Design, Optimization and Construction of MRTOF mass analyzer at IMP/CAS

Yongsheng Wang
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Motivation

- Mass has been measured directly, 16
- Average life $\tau \geq 1$ s
- Average life $\tau < 1$ s

To measure the mass value of fusion-evaporation products, especially for the transuranium nuclei, directly.

Data from AME2016 and Ito Y. et al., PRL 120, 152501(2018)
SHANS at HIRFL

Spectrometer for Heavy Atoms and Nuclear Structure

Heavy Ion Research Facility at Lanzhou

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SHANS setup

The reaction products are identified by using energy, spatial and time correlations between the implants and subsequent $\alpha$ decays.

\[ {_{187}^{36}Re}^{(36Ar, 4n)}_{219}Np \]
\[ {_{187}^{40}Re}^{(40Ar, 5n)}_{222}Np \]
\[ {_{187}^{40}Re}^{(40Ar, 3\sim 4n)}_{223\sim 224}Np \]
\[ {_{182}^{36}W}^{(36Ar, 4n)}_{214}U \]
\[ {_{185}^{40}Re}^{(40Ar, 5n)}_{220}Np \]
\[ {_{180}^{40}W}^{(40Ar, 4\sim 5n)}_{215\sim 216}U \]
\[ {_{169}^{40}Tm}^{(40Ca, 4n)}_{205}Ac \]
Gas catcher collects evaporation-residues separated by SHANS and thermalizes them

SPIG extracts the thermalized ions from gas catcher

Ion trap provides high quality pulsed beam for mass analyzer

Mass analyzer separates the ions with different $m/q$

BN Gate deflects the unwanted ions

MCP is a time-of-flight detector

LPT is a Penning trap system
MRTOF-MSs nowadays

- High sensitivity
- Non-scanning
- Large mass range
- Short measurement time
- Low construction cost……
Basic theory of MRTOF-MS

\[ ToF = \alpha \left( \frac{m}{q} \right)^{1/2} + \beta \]

- 1 or 2 reference nuclei with well-known masses are needed
- Mass resolving power: \( R = \frac{m}{\Delta m} = \frac{ToF}{2\Delta ToF} \)

Switching-mirror mode

In-trap-lift mode

Injection

Confinement

Ejection

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Optimization of MRTOF-MS

Why?

The initial conditions of a cluster are complex.
The phase space is large, but the usable parameters are limited.

Goal?

To find out the optimal parameters.

How?

SIMION code for ion trajectory calculation.
Local code developed using C++ with Nelder–Mead simplex algorithm for parameter search.
Optimization procedure

A model is created in the SIMION according to the configuration of the MRTOF-MS

Global search: the initial parameters are elements from a potential matrix estimated roughly according to the knowledge of the beam optics

Local refine: inputting a few sets of relatively high resolving power from global search, a large number of local minima can be obtained and the best are chosen to be the optimal parameter sets

Advantages: the best parameter sets can be found; easy to change or expand the configuration

Disadvantage: very time consuming
Optimization conditions

Initial conditions

<table>
<thead>
<tr>
<th>Ion</th>
<th>Kinetic energy</th>
<th>Position</th>
<th>Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$K$ (eV)</td>
<td>$\delta K$ (eV)</td>
<td>$x$ (mm)</td>
</tr>
<tr>
<td>$^{40}\text{Ar}^{1+}$</td>
<td>1500</td>
<td>8.5</td>
<td>0</td>
</tr>
</tbody>
</table>

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Potential optimization

The optimal voltages can be found in different conditions (6.5ms as example)

<table>
<thead>
<tr>
<th>Elec. No.</th>
<th>M₁</th>
<th>M₂</th>
<th>M₃</th>
<th>M₄</th>
<th>L</th>
<th>Drift</th>
</tr>
</thead>
<tbody>
<tr>
<td>switching-mirror</td>
<td>2502.5</td>
<td>2002.2</td>
<td>1420.9</td>
<td>817.1</td>
<td>-4473.1</td>
<td>0</td>
</tr>
<tr>
<td>in-trap-lift</td>
<td>1159.5</td>
<td>756.5</td>
<td>743.9</td>
<td>-1262.9</td>
<td>-2234.2</td>
<td>703.5</td>
</tr>
</tbody>
</table>

![Diagram showing potential optimization](image)

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Length of the drift tube

Optimal length: 398-402 mm

Drift tube
The mass resolving power increases with the increasing of revolution numbers.

Beam size affects $R_{max}$ little at optimal parameter sets, but shows more significant influence at other set points.
The mass resolving power increases with the increasing of revolution numbers.

Beam size affects $R_{max}$ little at optimal parameter sets, but shows more significant influence at other set points.
TOF, $\Delta TOF, R$ with fixed potentials

- TOF almost increases linearly with the increase of number of revolutions
- The temporal spread decreases until a minimum, $\approx 20\, ns$
- Resolving power $R > 10^5$
Potential inaccuracy influence on electrodes where the ions turn around shows more significant influence to mass resolving power.
Construction of MRTOF mass analyzer at IMP/CAS

- Total length ≈ 1.5 m, total weight ≈ 70 kg, total number of parts ≈ 160
- Electrode material: 304 stainless steel
- Insulation material: Ceramic (low outgassing rate), Poly-Ether-Ether-Ketone/PEEK (excellent mechanical properties)
- Wires: Kapton cable (good conductive, voltage-resistant and insulating properties, and low outgassing rate)
Geometry parameters of components

Energy Cavity
- Length: 100 mm
- Diameter: 20 mm
- $C_{EC} \approx 90 \text{ pF}$

Einzel Lens
- Length: 30 mm
- Diameter: 20 mm
- $C_{M1} \approx 130 \text{ pF}$
- $C_{M2} \approx 100 \text{ pF}$
- $C_{M3} \approx 100 \text{ pF}$
- $C_{M4} \approx 110 \text{ pF}$
- $C_L \approx 130 \text{ pF}$
- $C_D \approx 280 \text{ pF}$
Overall assembly diagram

- Ion source
- BNG
- Energy Cavity
- MRTOF mass analyzer
- Einzel lens
- Detector
- Bracket
Ion source

Gas ion \(^{40}\text{Ar}^{1+}, \ ^{22}\text{Ne}^{1+}\) or alkali metal ion …

- **Function**: provide stable beam for off-line test and reference ion for online operation
- **Hot cathode discharge ion source**
  - advantage: large beam intensity, many kinds of ions, no limits on the life of ions
  - disadvantage: poor vacuum, regular maintenance
- **Surface ionization source**
  - advantage: stable, little impact on vacuum, no need for maintenance
  - disadvantage: limited types of ions, short service life at strong current
Pulsed Bradbury-Nielsen Gate (BNG)

- Convert a continuous beam into a pulse beam with a time-width of about 100 ns.
- Material: stainless-steel; diameter of wires: 50 μm; wire spacing: 250 μm

Timing control
Detector – MCP

- Integrated and compact electronics
- Strong anti-interference ability
- high signal-to-noise ratio

- Two outputs: Anode channel and HV channel
- Signal of anode channel: 600 mV
- Rise time: ≈ 2 ns

Provided by Dr. Wei Wang from IMP
Distributed control and data acquisition system
Sequential control system

- NI PXI-6602, a timing and digital input and output module
- 80 MHz internal clock source
- Set the delay time and pulse width of the controlled objects as needed
EPICS control interface
EPICS control interface

SR430 Control Panel

- Configuration:
  - Year: 2018
  - Month: 12
  - Day: 21
  - Hour: 10
  - Minute: 13
  - Second: 53

- Measurement:
  - Trigger:
    - Slope: Falling
    - Level (V): 1.100
    - Offset: 0

- Function Generator:
  - Discriminator:
    - Slope: Falling
    - Level (V): -0.025

- AUX Output:
  - AUX1 level (V): 2.00
  - AUX2 level (V): 2.00

- Load
- Save

General description:

Directory for config and data saving: f:\exp_data

Busy time: 0.000488 seconds

Mode:
- Bin clock source: Interr
- Bin width: 80 ns
- Bins/record (K): 1
- Records/Scan: 10000
- Accumulation mode: Add

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Photo of MRTOF mass analyzer
1. Ion source produces ion beam with energy of 200 eV.
2. The beam is pulsed under the action of the BNG.
3. The pulse beam is accelerated to 1500 eV.
4. The number of cycles specified by ions constrained and flown in the MRTOF mass analyzer.
5. The ions are detected by MCP detector to obtain the arrival time of ions recorded by the acquisition system.
How to test

- Test mode: Switching-mirror & In-trap-lift
- Test steps: Preliminary & Fine
- Test object: Time sequence & Voltage
Shoot-through TOF Spectrum ($^{40}$Ar$^+$)

The assignments confirmed by SIMION
According to the sequence diagram of $^{40}\text{Ar}^{1+}$, the low level pulse width of drift tube should be adjusted according to the actual situation.
Preliminary test results ($^{40}$Ar$^+$)

- $^{40}$Ar$^+$ can be constrained up to 120 revolutions, and there is a good linear relationship between TOF and the number of revolutions.
- When the number of revolutions is 75, mass resolving power $R \approx \frac{\text{TOF}}{2\Delta\text{TOF(FWHM)}} \approx 7,000$
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Upgrade

<table>
<thead>
<tr>
<th>Previous</th>
<th>Now</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion source:</td>
<td>Surface ion source</td>
</tr>
<tr>
<td>Discharge ion source</td>
<td>Surface ion source</td>
</tr>
<tr>
<td>$^{40}$Ar</td>
<td>$^{133}$Cs</td>
</tr>
<tr>
<td>Vacuum is very bad (~$10^{-5}$ mbar)</td>
<td>Vacuum is good (~$1.7x10^{-7}$ mbar)</td>
</tr>
<tr>
<td>• Ions could not fly beyond 120 laps</td>
<td>• Ions can not fly beyond 250 laps</td>
</tr>
<tr>
<td>• MCP detector died very quickly</td>
<td>• MCP detector works fine</td>
</tr>
<tr>
<td>• Ion current was high</td>
<td>• Ion current is low</td>
</tr>
</tbody>
</table>

HV switches: BELKE PS → CGC PS
Preliminary test results ($^{133}$Cs$^+$)

- $^{133}$Cs$^+$ can be constrained up to 250 revolutions, and there is a good linear relationship between TOF and the number of revolutions.
- When the number of revolutions is 150, mass resolving power

$$R \approx \frac{TOF}{2\Delta TOF(FWHM)} \approx 18,000.$$
Summary

- An MRTOF-MS at IMP/CAS is under construction.
- A new method for MRTOF-MS design is presented. Geometry, potential parameters can be optimized
- By simulation, $R_{max}$ for 1.5 keV $^{40}$Ar$^{1+}$ in a 4-electrodes mirror MRTOF-MS is $>10,0000$ both in switching-mirror and in-trap-lift modes
- Preliminary experimental test is completed. For $^{133}$Cs$^{1+}$, the mass resolving power $R$ has been achieved to be 18,000.

Collaborators

- Wenxue HUANG, Yulin TIAN, Junying WANG, Zaiguo GAN, Xiaohong ZHOU

Acknowledgements

- Peter SCHURY, Tommi ERONEN, Michiharu WADA, Yuta ITO, Ryan RINGLE, ……

Thanks for your attention!