Breakup of proton-rich nuclei at SAMURAI for investigation of astrophysical reaction rates in explosive hydrogen burning

Valerii Panin for HI-p SAMURAI collaboration

DRF, IRFU, DPhN Département de Physique Nucléaire, CEA Saclay, France
Spin-Isospin Laboratory, RIKEN Nishina Center for Accelerator-Based Science, Japan
• Half or more stars in our galaxy are binary systems:
  $\rightarrow \sim 10^{10}$ binaries in the Milky Way !!!
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• **Neutron star** companion:
  → information on neutron star properties
    (e.g. mass, radius, spinning frequency)
  → Constraining **Equation of State** of nuclear matter
    in high density and symmetry domain
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• **Accretion** of H/He matter from the companion star:
  → **thermonuclear runaway**
  → Boosted luminosity in X-ray wavelengths
  → Can be observed on Earth.
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- **Type I X-ray bursts**
  - Most common thermonuclear explosions in our Galaxy
    - over 100 LMXBs are known, thousands of bursts have been observed
  - Can be used as standard candles
  - Can explain antimatter (positron) distribution in the Milky Way  
    \((Nature \ 451, \ 159-162, \ 2008)\)
  - Possible production mechanism of p-nuclei via **rp-process** (e.g. \(^{92,94}\text{Mo}, \^{96,98}\text{Ru}, \text{etc.}) \)?

**Nuclear physics input is crucial for interpretation of XRB observables**
Type I X-ray bursts

- Low-mass binaries with a neutron star
- Accretion of matter from a donor star:
  - $10^{-8}/10^{-10} \, M_\odot/yr \ (0.5-50 \, \text{kg/s/cm}^2)$
- Compression of and heating of H/He-rich material on surface of the neutron star
  - Density: $\sim 10^6 \, \text{g/cm}^3$
  - Temperature: 1-2 GK
- Ignition and thermonuclear runaway, X-flash
  - $\sim 10^{39} \, \text{erg/s}$
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Typical XRB properties
- rise time: 0.5-5 s
- intensity increase: $\sim10$
- decrease: 10-100 s

Anomalous behaviour
- multiple peaked bursts
- long bursts: 30 min, $10^{41} \, \text{erg}$
- superbursts: 1-3 h, $10^{42} \, \text{erg}$

rp-process nucleosynthesis

$\alpha + \alpha + \alpha \rightarrow ^{12}\text{C}$

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\((\alpha, p)\) process

rp-process nucleosynthesis

- Waiting-point nuclei: bottlenecks of rp-process
  - Low Qp values: \((p,\gamma)-(\gamma,p)\) equilibrium
  - \(\beta\)-decay lifetimes are relatively long
    - rp-process is halted
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State-of-the-art sensitivity studies of several XRB models with respect to the nuclear physics input

- 606 isotopes network (from $^1$H to $^{113}$Xe) + over 3500 nuclear processes
- Different XRB models (variation of burst duration, peak temperatures, initial metallicities etc.)

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- 606 isotopes network (from $^1$H to $^{113}$Xe) + over 3500 nuclear processes
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Nuclear physics input:
- masses
- half-lives
- reaction rates

Theoretical XRB models
- Reaction network
- Fluid dynamic

XRB observables
- (e.g. light curves)

Around 50 reactions were identified as most influential

Most intense RI beams in the world

HI-p setup @ SAMURAI

Systematic study of the most important (p,$\gamma$) reaction rates:
- Complete and inverse kinematics measurements
- Decay of proton-unbound states (proton + HI in the exit channel)
- Wide range of nuclear masses (up to A~100)
SAMURAI29: Spectroscopy of $^{66}\text{Se}$

Abundance flow around $^{64}\text{Ge}$ ($T_{1/2} \approx 64\text{s}$)

- Is $^{64}\text{Ge}$ a strong waiting point?
- Large deviation of theoretical rates for $^{65}\text{As}(p,\gamma)^{66}\text{Se}$ (factor of $\sim 3$)
- Strong effect on light curves and energy generation rates
- Significant impact on the final abundances
- Suppressed abundance flow towards $A=100$?

SAMURAI25 (Z. Elekes, Atomki): Coulomb breakup of $^{36}$Ca, $^{36}$K and $^{35}$K

Parikh: energy output varying $^{35}$K$(p,\gamma)^{36}$Ca rate

Thielemann: light curve varying $^{35}$Ar$(p,\gamma)^{36}$K and 3 other rates
SAMURAI28 (B.C. Rasco): Coulomb and nuclear breakup of $^{28}$S and $^{32}$Ar


Experimental method

1. Nucleon removal to populate unbound excited states

1. Neutron removal from $^{67}\text{Se}$ and $^{59}\text{Zn}$
2. Proton-decay of the intermediate $^{66}\text{Se}$ and $^{58}\text{Zn}$
3. Invariant mass and excitation energy

$$E^* = \sqrt{\sum_{j} m_j^2 + \sum_{j \neq k} \gamma_j \gamma_k m_j m_k (1 - \beta_j \beta_k \cos \theta_{jk}) - M_0}$$
### Experimental method

#### 1. Nucleon removal to populate unbound excited states

<table>
<thead>
<tr>
<th>67Se</th>
<th>66Se</th>
<th>65As</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A+1)Z</td>
<td>A^Z</td>
<td>(A-1)Z-1</td>
</tr>
<tr>
<td>target</td>
<td></td>
<td>proton</td>
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</tbody>
</table>

#### 2. Coulomb dissociation

<table>
<thead>
<tr>
<th>36Ca, 36K, 35K</th>
<th>35K, 35Ar, 34Ar</th>
</tr>
</thead>
<tbody>
<tr>
<td>A^Z</td>
<td>A^Z</td>
</tr>
<tr>
<td>Pb target</td>
<td>proton</td>
</tr>
</tbody>
</table>

#### Calculations

1. Neutron removal from 67Se and 59Zn
2. Proton-decay of the intermediate 66Se and 58Zn
3. Invariant mass and **excitation energy**

$$E^* = \sqrt{\sum_{j} m_j^2 + \sum_{j \neq k} \gamma_j \gamma_k m_j m_k (1 - \beta_j \beta_k \cos \theta_{jk})} - M_0$$

4. Calculating CD cross section \(\rightarrow\) **resonance strength**

#### 1. \((\gamma,p)\) breakup of 36Ca, 36K and 35K \(\leftrightarrow\) time reversal (p,\(\gamma\))
2. 35K, 35Ar and 34Ar + proton(s) in the final state.
3. Invariant mass and **excitation energy**
Experimental method

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2. Coulomb dissociation

- $(\gamma,p)$ breakup of $^{36}\text{Ca}$, $^{36}\text{K}$ and $^{35}\text{K}$ $\leftrightarrow$ time reversal $(p,\gamma)$
- $^{35}\text{K}$, $^{35}\text{Ar}$ and $^{34}\text{Ar}$ + proton(s) in the final state.
- Invariant mass and excitation energy
- Calculating CD cross section $\rightarrow$ resonance strength

3. Nuclear breakup to measure ANC

- Nuclear breakup of $^{9}\text{C}$, $^{28}\text{S}$ and $^{31}\text{Ar}$
  - (removing valence proton)
- Momentum distributions of the residuals
- Asymptotic Normalization Coefficient $\rightarrow$ direct-capture cross section.
- Complementary measurements of Coulomb breakup to constrain systematic model uncertainties.
HI-p setup @ SAMURAI

Current beauty states:

- CATANA γ-ray detector + target
- GLAST SSDs
- SAMURAI magnet
- FDC2 (drift chamber): ToF wall for fragments
- PDCs (drift chambers for protons): ToF wall for protons
- BDCs
- STQ: beam 200 - 300 MeV/u
67Se beam energy: 269.2 ± 5.1 MeV/u
Angular spread of the beam: 5 mrad (sigma)

Target position: -4638 mm

Se beam energy: 269.2 ± 5.1 MeV/u
Angular spread of the beam: 5 mrad (sigma)

SBT: 2 x 0.2mm
Target position: -4638 mm

Protons from 66Se breakup @ $E_{\text{rel}} = 1$ MeV
PDCs+HODF acceptance 48%
Dual-gain ASIC preamplifiers for SSDs (RIKEN + Atomki)  
(PCB design by Gy. Hegyesi and Csaba Dósa, Atomki)

16 input signals from Si-strips

Stack of 4 PCBs -> 64 Si-strips

AUX input:
- Si-bias
- ASIC bias
- GND
- Test signal

Back side of the PCB

ASIC cooling ports

Fully equipped pair of silicons (256 strips)

A pair of single-sided
GLAST type SSDs
Thickness: 325 um
Readout pitch: 684 um
Active area: 87.6 x 87.6 mm$^2$
Number of strips: 128
Vacuum chamber and support structure for SSDs

3D model
(by Z. Halasz and N. Chiga)

SSDs
4 x 128 strips

beam

PCB support + cooling

Final setup
Vacuum chamber and support structure

- Vacuum chamber with SSDs inside
- Manual drive for alpha source
- Support structure and electronics racks
- 2 x HINP motherboards from Texas A&M with upgraded power units
- Pumping ports
- Feed-throughs
Detection $dE$ range from ~100 keV up to ~1 GeV

Simultaneous detection of protons and $Z \approx 50$ ions is possible at RIBF energies!
S29 experiment in June 2018 (L. Trache)

$^9$C @ $\sim$160 AMeV

PANDORA was removed for S29 run

See the presentation of A. Chilug

<table>
<thead>
<tr>
<th>Exp. No.</th>
<th>Name</th>
<th>Spokesperson</th>
<th>Primary beam</th>
<th>Secondary beam</th>
<th>Time</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>NP1412-SAMURAI 29R1</td>
<td>Inclusive and exclusive breakup of $^9$C in nuclear and Coulomb fields</td>
<td>L. Trache</td>
<td>18O @ 230MeV/u 500 pnA (originally 16O@345 MeV/u)</td>
<td>9C @ 160 MeV/u 50 kcps</td>
<td>3days</td>
<td>completed</td>
</tr>
</tbody>
</table>
Beam profile in SSDs

Proton signal in SSDs

Proton beam run

CD run
Summary

• Experimental program at RIKEN for astrophysics studies using exotic proton-rich nuclei

• Development of the silicon trackers and dual-gain preamplifier for heavy-ion-proton tracking
  • In collaboration with: Atomki (Hungary), IFIN-HH (Romania), Texas A&M (USA), Washington University (St. Louis, USA), Ewha Woman University (South Korea), …

• Successful tests and first experimental data with the fully equipped tracking system

• First experiment S29 from the HI-p campaign is completed. The analysis is ongoing

Outlook

• Purchasing/bonding additional sensors, manufacturing additional PCBs (one full set), improving the cooling system of preamp PCBs, importing HINP electronics from the US etc.

• Next HI-p experiment using 78Kr primary beam: probably in spring 2019 (S24)

• Development of $^{40}$Ca beam or other “uncommon” primary beams (e.g. $^{36}$Ar, $^{28}$Si) is needed for the production of secondary proton-rich beams with SRC+BigRIPS

• New experimental proposals

• Combining SSDs with MINOS for future experiments (?)