3. Lecture:
Production of radioactive nuclei and highly-charged ions

1. Production techniques for radioactive ion beams (RIB)
2. The heavy ion accelerator facility GSI
3. The on-line isotope separator ISOLDE at CERN
4. Production of highly-charged ions (HCl)
   - at GSI
   - with an Electron Beam Ion Trap (EBIT)
Ion traps, heavy ion cooler rings and laser traps at accelerators

- Stockholm
- Aarhus
- Tokyo
- CERN
- GSI
- Heidelberg
- Argonne
- Stony Brook
- Berkeley
- Vancouver
- MSU
- Lanzhou
- Jyväskylä
- GANIL
- KVI Groningen
- Leuven
- Penning trap for neutron lifetime at ILL, Grenoble
- off-line experiments at Los Alamos
Radioactive ion beam production: principle

**Principle**

- Primary beam: $I_0$
- Nuclear reaction
- Ion beam preparation, separation, acceleration/deceleration, ...
- Secondary beam: $I_{\text{RIB}}$

**Reaction rate**

Reaction rate:

$$R = \sigma_{\text{reaction}} \cdot \phi_{\text{primary}} \cdot N_{\text{target}}$$

**RIB intensity**

$$I_{\text{RIB}} = \varepsilon \cdot R$$

**Values**

- Cross sections: $1 \text{ pb} \rightarrow >10 \text{ b}$
- Beam flux: $10^{11} - 10^{15} / \text{cm}^2 / \text{s}$
- Target thickness: $0.1 - 100 \text{ g/cm}^2$

**Transmission factor**

$$\varepsilon = f (\text{Transmission, element, half-life, ionization, ...})$$

**Intensities**

- $0.1 / \text{day} \rightarrow >10^{12} / \text{s}$
Proton-induced reactions (e.g. ISOLDE, ISAC)

Protons

1 GeV

$^{238}\text{U}$ + protons

$^{201}\text{Fr}$, $^{11}\text{Li}$, $^{143}\text{Cs}$

Spallation

Fragmentation

Fission
Heavy-ion-induced reactions (e.g. GSI)

- Fragmentation
- Coulomb dissociation
- Fusion
ISOL versus fragmentation

**ISOL**
- 1 GeV protons, Light ions
- Thick target
- Ion source
- 100 keV
- Electromagnetic separation
- Postaccelerator
- Some MeV
- High intensities for long-lived isotopes
- Limitation at $T_{1/2} < 10$ ms
- High beam quality
- No refractory elements

**Fragmentation**
- 1 GeV/u heavy ions
- Thin target
- Production target
- 1 GeV/u
- Electromagnetic separation
- Decelerator
- At rest
- Low intensities
- Limitation only at $T_{1/2} < 1\mu$s
- Low beam quality
- All elements

**ISOL and fragmentation facilities are complementary**
Concept for in-flight separation

Primary beam

Target

Separation

\[ B\rho = \frac{mv}{q} \]
\[ E\rho = \frac{mv^2}{q} \]

\( <q> = Z^{1/3} \frac{v}{v_{\text{Bohr}}} \)

Experiment

\( B: \) magnetic field  \( E: \) electric sector field
\( \rho: \) deflection radius  \( m: \) mass
\( v: \) velocity  \( q: \) charge state
\( Z: \) atomic number
Concept for ISOL

Primary beam

Target

Catcher

Ion Source

Extraction + Separation

ions

thin

gas

solid

various

p, d, n

thick
Manipulation and cooling of RIB and HCl

Demands:
- good beam quality
- high intensity

Improvements via:
- beam cooling: low emittance, energy spread
- accumulation and bunching: signal-to-noise ratio, beam transfer, beam energy variation
- beam purification: clean ion beams
The heavy ion accelerator GSI

**Mission:**
Construction and operation of accelerators; research with heavy ions

**Personnel:**
ca. 700 employees (250 scientists and engineers)

**Budget:**
65 Mio €
Operation: 52 Mio €
Investments: 13 Mio €

**Altogether over 1000 users, 400 from abroad**
(100 internal users)

**Instruments:**
Accelerators UNILAC/SIS/ESR; large spectrometers and detector systems

http://www.gsi.de
Research programm at GSI

- **Nuclear Physics** 50%
- **Atomic Physics** 15%
- **Plasma Physics** 5%
- **Biophysics & Tumortherapy** 15%
- **Materials Research** 5%
- **Accelerator Development** 10%
- **Clinical Application**
- **New Technologies**
- **New Materials**

**Joint effort of GSI & university groups and international collaboration**
Ion (stopping and) collection devices at GSI

Existing Collection Devices
- SIS
- ESR
- + STOPPING
- SHIPTRAP

Planned Devices
- HITRAP
- FRS gas cell
The ISOLDE facility at CERN

Radioactive laboratory

GPS-Target

1.4 GeV protons from PS-Booster

HRS-Target

HRS

RILIS laser hut

GPS

1.4 GeV protons from PS-Booster

COLLAPS

ISOLTRAP

ASPIIC

COMPLIS

MISTRAL

REX-ISOLDE

NICOLE

Control room

http://isolde.web.cern.ch/isolde

Ionization techniques:
- Surface ionization
- Plasma ionization
- Resonant laser ionization

1. **Surface Ionization Ion Source:**
   *No isobaric selectivity, limited applicability*

2. **Plasma Ion Source (ECR-Source):**
   *No isobaric selectivity*

3. **Resonance Ionization Laser Ion Source (RILIS):**
   *High isobaric selectivity by resonant laser ionization*
   *Limitation by surface ionized isobars*

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Accessibility of elements by RILIS

At ISOLDE in total >70 elements, >600 isotopes available!
Physics at ISOLDE

Nuclear Physics
- Nuclear Decay Spectroscopy and Reactions
  - Structure of Nuclei
  - Exotic Decay Modes

Atomic Physics
- Laser Spectroscopy and Direct Mass Measurements
  - Radii, Moments, Nuclear Binding Energies

Applied Physics
- Implied Radioactive Probes, Tailored Isotopes for Diagnosis and Therapy
- Condensed matter physics and Life sciences

Fundamental Physics
- Direct Mass Measurements, Dedicated Decay Studies – WI
- CKM unitarity tests, search for $\beta$-$\nu$ correlations, right-handed currents

Nuclear Astrophysics
- Dedicated Nuclear Decay/Reaction Studies
  - Element Synthesis, Solar Processes

Applied Physics
- 19%

Atomic Physics
- 18%

Nuclear Physics
- 49%

Fundamental Physics
- 14%
Existing Devices
- REXTRAP
- WITCH Penning traps
- ISOLTRAP RFQ buncher
- ISOLTRAP cooler trap

Planned Devices
- ISOLDE HRS cooler
- MISTRAL cooler
Production of highly-charged ions at GSI
The electron beam ion trap (EBIT) was developed at the Lawrence Livermore National Laboratory (LLNL) in the late 1980s by R. Marrs and M. Levine.
The ionization process

Sequential electron impact ionization in an electron beam ion trap

As the ion charge state goes up:

- growing ionization potential: $10 \text{ eV} \rightarrow 130000 \text{ eV}$
- diminishing cross section: $10^{-16} \text{ cm}^2 \rightarrow 10^{-24} \text{ cm}^2$

electron beam with energy $E_k$
Competing processes: recombination

Charge exchange with restgas neutral atoms

Ne\(^{9+}\)

Solution: vacuum 10\(^{-13}\) Torr
(1000 atoms/cm\(^3\))

capture of free electrons

Radiative recombination (RR)

Solution: raising electron beam energy
Principles of an EBIT (electron beam ion trap)

- **e-beam**
- **B**
- **60 µm**
- **40 mm**
- **6000 A/cm²**
- **$n_e \approx 10^{13}$ e-/cm³**
- **trap potential $U_t \approx 100$ V**
  - $(U_t \times \text{ion charge}) \approx 5000$ eV

**the trap:**
- **axially:**
  - electron beam space charge
- **longitudinally:**
  - electrodes

**trap potential $U_t \approx 100$ V**

$(U_t \times \text{ion charge}) \approx 5000$ eV
Evaporative cooling

- Collisions with beam electrons heat up ion ensemble.
- Light, less tightly trapped ions (e.g., Ne$^{10+}$) evaporate removing thermal energy: a single Ne$^{10+}$ takes away 2 keV (1 second additional life for a heavy ion).
- Heavy, highly charged ions (e.g., Ba$^{53+}$) remain trapped indefinitely.

Ion temperatures from 1000 eV to 10 eV

Doppler width $\Delta\lambda/\lambda \approx 1/20.000$ (Ba$^{53+}$)

High resolution spectroscopy