Charge-state distribution measurements of $^{238}\text{U}$ using nitrogen gas and carbon foil charge strippers at 11, 14, and 15 MeV/nucleon

- Introduction
- Charge-state distribution measurements
  - $\text{N}_2$ gas stripper
  - C-foil stripper
- Results
- Empirical formulae
- Summary

RIKEN Nishina Center
Introduction

- RIBF: $^{238}\text{U}$ beam intensity > more than 10 times higher in near future
- Lifetime of carbon foil (C-foil) strippers will become more shorter.
  (now 5-9 hours for 60-90 pnA (2-3W) in Apr. 2010)
- Gas stripper: long lifetime
  but lower charge states
- $U^{69+}$: lowest charge state acceptable for fRC acceleration (at present)

![Charge stripper diagram]

- Higher energy incident on a charge stripper
  $\Rightarrow$ Higher charge states
- Which energy for $U^{69+}$?
  $\Rightarrow$ estimation from an empirical formula
- Possibility: remodeling accelerators upstream and downstream of charge stripper
  for U beam acceleration using gas stripper with the desired energy
- No data set for the charge states in C-foils obtained at RIBF
  $\Rightarrow$ charge distribution measurement using C-foil stripper
Energy at RRC exit:
$\text{U}^{35+,41+} \ 11, 14, 15 \text{ MeV/u}$

Experimental setup

- Beam from RILAC
- Gas charge stripper
- C-foil charge stripper
- Faraday cup F41
- Faraday cup A11
- RRC
- AVF

Experimental setup diagram dated Apr. 2010
Energy at RRC exit: $^{\text{U}^{35+,41+}}$ 11, 14, 15 MeV/u

**Experimental setup**

- Gas charge stripper
- C-foil charge stripper
- Faraday cup F41
- fRC

- Beam from RILAC
- Energy at RRC exit: $^{\text{U}^{35+,41+}}$ 11, 14, 15 MeV/u

**Table**

<table>
<thead>
<tr>
<th>Energy (MeV/u)</th>
<th>11</th>
<th>14</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (MHz)</td>
<td>18.25</td>
<td>18.25</td>
<td>19.00</td>
</tr>
<tr>
<td>Harmonics</td>
<td>9</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Initial charge state</td>
<td>35</td>
<td>41</td>
<td>41</td>
</tr>
</tbody>
</table>
Experimental setup

Apr. 2010

Energy at RRC exit:

$^{35,41+} 11, 14, 15 \text{ MeV/u}$

Faraday cup F41

Experimental setup

Gas charge stripper

Beam from RILAC

RRC

C-foil charge stripper

Faraday cup A11

Prof. Felix Marti
Accelerator group leader at MSU
Faraday cup D17

Faraday cup F41

Each charge state (q) was selected by bending magnets

Fractions:

\[ f = \frac{I_{F41}/q \text{ (pnA)}}{I_{D17}/q_{ini} \text{ (pnA)}} \]

\( q_{ini} \): 35 for 11MeV/u, 41 for 14, 15MeV/u
Charge-state distribution measurement (C-foil)

Each charge state \( q \) was selected by bending magnets.

Beam from RRC
\[ U^{35+, 41+} \]
11, 14, 15 MeV/u

Faraday cup A01a
C-foil charge stripper (Arizona Carbon Foil)

Faraday cup A11

\[ f = \frac{I_{A11}/q \text{ (pnA)}}{I_{A01a}/q_{\text{ini}} \text{ (pnA)}} \]

\( q_{\text{ini}} \): 35 for 11 MeV/u, 41 for 14, 15 MeV/u

C-foil charge stripper
ACF–Metals
Arizona Carbon Foil Co. Inc.
Charge-state distribution

<table>
<thead>
<tr>
<th>Energy(MeV/u)</th>
<th>Eq. charge</th>
<th>C-foil</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>56</td>
<td>72</td>
</tr>
<tr>
<td>14</td>
<td>61</td>
<td>76</td>
</tr>
<tr>
<td>15</td>
<td>62</td>
<td>77</td>
</tr>
</tbody>
</table>

Empirical formula

Form of fitting function: 

\[ q_{eq} = Z \left[ 1 - A \exp\left\{ - \left( \frac{v}{v_0} \right)^\delta \right\} \right] \]

\( (v_0: \) Bohr velocity)
Empirical formula

Form of fitting function: \[ q_{eq} = Z \left[ 1 - A \exp \left( - \left( \frac{v}{v_0} \right)^{\delta} \right) \right] \]

\(v_0\): Bohr velocity

Range of fitting
Gas: 0.008 – 60 MeV/u
Solid: 0.008 – 962 MeV/u

The value predicted by the new empirical formula is lower than the data by 1 charge state.

$U^{69+}$ can be obtained at 24 MeV/u in $N_2$ gas stripper.

The value predicted by the new empirical formula is lower than the data by 3-4 charge states.

The formula proposed by Baron agrees quite well with the data.

$$q_{eq} = Z \left[ 1 - A \exp\left( - \frac{v}{v_0} \right)^\delta \right] Z^\gamma$$

<table>
<thead>
<tr>
<th></th>
<th>$A$</th>
<th>$\delta$</th>
<th>$\gamma$</th>
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</thead>
<tbody>
<tr>
<td>$N_2$ gas</td>
<td>1.01</td>
<td>0.989</td>
<td>0.673</td>
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<tr>
<td>carbon</td>
<td>1.09</td>
<td>0.747</td>
<td>0.412</td>
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Summary

- U beam with 100 times higher intensity than present in near future
- Lifetimes of C-foil strippers will become shorter.  
  - possibility to use a gas stripper
- Charge-state distribution measurement using gas and C-foil strippers
- The empirical formulae for gas and solid media have been devised.
- Predicted value of energy for $U^{69+}$: 24 MeV/u in $N_2$ gas stripper

<table>
<thead>
<tr>
<th>Energy (MeV/u)</th>
<th>11</th>
<th>14</th>
<th>15</th>
<th>(24)</th>
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<tbody>
<tr>
<td>$N_2$ gas</td>
<td>56</td>
<td>61</td>
<td>62</td>
<td>(69)</td>
</tr>
<tr>
<td>carbon</td>
<td>72</td>
<td>76</td>
<td>77</td>
<td></td>
</tr>
</tbody>
</table>

- The charge states predicted by the emp. formula for gas agree with the data within 1 charge state.
- Those for solid are lower by 3-4 than the data.  
  Baron’s formula agrees quite well with the data.
Acknowledgements

We would like to thank:

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