Activities at KEK Wako Nuclear Science Center
KISS to KISS-II

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Abstract
KEK WNSC, located in the RIKEN RI-beam factory, aims to study the origin of heavy elements via precision spectroscopy of neutron-rich short-lived nuclides. KISS (KEK Isotope Separator System) pioneered multi-nucleon transfer (MNT) reactions to access neutron-rich nuclides that other facilities worldwide cannot access. Multi-reflection Time-of-Flight Mass Spectrograph (MRTOF-MS) plays an essential role in comprehensive atomic mass measurement of short-lived nuclides. KISS-II combines these original technologies to explore the origin of uranium for the first time.
Study of the origin of heavy elements:

**KEK WNSC**

**Observation**
- astronomical spectroscopy
- gravitational wave, etc

**Experiment**
- nuclear properties of nuclides,
  atomic spectroscopy, etc

**Theory**
- reaction network
calculation, etc

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s-process: almost done
r-process: few experimental data

\[ S_n = \text{“chemical potential” of equilibrium} \]
\[ \Delta S_{2n} \text{ shows Magic Number that causes “waiting point”} \]

Atomic masses of n-rich nuclides are essential properties

Comprehensive precision spectroscopy on mass, T/2, moments, level structure…

**Key inputs for theory**

neutron separation energies and atomic mass:

\[ S_n(N, Z) = M(N - 1, Z) + M_n - M(N, Z) \]
\[ S_{2n}(N, Z) = M(N - 2, Z) + 2M_n - M(N, Z) \]
\[ \Delta S_{2n}(N, Z) = S_{2n}(N, Z) - S_{2n}(N - 1, Z) \]
Status of WNSC activity
- territory of KISS is blue ocean
- > 300 more masses were measured
- many physics publications has been/will be published
- some great technical achievements
- many experimental plans are accepted
  (Mc,Nh, Db, Sg, Ta-Os, ~Ni78, N~126, N~Z, etc)

~ using KISS as well as other devices of RIBF ~

- M. Rosenbusch et al, in preparation
- S. Chen et al, in preparation
- M. Rosenbusch et al, in preparation

[Diagram of various facilities and nuclides studied at WNSC 2017-]
KISS (KEK Isotope Separator System)

- Origin r-process-III peak (Pt, Au)
  - Production & spectroscopy near N=126
  - Multi-nucleon transfer (MNT) for n-rich nuclide

ex. $^{136}\text{Xe} + ^{198}\text{Pt}$

- confirm $\sigma_{\text{MNT}}$ @VAMOS (GANIL)

Many people suggested MNT won’t work!!

Reasonably High $\sigma$ (> theory)

FIG. 2 (color online). Experimentally deduced (open circles) and calculated by GRAZING (histograms) cross sections for Hg (left) and Os (right) isotopes. Isotopic distributions for different
1. TLF of MNT, thermalize & neutralize in Ar
2. Element selection by laser ionization
3. Mass separation by ele-mag separator
4. Spectroscopy (β, γ, mass)

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

The KISS device

- High voltage (~20 kV)
- Target ($^{198}$Pt)
- MNT reaction
- Gas cell (Ar gas, neutralization)
- Laser resonance ionization (Z selection)

Y.H. et al. NIMB353(2015)4
NIMB376(2016)52
Nuclear spectroscopy at KISS

198Pt, nat.Pt, nat.W targets

- β-γ spectroscopy at KISS
- Mass at KISS
- Laser spectroscopy at KISS

Charge radius known

Not reached N=126 yet, however
- Laser spectroscopy (radii, moments)
- β γ (T1/2, level scheme) for difficult elements
- Mass measurements

many fruitful results (blue ocean!!)
MRTOF Mass Spectrograph

Ion Trap  Ion Mirror  Ion Mirror  detector

(Multi Reflection Time of Flight…)

1. Open entrance to inject
2. Close entrance before coming back
go back and forth for \( \approx 200 \) times
3. Open exit at pre-defined timing
4. Detect ions’ ToF

\[
m_x = \left( \frac{ToF_x}{ToF_r} \right)^2 m_r
\]

- fast (~15 ms)
- high mass resolving power (10^6)
- multiple isobar chains at once

we showed >300 atomic mass measurements
Mass Measurement of Superheavy elements

Spontaneous Fission

RIKEN’s nihonium.

Dubna’s nihonium

known nuclides

Spontaneous Fission

no link to known nuclides

ToF Singles Spectrum for Db isotopes

Direct Mass Determination of SHN for the first time!
Goal of Heavy Element Synthesis in the Universe: U & SHE

However, inaccessible by present world-class facilities: RIBF(Japan), FRIB(USA), FAIR(Germany)

Multi-Nucleon-Transfer (U+U, U+Am, Cm..) is a possible solution

However, some difficulties:
- Low energy (< few MeV/u)
- High multiplicity (> few hundreds)
- Large emittance
- Large scattering angle

A technical breakthrough is required!
**KISS-2**

**comprehensive measurements of all procured nuclides at once**

1) **Primary beam separation**
   - Remove majority of primary beam using a gas-filled solenoid allowing >1 particle-μA uranium beam

2) **Big Gas Cell + 3) MRTOF**
   - He gas catcher and RF-carpet provide low-energy beams of all produced nuclides
   - Multi-Reflection Time-of-Flight (MRTOF) mass spectrograph can measure masses of many nuclides at once

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### Projected relative gain compared with KISS

<table>
<thead>
<tr>
<th></th>
<th>primary beam</th>
<th>total efficiency</th>
<th>#nuclides / unit time</th>
<th>total gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>KISS</td>
<td>10 pnA</td>
<td>0.1%</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>KISS-2</td>
<td>1 puA</td>
<td>&gt;1%</td>
<td>&gt;10</td>
<td>&gt;10000</td>
</tr>
</tbody>
</table>

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**Primary beam separation**

- **1) Gas Filled Solenoid**
- **2) Big Gas Cell**
- **3) MRTOF-1**
- **4) ISOL (Achromatic or High Res)**

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**Cf. original KISS setup**

- Ar gas cell + Laser ionization for element selectivity and ISOL for mass number selection
- 5) GCCB+Ion Trap
- 6) MRTOF-2
- 7) α β γ spectrometer

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**Total budget:** $15M in 5 (setup) + 5 (exp.) years
We will discover >100 new nuclides in actinides.

Our “discovery” will not be in terms of existence but also atomic mass determination