Precision mass measurements at CSRe storage ring in Lanzhou

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(1) Motivation
(2) Experiment & results
(3) Recent technical developments
(4) Outlook
Motivation

Chemistry
\( \delta m/m < 1 \times 10^{-6} \)

Nuclear Physics
\( \delta m/m < 5 \times 10^{-7} \)

Nuclear Astrophysics
\( \delta m/m < 1 \times 10^{-7} \)

CPT, QED
\( \delta m/m < 1 \times 10^{-11} \)

Atomic physics, QED
\( \delta m/m < 1 \times 10^{-9} \)

Weak Int. Studies
\( \delta m/m < 1 \times 10^{-8} \)

Mass spectrometers for short-lived nuclei

MR-TOFs or Bρ-TOFs
Penning traps
Storage rings

CSRe Isochronous Mass Spectrometry

Unique features:
① Fast in production and detection: lower limit >0.05ms;
② Sensitive to single ion;
③ Broadband coverage of m/q in one experiment;
④ Accurate: isochronous condition (R~10^5)

\[ T = \frac{L}{v} = L \sqrt{\frac{1}{c^2} + \left(\frac{m/q}{B \rho}\right)^2} \]

\[ \frac{\delta T}{T} = \left( \frac{1}{\gamma_t^2} - \frac{1}{\gamma^2} \right) \frac{\delta (B \rho)}{B \rho} \]

Pulsed primary beam from CSRm, 1e8 ppp, v/c ~0.7

Production target

CSRe (experimental Cooler Storage Ring)
Summary: mass results from CSRe

Achieved precision
$10^{-6} \sim 10^{-7}$
(10-200 keV)
Experiment with $^{58}$Ni fragments

Precision mass measurements of short-lived N=Z−3 nuclei which were relevant to the rp-process (Rapid proton capture process).

$X$-ray burst

$p, \gamma \rightleftharpoons \gamma, p$ equilibrium

$$\frac{Y(Z + 1, N)}{Y(Z, N)} \propto \rho \exp\left[-\frac{M_{(Z+1,N)} + M_{(Z,N)} + M_p}{kT}\right]$$

For some key nuclei, $\sigma(m) < 50$ keV are required in the X-ray burst model calculations.

Experimental results

\[ R = \frac{m/q}{\Delta(m/q)} = \frac{1}{\gamma^2 \Delta T} \leq 0.8 \times 10^5 \text{ (FWHM)} \]

\[ \sigma(T) = 1.71(2) \text{ ps [minimum]} \]

Experimental results

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Count</th>
<th>ME(CSRe)</th>
<th>$T_{1/2}$ (Atom)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{41}$Ti</td>
<td>76</td>
<td>$-15698(28)$</td>
<td>82.6(5) min</td>
</tr>
<tr>
<td>$^{43}$V</td>
<td>42</td>
<td>$-17916(42)$</td>
<td>79(2) ms #</td>
</tr>
<tr>
<td>$^{45}$Cr</td>
<td>218</td>
<td>$-19514(35)$</td>
<td>60.9(4) ms #</td>
</tr>
<tr>
<td>$^{47}$Mn</td>
<td>119</td>
<td>$-22566(32)$</td>
<td>88(1) ms #</td>
</tr>
<tr>
<td>$^{49}$Fe</td>
<td>338</td>
<td>$-24750(23)$</td>
<td>64.7(3) ms #</td>
</tr>
<tr>
<td>$^{53}$Ni</td>
<td>651</td>
<td>$-29630(25)$</td>
<td>55.2(7) ms #</td>
</tr>
<tr>
<td>$^{55}$Cu</td>
<td>19</td>
<td>$-31635(181)$</td>
<td>27(8) ms #</td>
</tr>
</tbody>
</table>

$\sigma(m)/m \sim 0.5 - 3.5 \times 10^{-6}$

Effects of the newly measured masses

With our new measurement of the $^{45}\text{Cr}$ mass, we obtain $\text{Sp}^{(45}\text{Cr}) = 2.69 \pm 0.13 \text{ MeV}$, basically excluding the formation of a significant Ca–Sc cycle in X-ray bursts. One uncertainty in rp-process caused by $^{45}\text{Cr}$ nuclear mass has been removed.
Recent developments

 Maximum mass resolving power (FWHM)

- ① data analysis improvements
- ② Slit cuts in the beam-line
- ③ 2-TOF IMS

New direction: 2-TOF IMS
Slit cuts in the beam-line

Data from P. Shuai & X. Xu (2014)

\[
\frac{\sigma_{\beta\rho}}{B\rho} = 6.60(6) \times 10^{-4}
\]

\[
\frac{\sigma_{\beta\rho}}{B\rho} = 4.39(5) \times 10^{-4}
\]

\[
R = \frac{m/q}{\Delta(m/q)} = \frac{1}{\gamma^2} \frac{T}{\Delta T} = \frac{1}{\gamma^2} \frac{T}{2.355\sigma(T)} = \frac{1}{2.355} \left( \frac{1}{\gamma^2/\gamma_t^2} - 1 \right) \frac{B\rho}{\sigma(B\rho)}
\]

\[
R \leq 1.5 \times 10^5 (FWHM)
\]

\[
R \leq 1.8 \times 10^5 (FWHM)
\]

Side effect: the statistics will be reduced.
In-ring velocity measurement

Preliminary results from R. J. Chen (2016)

\[
v = \frac{l}{t}, \quad B\rho = \frac{m}{q} \gamma v
\]

\[
\frac{\delta_T}{T} = \left( \frac{1}{\gamma_t^2} - \frac{1}{\gamma^2} \right) \frac{\delta_B\rho}{B\rho}
\]

The technical challenges in order to achieve improved mass resolving power:

\[
\frac{\sigma(\gamma_t)}{\gamma_t} \leq 1 \times 10^{-4} \quad & \quad \frac{\sigma(v_i)}{v_i} \leq 1 \times 10^{-5} \quad (\Rightarrow \frac{\sigma(l)}{l}, \frac{\sigma(t)}{t} \leq 1 \times 10^{-5})
\]

Under development: 2-TOF IMS@CSRe
Outlook: a new storage ring SRing

Max $B\rho$ [Tm]

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>CSRe</td>
<td>8.4</td>
</tr>
<tr>
<td>SRing</td>
<td>15</td>
</tr>
</tbody>
</table>

Two ToFs

B. Wu et al., NIM. A, In press (2017)

Precision Mass Measurement of Neutron-rich Nuclei relevant to r-process
Thanks for listening
A new storage ring SRing @ HIAF

Max $\beta_\rho$ [Tm]

- CSRe: 8.4
- SRing: 15

$\beta_\rho$ acceptance

- CSRe: $\sim0.2\%$
- SRing: $\sim0.2\%$

@Isochronous mode

Typical intensity [ppp]

- CSRm: $1\times10^8$
- BRing: $1\times10^{11}$

**SRing, 270.5 m**

ToF detectors

**CSRe, 128.8 m**

ToF detectors

B. Wu et al., NIM. A, In press (2017)
Research vision

Precision mass measurements of short-lived neutron-rich nuclei relevant to r-process.

How are the elements from iron to uranium produced in the Universe?

For modelling of r-process nucleosynthesis, basic knowledge such as masses, beta-decay and neutron capture rates etc. are critical inputs. It is stated that a mass precision of $\delta m/m$ in the order of $10^{-6}$ is needed, whereas $10^{-7}$ or even better is necessary for specific cases such as waiting-point nuclei in the r-process path.


CSRe VS Penning trap

X. Xu et al.,
PRL 117, 182503 (2016)

D.A. Nesterenko et al.,
Revolution-time drifts caused by fluctuations of CSRe dipole magnetic field
The effects of $\Delta B$ on $\Delta T$

\[
\frac{\Delta T}{T} = \frac{\Delta L}{L} - \frac{\Delta v}{v} \quad \Delta L=0 \quad \frac{\Delta T}{T} = \frac{1}{\gamma^2} \frac{\Delta B}{B}
\]

\[
\left| \frac{\Delta B}{B} \right| \_{\text{fitted}} = 3.6(2) \times 10^{-5}
\]

\[
\left| \frac{\Delta B}{B} \right| \_{\text{hall-probe}} = 3.14(2) \times 10^{-5}
\]
grouped into 761 sub–spectra; \[ \Delta T = - \frac{\Delta B}{B} T + \frac{L^2}{c^2} \frac{\Delta B}{B} \frac{1}{T} = aT + \frac{b}{T} \approx kT + b \]
Further development 1: data analysis


\[ R \leq 0.8 \times 10^5 (FWHM) \]
\[ \sigma(T) = 1.73 \text{ ps [minimum]} \]

\[ R \leq 1.3 \times 10^5 (FWHM) \]
\[ \sigma(T) = 1.05 \text{ ps [minimum]} \]

\[ \frac{\Delta T}{T} = \frac{1}{\gamma^2} \frac{\Delta B}{B} \]
难点：
- 产额极低：每天1-5个
- 复杂系统最佳状态设置
- 高时间分辨
- 相同荷质比离子的鉴别
- 系统误差

建立先进的等时性质谱仪

CSRm

CSRe

RIBA2

千亿元枚炮弹产生一个目标离子

CSRe foil

MCP

TOF Detector
The Collaborations