>45%</td>
</tr>
</tbody>
</table>

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

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

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

Somatostatin analogues: Peptide Receptor Radionuclide Therapy (PRRT)

[177Lu-DOTA,Tyr³]octreotate  Roelf Valkema, EANM-2008
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 capcitabine
Partial remission


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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


Erasmus MC
Lymphoma therapy: RITUXIMAB+\(^{177}\)Lu

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

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

Production of non-carrier-added \(^{177}\)Lu

\[\text{Still in CR}\]

The rising star for targeted therapy

ESI-TOF-MS for DOTA-peptides analysis

Electrospray ionization/TOF-MS positive ion mode

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”)  
- 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

O. Kofoed-Hansen and K.O. Nielsen, 
Isotope Separation On-Line

Isotope selection

$^{122}$Sn
Isotope selection with ISOL method

- Ionization to \( q = 1^+ \)
- Acceleration to 60 keV
- Mass selection by magnetic deflection
- \( B_p = p/q \propto \sqrt{A} \)

The challenge of the extremes!

1. low cross-sections  \(\Rightarrow\) optimize efficiency
2. enormous production of isobars  \(\Rightarrow\) optimize selectivity
3. short half-lives  \(\Rightarrow\) optimize rapidity
Optimize event rate

All steps of the separation chain need to be optimized!

\[ r = \Phi \cdot \sigma \cdot N \cdot \epsilon_{\text{target}} \cdot \epsilon_{\text{source}} \cdot \epsilon_{\text{transp}} \cdot \epsilon_{\text{det}} \]

- In-target production
- Efficiency

Optimize RIB intensity

All steps of the separation chain need to be optimized!

\[ r = \Theta \cdot \sigma \cdot N \cdot \epsilon_{\text{target}} \cdot \epsilon_{\text{source}} \cdot \epsilon_{\text{transp}} \cdot \epsilon_{\text{det}} \]

- powerful accelerator
- \( \Rightarrow \) accelerator technology
Optimize RIB intensity

All steps of the separation chain need to be optimized!

\[ r = \Phi \cdot \sigma \cdot N \cdot \epsilon_{\text{target}} \cdot \epsilon_{\text{source}} \cdot \epsilon_{\text{transp}} \cdot \epsilon_{\text{det}} \]

high production cross-sections
⇒ nuclear physics

reliable “thick” targets
⇒ materials science
Optimize RIB intensity

All steps of the separation chain need to be optimized!

\[ r = \Phi \cdot \sigma \cdot N \cdot \varepsilon_{\text{target}} \cdot \varepsilon_{\text{source}} \cdot \varepsilon_{\text{transp}} \cdot \varepsilon_{\text{det}} \]

Extraction efficiency from target determined by:

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

strongly element dependent!

high ionization and extraction efficiency
⇒ ion source technology
Optimize RIB intensity

All steps of the separation chain need to be optimized!

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

- efficient transport of RIB
  - ion optics

Mind the decay losses during delays

- efficiency strongly half-life dependent
- rapid extraction required!
Optimize RIB intensity

All steps of the separation chain need to be optimized!

\[ r = \Phi \cdot \sigma \cdot N \cdot \varepsilon_{\text{target}} \cdot \varepsilon_{\text{source}} \cdot \varepsilon_{\text{transp}} \cdot \varepsilon_{\text{det}} \]

Detection efficiency

Optimize RIB intensity and purity

All steps of the separation chain need to be optimized!

\[ r = \Phi \cdot \sigma \cdot N \cdot \varepsilon_{\text{target}} \cdot \varepsilon_{\text{source}} \cdot \varepsilon_{\text{transp}} \cdot \varepsilon_{\text{det}} \]

Selective separation required for exotic isotopes!

⇒ chemistry

I mog a Hopf!
Optimize RIB intensity

Factors are highly correlated and isotope dependent!

\[ r = \Phi \cdot \sigma \cdot N \cdot \varepsilon_{\text{target}} \cdot \varepsilon_{\text{source}} \cdot \varepsilon_{\text{transp}} \cdot \varepsilon_{\text{det}} \]

Individual optimisation!

Particle accelerators

\[ r = \Phi \cdot \sigma \cdot N \cdot \varepsilon_{\text{target}} \cdot \varepsilon_{\text{source}} \cdot \varepsilon_{\text{transp}} \cdot \varepsilon_{\text{det}} \]
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

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

$I_{\text{average}} = 4$ µA

$P_{\text{average}} = 6$ kW
Nuclear reactions

\[ r = \Phi \cdot \epsilon \cdot N \cdot \epsilon_{\text{target}} \cdot \epsilon_{\text{source}} \cdot \epsilon_{\text{transp}} \cdot \epsilon_{\text{det}} \]

Direct reactions
Nuclear reactions

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

\[ \text{O}^\text{18}(p,n)\text{F}^{18\text{F}} \text{ cross-sections} \]
Nuclear reactions

1. Direct reactions
   • (p,n), (\(^3\)He,n), (\(\alpha\),n), (n,\(\alpha\))…
   • 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

\[ ^{186}W(^{64}\text{Ni},X)^{184}\text{Lu} \]


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 \( N_{\text{product}} > N_{\text{target}} + 1 \)

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

\[ {^{208}}\text{Pb} + {^1}\text{H} (1 \text{ A GeV}) \]


Low-energy fission

UCD: unchanged charge distribution

Fission products
"Low-energy" fission ($^{238}\text{U}(\gamma,f)$ from 50 MeV $e^-$)

High-energy fission (500 MeV p on $^{238}\text{U}$)
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,…