Ion traps

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Outline

• Fundamentals of ion traps.

• Ion traps at Radioactive Ion Beam facilities. Cooling.

• High-precision experiments in nuclear physics.
Fundamentals of ion traps
Why ion traps?

• Extended preparation.
• Extended interactions.
• Extended reaction periods.

• Which leads to
  Effective non-destructive (re)-use of rare species.
  Easy manipulation of trapped particles.
  Selection by $q/m$ separation.
  Accumulation and bunching.
  Cooling.
  Charge breeding.
  Polarization.
  Increase of luminosity, signal/noise.
  ….
Why ion traps?

- Prominent argument:

\[ \Delta t \cdot \Delta E > h \]

Storage

\[ \Delta t \cdot \Delta \nu > 1 \]

Resolving power
Applications

CHEMISTRY
- Atomic Physics
- Molecular & Clusters
- Laser, microwave, life-times

PLASMA PHYSICS
- Ordered structures

ION BEAM MANIPULATION
- Cooling
- Beam bunching
- New accelerator, decelerator concepts
- Accumulation
- Ultra-high mass separation

NUCLEAR PHYSICS
- Nuclear binding energies
- Decay studies

MOLECULAR & CLUSTERS
- Laser, microwave, life-times

FUNDAMENTAL TESTS
- CPT, QED, parity violation, CVC

METROLOGY
- Kilogram, fine structure constant, frequency standards
Trapping of charged particles

• Required:
  3-dimensional potential minimum.  
  Force acting towards a center.

• Convenience:
  a) \( F \sim -r \) (Harmonic oscillator)
  b) Rotational symmetry

• Consequences:
  From a)
  \[
  F = -e \nabla \Phi \propto -\vec{r}
  \]
  \[
  \Rightarrow \Phi = ax^2 + by^2 + cz^2
  \]
  Laplace equation \( \Delta \Phi = 0 \)  
  Rotational symmetry around z-axis  

  \[
  a + b + c = 0
  \]

• THERE IS NOT 3-DIMENSIONAL CONFINEMENT WITH ELECTROSTATIC FIELDS
Confinement with RF fields: Paul traps

- Equipotential lines are hyperboloids of revolution.

\[ \Phi = \Phi_0 \left( \frac{r^2 - 2z^2}{2r_0^2} \right) \]

\( \Phi = \Phi(t) \) → Paul trap
Confinement with RF fields: Paul traps

- Potential:

\[ \Phi = (U_0 + V_0 \cos \omega_{RF} t) \cdot \frac{(r^2 - 2z^2)}{2r_0^2} \]

- Equation of motion (Mathieu equation):

\[ \frac{d^2 u}{d\tau^2} + (a - 2q \cos 2\tau) u = 0 \]

\[ \begin{align*}
    u &= r, z \\
    \tau &= \omega_{RF} t / 2
\end{align*} \]

\[ a_z = -\frac{8eU_0}{mr_0^2 \omega_{RF}^2} = -2a_r \]

\[ q_z = \frac{4eV_0}{mr_0^2 \omega_{RF}^2} = 2q_r \]
Confinement with RF fields: Paul traps

• Stable solution for certain values of $a,q$:

• Ion trajectories:

$$u(t) = A \sum c_{2n} \cos(\beta + 2n)(\omega_{RF} t/2) + B \sum c_{2n} \sin(\beta + 2n)(\omega_{RF} t/2)$$

$$\begin{cases} 
\beta = \beta(a,q) \\
c_{2n} = c_{2n}(a,q) \\
0 < \beta < 1
\end{cases}$$

• If $a,q << 1 \Rightarrow c_{2n}(n>1) \approx 0$

$$u(t) = A \left(1 - \frac{q}{2} \cos \omega t\right) \cdot \cos \omega_{RF} t$$
Confinement with RF fields: Paul traps

- Fundamental frequencies of the ion motion:

\[ \omega_{u,n}(t) = \left(n + \frac{1}{2} \beta_u \right) \omega_{RF} \]

\[ \omega_{u,0}(t) = \left( \frac{1}{2} \beta_u \right) \omega_{RF} = \frac{1}{2} \left( \sqrt{a_u + \frac{1}{2} q_u^2} \right) \omega_{RF} \]

- Time-average potential depth:

\[ \bar{D}_u = \frac{m}{8} \omega_{RF}^2 r_0^2 \beta_u^2 \]
Stability diagrams: Paul traps
Stability diagrams: Paul traps

- Optimum trapping conditions in Paul traps
- Theory
- Laser fluorescence
Several configurations: Paul traps
Paul traps

\[ V_{\text{RF}} \cos(\omega_{\text{RF}} t) \]

\[ V_{\text{dip}} \cos(\omega_{\text{dip}} t) \quad \text{or} \quad -V_{\text{dip}} \cos(\omega_{\text{dip}} t) \]

\[ V_{\text{quad}} \cos(\omega_{\text{quad}} t) \quad \text{or} \quad V_{\text{quad}} \cos(\omega_{\text{quad}} t) \]

Ring #1, 2

\[ V_{\text{RF}} = 130V_{\text{pp}} \]

\[ \nu_{\text{RF}} = 1.15 \text{ MHz} \]

Storage time

Excitation time

Pulsed C.
Oscillation frequencies

Counts

Secular frequency /kHz

ν

ν_{z}

2ν_{z}

ν_{RF}-2ν_{z}
Excitation frequencies: Paul traps

\[ ^6\text{Li}^+ \quad \nu_{RF} = 1.15 \text{ MHz} \]

\[ ^{23}\text{Na}^+ \quad \nu_{RF} = 650 \text{ kHz} \]
Confinement with RF fields: Mass filters

- Equipotential lines are hyperbola.

\[ \Phi = \Phi_0 \left( \frac{x^2 - y^2}{r_0^2} \right) \]

\[ \Phi = \Phi(t) \rightarrow \text{RFQ} \]
Confinement with RF fields: Mass filters

- Potential:
  \[
  \Phi = (U_0 + V_0 \cos \omega t) \cdot \frac{(x^2 - y^2)}{2r_0^2}
  \]

- Equations of motion (Mathieu equations):
  \[
  \frac{d^2 x}{d^2 t} + \frac{\omega_{RF}^2}{4} (a + 2q \cdot \cos(\omega_{RF} t)) x = 0
  \]
  \[
  \frac{d^2 y}{d^2 t} - \frac{\omega_{RF}^2}{4} (a + 2q \cdot \cos(\omega_{RF} t)) y = 0
  \]
  \[
  \frac{d^2 z}{d^2 t} = 0
  \]
Stability diagrams: Mass filter

\[ q = \frac{2eV}{mr_0^2 \omega_{RF}^2} \]
\[ a = \frac{4eU}{mr_0^2 \omega_{RF}^2} \]

\[ b_x = 1 \quad b_y = 0 \]

Tip of the stability diagram
Ion motion in Paul traps

Secular motion

\[ u_{\text{sec}}(t) = u_{\text{sec}} \cos(\omega_{\text{sec}} t) \]

\[ \omega_{\text{sec}} = \frac{q \omega_{RF}}{2\sqrt{2}} \]

\[ V_{\text{eff}} = \frac{qV}{4u_0^2} u^2 \]

Micromotion

\[ u_{\text{mic}}(t) = \frac{q}{2} u_{\text{sec}} \cos(\omega_{\text{mic}} t) \]

\[ \omega_{\text{mic}} = \left( n \pm \frac{q}{2\sqrt{2}} \right) \omega_{RF} \quad n = 1, 2, \ldots \]
Confinement with Magnetic fields: Penning traps

- Equipotential lines are hyperboloids of revolution.

\[ V = \frac{V_0}{2d^2} \left( z^2 - \frac{r^2}{2} \right) \]

\[ d^2 = \frac{1}{2} \left( z_0^2 + \frac{r_0^2}{2} \right) \]
Different geometries: Penning traps
Confinement with magnetic fields: Penning traps

- Electric field:
  \[ \vec{E}_r = \frac{V_0}{2d^2} \hat{r} \]
  \[ \vec{E}_z = -\frac{V_0}{d^2} \hat{z} \]

- Equations of motion:
  \[ m \frac{d^2 \hat{z}}{dt^2} = q \cdot \vec{E}_z \]
  \[ m \frac{d^2 \hat{r}}{dt^2} = q \cdot (\vec{E}_r + \frac{d \hat{r}}{dt} \times \vec{B}) \]
  \[ \Rightarrow i \omega_c \frac{du}{dt} - \frac{\omega_z^2 u}{2} + \frac{d^2 u}{dt^2} = 0 \]
  \[ \Rightarrow u(t) = u_0 e^{-i\omega t} \]
Ion motion: Penning traps

Axial motion

\[ \omega_z = \sqrt{\frac{Q \Phi_0}{md^2}} \]

Reduced cyclotron motion

\[ \omega_+ = \frac{1}{2} \left[ \omega_c + \sqrt{\left( \omega_c^2 - 2 \omega_z^2 \right)} \right] \]

\[ \omega_- = \frac{1}{2} \left[ \omega_c - \sqrt{\left( \omega_c^2 - 2 \omega_z^2 \right)} \right] \]

Magnetron motion

\[ \omega_c = \frac{Q}{m} B \]

\[ \omega_c = \omega_+ + \omega_- \]

\[ \omega_+ > \omega_z > \omega_- \]

\[ \omega_+^2 + \omega_z^2 + \omega_-^2 = \omega_c^2 \]
Ion motion: Penning traps

\[
2 \frac{\omega_+}{\omega_z} = \frac{\omega_z}{\omega_-}
\]

\( R_+ < R_- \quad R_+ > R_- \)
Several configurations: Penning traps
Landau levels of ions in a Penning trap

Energy of the harmonic oscillators

\[ E = \hbar \omega_+ \left( n_+ + \frac{1}{2} \right) + \hbar \omega_z \left( n_z + \frac{1}{2} \right) - \hbar \omega_- \left( n_- + \frac{1}{2} \right) \]

Reduced Cyclotron motion
Axial motion
Magnetron motion

MAGNETRON MOTION IS UNSTABLE
Ion traps at radioactive beam facilities. Cooling
Production and separation of exotic nuclei

- **ISOL method**
  - Spallation
  - Fusion evaporation
  - 1 GeV
  - $^20_1\text{Fr}$
  - $^11_2\text{Li}$
  - $^{143}_{85}\text{Cs}$
  - $^8_{16}\text{Zn}$
  - $^{208}_{82}\text{Pb}$
  - $^{277}_{112}$

- **In-flight method**
  - Fragmentation
  - Fission
  - 5 MeV/u

**In-flight method**
Production and separation of exotic nuclei

\[ \vec{F}_{\text{res}} = q (\vec{E} - \vec{v} \times \vec{B}) = 0 \]

\[ \vec{v} \perp \vec{B} : v = -\frac{E}{B} \]

Intensity of the primary beam from UNILAC: \(2 - 5 \times 10^{12}\) ions/s

Mass of the projectile: 40 - 80

Target: e.g. Pb, Bi

Target thickness: 0.5 mg/cm$^2$
Advantages of ion traps

Production and separation of heavy elements

Pure and cool ensembles of transuranium nuclides at rest or at low and well defined energies.

Investigations of nuclear, atomic and chemical properties in high precision experiments.

Long storage time

Precise manipulation of the ion motion

Small phase space
But...

- Radioactive ion sources provide exotic nuclei at very high energies.
- The exotic nuclei are delivered with non-ideal ion optical properties.

Large transverse emittance
Large energy spread ($\Delta E$).
Large time structure ($\Delta t$).

\[ \varepsilon_{\text{trans},x} = \pi \cdot \Delta x \times \Delta \theta_x \]
Ion manipulation and cooling

- Resistive cooling.
- Buffer-gas cooling (collisional cooling).
- Laser cooling.
- Sideband cooling.
- Radiative cooling (for cyclotron motion of electrons).
- Adiabatic cooling.
- Evaporative cooling.
- Sympathetic cooling (by second ion species).
- Stochastic cooling.
The phase-space density of a system is conserved in the absence of dissipative forces

\[ \Delta p_x \Delta p_y \Delta p_z \Delta x \Delta y \Delta z = \text{constant} \]

The evolution of the system can be described separately in each direction

- The phase space can be divided in three action diagrams.

\[ \Delta p_u \Delta u = \text{constant} \quad u = x, y \]
\[ \Delta E \Delta t = \text{constant} \]

Collisions of ions with buffer gas atoms or molecules

- Can reduce the area of the action diagrams (emittance).
- Universal. Any ion can be practicable.
- Fast. Within less than 1 ms.
- Easy implemented.

Confinement of the ions is needed

- Electromagnetic forces can provide this confinement.
Buffer-gas cooling

Hard ball collisions

\[ V(r) = \frac{C}{r^n} \]

\[ \frac{\partial E}{\partial t} = -\frac{m_{ion} \cdot m_{gas}}{(m_{ion} + m_{gas})^2} n \sigma v \cdot E \]

Ion polarizes the atoms in the gas

\[ V(r) = -\frac{A}{r^4} \]

Viscous drag

\[ \frac{\partial E}{\partial t} = -\frac{2e}{Km} \cdot E \]
Mobility versus collisions

\[ \alpha_E = \frac{m_{\text{ion}} \cdot m_{\text{gas}}}{(m_{\text{ion}} + m_{\text{gas}})^2} n \sigma v \]

\[ K_c = \frac{2e}{m} \cdot \frac{1}{\alpha_E} \]

Ar\(^+\) ions in He at \(10^{-3}\) mbar
Coupling of ion traps to RIB facilities

In-Flight method

$E_{ ions } = 20 \text{ keV/u} - 400 \text{ MeV/u}$

Gas-filled stopping chamber

ISOL method

$E_{ ions } = 30-60 \text{ keV}$

RFQ buncher

Penning/Paul traps

$E_{ ions } \sim eV$

Gas-filled stopping chamber

In-Flight method

$E_{ ions } = 20 \text{ keV/u} - 400 \text{ MeV/u}$

ISOL method

$E_{ ions } = 30-60 \text{ keV}$

RFQ buncher

Penning/Paul traps

$E_{ ions } \sim eV$
In-flight: the gas-filled stopping chamber

Gas flow + RF + DC fields

Detector
Nozzle
Extraction RFQ

DC voltage cage

Entrance window

Beam from SHIP

Funnel

To the SHIPTRAP Buncher
Gas flow
RF+DC fields
ISOL-method: the RFQ buncher

- Ion cooling in buffer gas.
- Ion extraction in short bunches with low emittance.
- Ion collection and accumulation.

\[ V_{RF} \cos(\omega_{RF} t + \pi) \]
Time constant

\[ \tau \text{ [ ms ]} \]

Ar\(^+\) ions in He at \(10^{-3}\) mbar

\[ \frac{d^2 u_{sec}}{dt^2} - \delta \frac{du_{sec}}{dt} - \frac{q^2 \omega_{RF}^2}{8} u_{sec} = 0 \quad \tau_{sec} = 4\tau_E \]
Cooling

- Radial motion

\[ x(t) = A_1 \]

- Effect of the buffer gas on the radial motion

\[ x(t) = A_2 \]
Bunching: SHIPTRAP

• A potential well is needed in the axial direction
  • Fast cooling in transverse direction.
  • Enough length to reduce the axial energy.
  • Transport of the ions (axial electric field).

• Segmentation of the RFQ.

\[ V_{RF} \cos(\omega_{RF} t) \]
\[ V_{RF} \cos(\omega_{RF} t+\pi) \]

• Inclined electrodes.

R.B. Moore \textit{et al.}

A. Loboda \textit{et al.}
A potential well is needed in the axial direction.
Fast cooling in transverse direction.
Enough length to reduce the axial energy.
Transport of the ions (axial electric field).

Segmentation of the RFQ.

Injected ions

Extracted ion bunch

Buffer gas

$U_{DC}$

$z$

Trapping

Ejection

Ion bunch

$V_{RF}$

$V_{RF} \cos(\omega_{RF} t)$

$V_{RF} \cos(\omega_{RF} t + \pi)$

R.B. Moore et al.

Inclined electrodes.

A. Loboda et al.


COUNTS

FWHM = 1.5 $\mu$s

FWHM = 1.01 $\mu$s

FWHM = 510 ns

FWHM = 260 ns

FWHM = 230 ns

COUNTS

COUNTS

COUNTS

COUNTS

Bunching: SHIPTRAP
Cooling and bunching of $^4$He$^+$ ions

- $P_{H_2} = 8 \cdot 10^{-3}$ mbar
- $I_{\text{incident}} = 75$ pA
- $\forall \tau_R (^4\text{He}^+) = 1$ ms
- $N_{\text{max}} = 4 \cdot 10^5$ ions/bunch
- Efficiency = 5 %
- $FWHM (^4\text{He}^+) = 100$ ns

ISOLTRAP, University of Jyväskylä

• First coupling of traps to radioactive ion beams
  - ISOLDE beam
    \[ \varepsilon \sim 30 \pi \text{ mm mrad} \]
    \[ E \sim 60 \text{ keV} \]
    \[ \text{DC-like} \]
  - Buncher beam
    \[ \varepsilon_{\text{trans}} \sim 10 \pi \text{ mm mrad} \]
    \[ E \sim 2.5 \text{ keV} \]
    \[ \varepsilon_{\text{long}} \sim 10 \text{ eV}\mu\text{s} \]

• Efficiency of 12-15%.
  • An improvement of several orders of magnitude.

F. Herfurth et al., NIMA 469, 264 (2001)

Laser spectroscopy

• IGISOL beam
  \[ \varepsilon \sim 13 \pi \text{ mm mrad} \]
  \[ E \sim 60 \text{ keV} \]
  \[ \Delta E \sim 80 \text{ eV} \]
  \[ \text{DC-like} \]

• Buncher beam
  \[ \varepsilon \sim 3 \pi \text{ mm mrad} \]
  \[ \Delta E < 1 \text{ eV} \]
  \[ \Delta t \sim 5-10 \mu\text{s} \]

• Efficiency of 60%.

A. Nieminen et al., NIMA 469, 244 (2001)

Laser spectroscopy on \(^{175}\text{Hf}\)

A. Nieminen et al., PRL 88, 094801 (2002)

Laser spectroscopy on \(^{96-102}\text{Zr}\)

P. Campbell et al., PRL 89, 082501 (2002)

Mass measurements

<table>
<thead>
<tr>
<th>Nuclid</th>
<th>Half-life</th>
<th>Uncertain</th>
<th>Yield</th>
</tr>
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<tbody>
<tr>
<td>(^{104}\text{Zr})</td>
<td>(1.2 \text{ s})</td>
<td>(50 \text{ keV})</td>
<td>(~200/\text{s})</td>
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</table>


Highlights 2003 / 2004

<table>
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<th>Nuclid</th>
<th>Half-life</th>
<th>Uncertain</th>
<th>Yield</th>
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<tr>
<td>(^{17}\text{Ne})</td>
<td>(109 \text{ s})</td>
<td>(~300 \text{ eV})</td>
<td>(~1000/\text{s})</td>
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<tr>
<td>(^{22}\text{Na})</td>
<td>(2.6 \text{ y})</td>
<td>(160 \text{ eV})</td>
<td>(~10^6/\text{s})</td>
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<td>(^{32}\text{Ar})</td>
<td>(98 \text{ ms})</td>
<td>(1.8 \text{ keV})</td>
<td>(~100/\text{s})</td>
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<tr>
<td>(^{72}\text{Kr})</td>
<td>(17.2 \text{ s})</td>
<td>(8.0 \text{ keV})</td>
<td>(~1000/\text{s})</td>
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<tr>
<td>(^{74}\text{Rb})</td>
<td>(65 \text{ ms})</td>
<td>(4.5 \text{ keV})</td>
<td>(~500/\text{s})</td>
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</table>

K. Blaum et al., Nucl. Phys. A 746, 305c (2004), private communication
High precision experiments in nuclear physics
Excitation of the ion motion in Penning traps

\[ V(t) = V \cos(\omega_{RF} t) \]

\[ V(t) = V \cos(\omega_{RF} t + \pi) \]
Buffer-gas cooling in Penning traps

- Increase of the cyclotron radius when no excitation is applied.
- Centering of the ions after excitation at $\omega_{RF} = \omega_c$. 
The principle of mass measurements in Penning traps.

External RF quadrupole field with \( \omega_{RF} = \omega_{C} (= \omega_{+} + \omega_{-}) \)

\[
t = 0 \\
\mu = \mu_{\text{min}}
\]

\[
t = T_{RF} \\
\mu = \mu_{\text{max}}
\]

\[
F_z = \mu \frac{\partial B}{\partial z}
\]

\[
\text{TOF}_{\text{min}} \Leftrightarrow \mu_{\text{max}} \Leftrightarrow \omega_{RF} = \omega_{C}
\]
Time of flight resonance

\[ E_r(t) = \frac{1}{2} mR^2 k_0^2 \frac{\sin^2(\omega_B T_{RF})}{\omega_B^2} \]
Mass measurements with SHIPTRAP

Statistical uncertainty
Magnetic field fluctuations
Mass-dependent uncertainty
Residual systematic uncertainty
Overall uncertainty of a mass determination

1–5 \cdot 10^{-8}
7.3(5) \cdot 10^{-11} \cdot \Delta T [\text{min}]
1.1(1.7) \cdot 10^{-10} \cdot \Delta (m/q) [u]
4.2 \cdot 10^{-8}
\sim 5 \cdot 10^{-8}
The measurement sequence

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<th>TARGET &amp; ION SOURCE</th>
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<tr>
<td>PROTON PULSE</td>
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<td>(1)</td>
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<td>DIFFUSION &amp; IONISATION</td>
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<td>ACCUMULATION</td>
<td>5 - 500 ms</td>
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<td>EXTRACTION</td>
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<tr>
<td>PULSED CAVITIES</td>
<td>* HF PulsDown</td>
<td>* Switch1</td>
<td>Delay1</td>
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<td>Delay2</td>
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<th>COOLER TRAP</th>
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<td>(6)</td>
</tr>
<tr>
<td>AXIAL COOLING</td>
<td>80 ms</td>
<td>20 ms</td>
<td>(7)</td>
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<tr>
<td>RF (MAGNETRON)</td>
<td>100 ms</td>
<td>10 ms</td>
<td>(8)</td>
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<tr>
<td>RF (CYC Lotron)</td>
<td>50 ms</td>
<td>35 ms</td>
<td>(9)</td>
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<tr>
<td>RADIAL COOLING</td>
<td>50 ms</td>
<td>10 ms</td>
<td>(10)</td>
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<tr>
<td>EXTRACTION</td>
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<td>CAPTURE</td>
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<td>Delay1</td>
<td>(12)</td>
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<td>RF (MAGNETRON)</td>
<td>Delay2</td>
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<td>(13)</td>
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<td>RF (CLEANING)</td>
<td>Delay3</td>
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<td>(14)</td>
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<td>RF (CYC Lotron)</td>
<td>Delay4</td>
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<td>(15)</td>
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<tr>
<td>EXTRACTION &amp; START OF MCA</td>
<td>150 ms</td>
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rp-process

- Nucleosynthesis e.g. on accreting neutron stars
- Explosive hydrogen burning (X-ray bursts)
- Steady-state burning

Evolution of the process depends on p-density and temperature in stellar environment

Astrophysical observations: elemental abundance, light curves

Required nuclear data:
- Masses (sep. energies, Q-values)
- $\beta$ decay half-lives
- Reaction rates

The Sn-Sb-Te cycle

H.Schatz et al., PRL 68, 3471 (2001)
Measurements along the rp-process
Mass measurements with ISOLTRAP

![Diagram of ISOLTRAP setup]

- **ISOLDE ion beam (DC):** 60 keV
- **Buffer-gas filled linear Paul trap**
- **HV Platform (60 kV)**
- **C cluster reference ion source**
- **Nd:YAG laser 532 nm**
- **C$_{60}$ pellet**
- **Alkali reference ion source**
- **$\nu_{RF} = 1230281.54$ (Hz)**
- **$^{74}$Kr**

**Graph:**
- **Mean time of flight (μs):**
  - 230
  - 220
  - 210
  - 200
  - 190
  - 180
  - 170
- **Frequency range:** -6 to 6
Mass measurements with ISOLTRAP

![Graph showing mass measurements with ISOLTRAP]
Mass measurements with ISOLTRAP

![Graph showing mass measurements with ISOLTRAP. The x-axis is labeled 'Datum' and the y-axis is labeled 'D (keV).']
Astrophysics: The mass of $^{72}$Kr

- Network calculations

- $^{74}$Sr 50 ms
- $^{73}$Rb <27 ns
- $^{72}$Kr 17 s

- ME($^{73}$Rb, $^{74}$Sr) using Coulomb shifts from Brown et al. PRC 65 (2002) 5802
- Proton capture rates as in Schatz et al. PRL 86 (2001) 3471

- Effective lifetime /s vs Temperature /GK

- ISOLTRAP
- AME 1995

D. Rodríguez et al., PRL 93 (2004) 161104
Decay in the buffer-gas-filled preparation trap

Produced at ISOLDE

Not produced at ISOLDE

- Make more radioactive species available
- Nearly simultaneous $\omega_c$ measurement of mother and daughter nuclei
- Test candidate: $^{37}\text{K} \to ^{37}\text{Ar}$
Standard Model: search for exotic couplings

• Nuclear $\beta$ decay spectrum

$$N \left| K_e, t_R \right| dK_e dt_R = F(\pm Z, E_e) C(\mathcal{E}_e) \left( p_v E_e + \frac{a}{2} (p_R^2 - p_e^2 - p_v^2) \right) \frac{p_R^2}{t} dK_e dt_R$$

$$a_F = \frac{C_V^2 - C_S^2}{C_V^2 + C_S^2} \quad a_{GT} = \frac{1}{3} \frac{C_T^2 - C_A^2}{C_T^2 + C_A^2}$$

- Experimental results
  - $^{6}\text{He}$ (1963)
  - $^{19}\text{Ne}$ (1959)
  - $^{35}\text{Ar}$ (1959)
  - $^{32}\text{Ar}$, $^{33}\text{Ar}$, $^{35}\text{Ar}$ (1999)
  - $^{37}\text{K}$, $^{38m}\text{K}$ (1978)

$$a_{GT} = -0.3308 \pm 0.0030$$

Standard Model: search for exotic couplings

$^6_2\text{He}^+$

0$^+$

806.7 ms

$Q_\beta = 3.5078 \text{ MeV}$

1$^+$

$^6_3\text{Li}^{++}$

- Pure Gamow-Teller transition.
- Maximal recoiling-ion energy 1.4 keV.
- High rate from SPIRAL 1$\cdot$10$^8$ ions/s.

- Any ion produced by the source can be practicable.
- Easy-to-use device.
- Easy to place at the low energy beam line of SPIRAL2.
- Better sensitivity to $a$.
- Better control of systematic errors.
The LPCTrap facility

Surface ion source $^{6,7}\text{Li}^+, 23\text{Na}^+$.. RFQ trap

LIRAT

PhD. Thesis G. Darius

HV

Diagnostics

PhD. Thesis P. Delahaye, A. Méry

Paul Trap

Pulsed cavities

3.5 m
Performance of the LPCTrap

<table>
<thead>
<tr>
<th>Buffer Gas</th>
<th>RFQ + Pulsed cavity 1</th>
<th>Transmission RFQ-Trap</th>
<th>Pulsed cavity 2</th>
<th>Trapping</th>
<th>Overall efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^4\text{He}^+$</td>
<td>5.6(8)%</td>
<td>40%</td>
<td>50(1)%</td>
<td>7.7(8)%</td>
<td>8.7(8)×10^{-4}</td>
</tr>
<tr>
<td>$^4\text{He}^+$</td>
<td>4.8(8)%</td>
<td>46%</td>
<td>25(1)%</td>
<td>12(2)%</td>
<td>6.6(12)×10^{-4}</td>
</tr>
<tr>
<td>$^4\text{He}^+$</td>
<td>119(5) ms</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>$^{36}\text{Ar}^+$</td>
<td>595(40) ms</td>
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</tbody>
</table>

Monte Carlo simulations GEANT4

- Control of the systematic effects on the measurements.
  - $e^-$ scattering and backscattering.
  - Size of the ion cloud.
  - Phase of the RF field.

- Using the SIMION grid concept to transport ions in GEANT4.

- Results compared to SIMION v.7 at energies down to 50 eV.
Kinematics properties

- Paul trap parameters:
  - $V_{RF} = 150$ V.
  - $v_{RF} = 1.15$ MHz.
- Detectors resolution:
  - Time of flight -> 400 ps.
  - Position MCP -> 120 μm.
  - Energy Scintillator -> 10%.
  - Energy DSSSD -> 1%.
  - Position DSSSD -> 1 mm.
The time of flight of the recoil ions

- Monte Carlo fit to the time-of-flight distribution of the recoil ions.
  - Size of the ion cloud.
  - RF Phase.
The main disturbance in the time-of-flight distribution arises from the RF field.