Status and Future Plans for MRTOF Mass Measurements at RIKEN-RIBF

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- Motivation for MRTOF Mass Measurements at RIKEN-RIBF
- Achievements in the Past at GARIS-II
- Setups in Preparation
- Approved (Big) Construction Proposal
- Future Experiments
RIKEN’s RIBF facility

<table>
<thead>
<tr>
<th>Beam particle</th>
<th>E/A(MeV)</th>
<th>Beam current (pnA)</th>
<th>Maximum (instantaneous) achieved so far</th>
<th>Expected % (for exp. planning in your proposal)</th>
<th>Injector</th>
</tr>
</thead>
<tbody>
<tr>
<td>d'</td>
<td>250</td>
<td>1000</td>
<td></td>
<td>200</td>
<td>AVF</td>
</tr>
<tr>
<td>d(pol.)</td>
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<td>120</td>
<td></td>
<td>30</td>
<td>AVF</td>
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<tr>
<td>^4He</td>
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<tr>
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<td>400</td>
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<td>400</td>
<td>AVF</td>
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<tr>
<td>^18O</td>
<td>220</td>
<td>550</td>
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<td>400</td>
<td>AVF</td>
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<tr>
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<td>230</td>
<td>400</td>
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<td>AVF</td>
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<tr>
<td>^16O</td>
<td>250</td>
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<tr>
<td>^18O</td>
<td>250</td>
<td>200</td>
<td></td>
<td>200</td>
<td>AVF</td>
</tr>
<tr>
<td>^18O</td>
<td>345</td>
<td>1000</td>
<td></td>
<td>500</td>
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<tr>
<td>^48Ca</td>
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<td>RILAC</td>
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<td>200</td>
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<tr>
<td>^26Ge</td>
<td>345</td>
<td>not tested</td>
<td></td>
<td>N/A</td>
<td>RILAC</td>
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<tr>
<td>^78Kr</td>
<td>345</td>
<td>486</td>
<td></td>
<td>300</td>
<td>RILACZ</td>
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<tr>
<td>^68Kr</td>
<td>345</td>
<td>30</td>
<td></td>
<td>50</td>
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<tr>
<td>^132Xe</td>
<td>345</td>
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<td></td>
<td>20</td>
<td>RILACZ</td>
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<tr>
<td>^124Xe</td>
<td>345</td>
<td>100</td>
<td></td>
<td>80</td>
<td>RILACZ</td>
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<tr>
<td>^238U</td>
<td>345</td>
<td>58</td>
<td></td>
<td>40</td>
<td>RILACZ</td>
</tr>
</tbody>
</table>

† Some intensities are limited by shielding requirements

Marco Rosenbusch, EMIS 2018, CERN, Switzerland
Motivation for MRTOF Mass Measurements at RIKEN-RIBF

Masses to be measured

Experimentally Synthesized: $\approx 3300$

Mass Known ($\delta m/m < 10^{-6}$): 2300

Synthesized but Mass unknown: $\approx 1000$

note: many known masses were measured indirectly

cf. AME2016
Achievements in the Past at GARIS-II

SHE-Mass-I @ RIKEN RILAC

- Achievements in the Past at GARIS-II

GARIS-II

1st Ion Trap
Cryogenic
RF carpet
Gas Cell
Beam Transport (5m)

2nd Ion Trap

MRTOF Mass Spectrograph
Masses Measured in 2016 summer - 2017 spring

- > 80 masses were measured in total 4 weeks beam time
- 6 first masses in trans-uranium elements (Es, Md isotopes)
- > 30 first direct mass measurements
- known masses agree in 1σ with Penning Trap data,
- while a few discrepancy in old indirect measurements
- shortest T_{1/2} = 10 ms, with precision 2×10^{-7}
Achievements in the Past at GARIS-II

$^{250}$Md$^{++}$ Time of Flight Spectra

- $n = 144$ laps $^{205}$Tl + $^{48}$Ca
  - 7 counts/6000 s

- $n = 145$ laps $^{205}$Tl + $^{48}$Ca
  - 5 counts/6000 s

- $n = 145$ laps $^{197}$Au + $^{48}$Ca
  - 0 counts/4000 s

For $^{250}$Md$^{2+}$, the measured counts are shown with expected values.

Mass determined with $\delta m/m = 6 \times 10^{-7}$

- $n = 145$ laps $^{250}$Md$^{2+}$
  - ToF($^{250}$Md$^{2+}$) = 5652 584.8(2.1) ns

ToF Difference from Expected ToF($^{250}$Md$^{2+}$) (ns)

$\approx 1$ event /1000 s

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**TABLE I.** Measured isotopes, reactions, reaction energies at target center squared time-of-flight ratio to reference ion of $^{133}$Cs$^+$ ($\rho^2$), mass excess ($\Delta m$), and work. Mass excesses from the atomic mass evaluation 2016 (AME16) [27].

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Reaction</th>
<th>$E_{lab}$ (MeV)</th>
<th>$E_{recoil}$ (MeV)</th>
<th>$\sigma_{ER}$ (nb)</th>
<th>$\rho^2$</th>
<th>$ME_{MRTOF}$ (keV/(c^2))</th>
<th>$ME_{AME16}$ (keV/(c^2))</th>
<th>$\Delta m$ (keV/(c^2))</th>
<th>$N_{ion}$ (counts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{246}$Es</td>
<td>$^{232}$Th($^{19}$F, 5n)</td>
<td>99.6, 103</td>
<td>7.5, 7.8</td>
<td>$\sim$800 [26]</td>
<td>0.92574(35)1(44)</td>
<td>6781(109)(32)</td>
<td>67900(224)</td>
<td>-88(109)(32)</td>
<td>33</td>
</tr>
<tr>
<td>$^{251}$Fm</td>
<td>$^{238}$U($^{18}$O, 5n)</td>
<td>93.9</td>
<td>6.9</td>
<td>4000 [28]</td>
<td>0.944587(101)(44)</td>
<td>7599(6)(34)(15)</td>
<td>7595(4)(15)</td>
<td>42(34)(25)</td>
<td>397</td>
</tr>
<tr>
<td>$^{251}$Md</td>
<td>$^{203}$Tl($^{48}$Ca, 2n)</td>
<td>215</td>
<td>41.1</td>
<td>$\sim$40 [26]</td>
<td>0.93706(792)</td>
<td>7725(999)(221)</td>
<td>77232(105)</td>
<td>27(221)(26)</td>
<td>14</td>
</tr>
<tr>
<td>$^{250}$Md</td>
<td>$^{205}$Tl($^{48}$Ca, 3n)</td>
<td>223</td>
<td>42.3</td>
<td>$\sim$200 [26]</td>
<td>0.94083(491)</td>
<td>7847(138)(25)</td>
<td>78636(298)</td>
<td>158(138)(25)</td>
<td>29</td>
</tr>
<tr>
<td>$^{251}$Md</td>
<td>$^{205}$Tl($^{48}$Ca, 2n)</td>
<td>215</td>
<td>40.8</td>
<td>760 [29]</td>
<td>0.9445992(24)</td>
<td>7902(58)(60)</td>
<td>78967(19)</td>
<td>58(60)(23)</td>
<td>173</td>
</tr>
<tr>
<td>$^{252}$Md</td>
<td>$^{238}$U($^{19}$F, 5n)</td>
<td>98.6</td>
<td>7.3</td>
<td>500 [26]</td>
<td>0.94836(715)</td>
<td>80476(89)(22)</td>
<td>80511(130)</td>
<td>-44(89)(22)</td>
<td>63</td>
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<tr>
<td>$^{254}$No</td>
<td>$^{208}$Pb($^{48}$Ca, 2n)</td>
<td>219</td>
<td>41.1</td>
<td>2000 [30]</td>
<td>0.95590832(17)</td>
<td>8467(42)(19)</td>
<td>84723(4.3)</td>
<td>-48(42)(19)</td>
<td>398</td>
</tr>
</tbody>
</table>

**See poster of Y. Ito**

Y. Ito et al, PRL. 120, 102501 (2018)

Marco Rosenbusch, EMIS 2018, CERN, Switzerland
Transfer Reaction Products

Fusion Evaporation Products

P. Schury et al, to be submitted.

M. Rosenbusch et al, PRC 97, 064306 (2018)
Parallel Measurements @ 3 facilities of RIKEN RIBF

1. Thermalize in He gas
2. Extraction by RF-carpet
3. Trap in Ion-Traps
4. Mass measurements with MRTOF

Marco Rosenbusch, EMIS 2018, CERN, Switzerland
Combination of Decay and Mass

A. Confirm rare TOF events by $\alpha$-Energy & Decay time

B. Isomer - Ground state identification by $\alpha$-Energy & Decay time

Energy Gate
KISS (KEK Isotope Separation System)

n-rich nuclei via Multi-Nucleon Transfer

Ar gas cell - Resonant Ionization - Mass Sepa.

β γ · HFS · Mass Spectroscopy

MNT reaction: $^{136}$Xe beam + $^{198}$Pt target

• Deflection of 30kV beam successful
• Ions extracted from low-pressure GC
• ”mini”-MRTOF MS to be tested
• Injection into gas cell to be tested

Doughnut-shaped gas cell

Ionization laser

RIs

$^{136}$Xe + $^{198}$Pt

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Development of a novel SLOWRI gas-cell

Setups in Preparation

1st RFC test @ 3.7 MHz for $^{133}\text{Cs}$
Assembly of a 5 keV MRTOF MS for SLOWRI

under construction:
• Installation of electrodes finished
• Now cabling and HV tests (15kV for lens electrodes)
• Soon closing and pumping
For neutron rich nuclei and neutron deficient nuclei

\( \rightarrow \) impact for nucleosynthesis by measurement of neutron-emission branches
Masses of Super Heavy Nuclides

1. *pin down masses of hot-fusion “island”*
2. *confirm A and Z of hot-fusion SHE*

**Future Experiments**

- Direct Mass (Our Work)
- Indirect Mass (Our Work)
- Direct Mass (GSI)
- Indirect Mass (GSI)
- Discovered Nuclides (Mass Number A)

- **Japanese Nihonium**
- **Russian Nihonium**

**Masses to be measured**

**Place a first bridge to the Island**

Marco Rosenbusch, EMIS 2018, CERN, Switzerland
Approved experiments for usage of a vanadium beam:

2μA of $^{51}$V available behind the RRC (RIKEN Ring Cyclotron)

Expected:
- 100 cpd for Db
- 10 cpd Sb
- other isotopes of SHE expected
Acknowledgements

Thank you very much, and many thanks to the RIKEN- and KEK-MRTOF collaboration!
Technical studies: doubly-charged ions


Proton-rich isotopes at GARIS II

P. Kimura et al. IJMS 430, 134 (2018)
Candidates in first Hot Fusion SHE Mass Measurement

$$^{243}\text{Am}(^{48}\text{Ca}, \, 3n)^{288}\text{Mc} \rightarrow ^{284}\text{Nh} \rightarrow ^{280}\text{Rg}$$

0.5 mg/cm²  2 pµA  8.5 p.b.  4 /day@GARIS

$$^{243}\text{Am}(^{48}\text{Ca}, \, 4n)^{287}\text{Mc} \rightarrow ^{283}\text{Nh} \rightarrow ^{279}\text{Rg}$$

\[ \varepsilon_{\text{total}} = 10\% \\
10 \text{ events/month}! \]

other interesting mass measurements

$$^{248}\text{Cm}(^{14}\text{N}, \, 4n)^{258}\text{Lr} \hspace{1cm} \text{mass anchor for } ^{278}\text{Nh}$$

$$^{244}\text{Pu}(^{48}\text{Ca}, \, xn)^{292-}x\text{Fl} \rightarrow ^{288-}x\text{Cn} \hspace{1cm} \text{anchor for even hot fusion SHE}$$
Physics cases

- Pin down masses of hot-fusion SHE
  \[ ^{288}\text{Mc} \rightarrow ^{284}\text{Nh} \ \alpha \rightarrow ^{280}\text{Rg} \ \alpha \rightarrow ^{276}\text{Mt} \ \alpha \rightarrow ^{272}\text{Bh} \ \alpha \rightarrow ^{268}\text{Db} \ sf \]
  \[ ^{287}\text{Mc} \rightarrow ^{283}\text{Nh} \ \alpha \rightarrow ^{279}\text{Rg} \ \alpha \rightarrow ^{275}\text{Mt} \ \alpha \rightarrow ^{271}\text{Bh} \ \alpha \rightarrow ^{267}\text{Db} \ sf \]

- First Masses \( N > 162 \) deformed shell
  Island of Stability prediction depends strongly on \( N = 162 \) sub shell (cf. H. Koura)

- A identification
  \[ ^{243}\text{Am} (^{48}\text{Ca}, \ x n)^{291-xn}\text{Mc} \]
  2 events is sufficient
  How many \( n \) evaporated?

- Z identification
  \[ ^{243}\text{Am} (^{48}\text{Ca}, \ 0p0\alpha, \ x n)^{291-xn}\text{Mc} \]
  10 events is sufficient if theories are accurate
  Zero charged particle evaporated?

X-ray ?
chemistry ?

Not accepted by JWP of IUPAC+IUPAP
But, they ask “Direct Physical Method to identify \( Z \) as well as \( A \)”

Marco Rosenbusch, EMIS 2018, CERN, Switzerland
Mass measurement of $^{278}$Nh?

Circled nuclei have been previously studied by PTMS

Different colors indicate primary beam to be used:

| Mass | Target
<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>$^{15}$N</td>
<td>$^{22}$Ne</td>
</tr>
<tr>
<td>$^{40}$Ar</td>
<td>$^{48}$Ca</td>
</tr>
</tbody>
</table>

Marco Rosenbusch, EMIS 2018, CERN, Switzerland