SAMURAI @ RIBF

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FRIB HRS Workshop
on July 11, 2014
at Michigan State University
"SAMURAI @ RIBF"
Today's contents

1. Overview
2. History
3. Properties/Constituents
4. Experimental programs
5. Summary
SAMURAI
~ New Spectrometer in RIBF ~

Construction ~ 2011
Commissioning : 2012/03
First experiments : 2012/05

Superconducting Analyzer for MUlti-particle from RAdio Isotope Beam with 7Tm of bending power

Kinematically complete measurements by detecting multiple particles in coincidence

- Superconducting Magnet 3T with 2m dia. pole (designed resolution 1/700)
  80cm gap (vertical)
- Heavy Ion Detectors
- Proton Detectors
- Neutron Detectors
- Large Vacuum Chamber
- Rotational Stage

Invariant Mass Measurement
Missing Mass Measurement
Various Physics scoped on SAMURAI

\[ xn + HI \text{ (neutron-rich side)} \]
\[ (\gamma, n), \text{ unbound nuclei…} \]

\[ p, n (\text{target frame}) + HI \]
\[ (p, p'), (p, 2p), (p, pn), \ldots \]

\[ p + HI \text{ (proton-rich side)} \]
\[ (\gamma, p), \text{ reaction,…} \]

\[ \text{pol. } d\text{-induced reaction} \]

\[ \text{EOS measurement} \]
Approved programs and SAMURAI configuration

*xn+HI (neutron-rich side) (γ, n), unbound nuclei...*

*Commissioning RUN:*
Day-one/two
SAMURAI21 (S grade): ²⁸O
SAMURAI20: ²⁶O life
SAMURAI09: Pigmy Dipole

*(γ, p) reaction,...*

Proposal Submitting to NPPAC on 2014/06

*p,n(target frame)+HI (p,p'), (p,2p), (p,pn), ...*

SAMURAI17,11: (p,n) inverse
SAMURAI14: Fission
SAMURAI12: Cluster on Be
SAMURAI13: Polarization
SAMURAI18 (w/ MINOS): 2n correlation

EOS measurement
SAMURAI15,22: EOS by π-/π+ measurement on HIC

On-Going
On-Preparation
~2014–2015

To be advanced
A>100 region

Budgetary Strategy Stage

To be completed
 xn+HI (neutron-rich side) 
\((\gamma, n)\), unbound nuclei…

\[ p + HI (proton-rich side) \quad (\gamma, p) \quad \text{reaction,} \ldots \]

\[ p, n \quad (\text{target frame}) + HI \quad (p, p') \quad (p, 2p) \quad (p, pn) \quad \ldots \]

pol. d-induced reaction

On-Going

<table>
<thead>
<tr>
<th>Stage</th>
<th>To be advanced</th>
<th>A&gt;100 region</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.(2014-2015) Budgetary Strategy</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Proposal Submitting to NPPAC on 2014/06

**Slide by Y. Kondo (Tokyo Tech)**

**Decay energy spectrum**

\[(^{27}F+C \rightarrow ^{26}O \rightarrow ^{24}O+2n)\]

- **Ground state**
  - 5 times higher statistics
  - Better determination of energy

- **Excited state** at \(~1.3\)MeV
  - First observation
  - Most probably \(2^+\)
  - No peak at \(~4.2\)MeV

**Counts /100keV**

- Er<200keV
- Er<120keV (95% CL)

**Decay energy spectrum**

\[ ^{27}F+C \rightarrow ^{26}O \rightarrow ^{24}O+2n \quad \text{(preliminary)} \]


C. Caesar et al. PRC88, 034313 (2013)

**Ground state**

**Excited state (new)**

**Q3D mode**

To be completed

**SAMURAI21 (S grade): \(^{28}O\)**

**SAMURAI20: \(^{26}O\) life**

**SAMURAI09: Pigmy Dipole**

\((\gamma, p)\) reaction,…
SAMURAI

History
- Broadband type spectrometer was originally designed as key device in RIBF project from the beginning (~1997).

* T. Kobayashi, TAC report, Fig. 1-3, 2004

**Diagram:**
- RI Beam
- Target: H, α, γ(Pb/U)
- Magnetic Field
- Neutron: angle = ±10°, velocity = 0.62, efficiency >70% (1n), +multiple neutron
- Light particle: (p, d, α,...) with γ-ray
- Proton: momentum = 0.7 GeV/c, angle = ±5°, σ_p/p < 1/100
- Heavy Proj. Fragment: momentum = R<2.2 GeV/c, angle = < few°, charge = < 50, velocity = 0.62, σ_R/R < 1/700, σ_p/p < 1/1000 (d), σ_α/β < few mrad, σ_α < 0.2, σ_β/β < 10^{-3}

250 MeV/A, A/Z=3

* T. Kobayashi, TAC report, Fig. 1-3, 2004
Magnetic spectrometer so far considered (till 2004)

T. Kobayashi, WG report, 2004

Super BENKEI

<table>
<thead>
<tr>
<th>Type</th>
<th>Q + C-magnet</th>
<th>H-type window frame</th>
<th>H-type round pole</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_{\text{max}}[T]$, BL[Tm]</td>
<td>3 T, 7 Tm</td>
<td>1.5 T, 2.3 Tm</td>
<td>3 T, 7 Tm</td>
</tr>
<tr>
<td>pole &amp; gap[m], weight[t]</td>
<td>1.6x2.8x1.0 m, 620 t</td>
<td>1.5x1.0x1.0 m, 140 t</td>
<td>2.0m diam. x 0.8 m, 650 t</td>
</tr>
<tr>
<td>AT &amp; Stored Energy cost</td>
<td>4.4 MAT, 36 MJ</td>
<td>1.4 MAT, 36 MJ</td>
<td>3.6 MAT, 28 MJ</td>
</tr>
<tr>
<td>angle for 2.2 GeV/c</td>
<td>1500 MY</td>
<td>100 MY (transfer + mod.)</td>
<td>&lt;1000 MY</td>
</tr>
<tr>
<td>angular focussing</td>
<td>55°</td>
<td>18°</td>
<td>53°</td>
</tr>
<tr>
<td>drawbacks</td>
<td>yes, force, cost, fringing field</td>
<td>no</td>
<td>no angular focus, focal plane</td>
</tr>
</tbody>
</table>
QD type
Magnetic spectrometer so far considered (till 2004)

T. Kobayashi, WG report, 2004

pole: 1.6(W)x 2.8 (D)x1.0m(G)
field: 3.0 T @4.4MAT
weight: 620 t (585 t + 35t)
stored energy: 36 MJ
max field on coil: 4.0 T

Disadvantage:
Inhomogeneous Power support of SC coil,
Power support for yoke
Coil link for SC coil, ...
Magnet construction (2009-2011)

Rails for rotatable base
Rotatable base with the first layer
Magnet yoke with poles

Coils with cryostats, LHe vessels
Vacuum chamber
COMPLETED 2011/03
SAMURAI: large/huge acceptance broadband type
- Planned on RIBF design (~1997?)
- Construction completed: 2011
- First beam: 2012
- $\frac{d\delta}{\delta} \approx 1/1500$ (achieved value), $1/1000$ (designed value)
- $R_{max}/R_{min} : 2\sim 3$
- Vertical acceptance: 170 mrad ($\pm 5^\circ$) designed $\rightarrow$ 140 mrad
- Horizontal acceptance (for n): 340 mrad ($\pm 10^\circ$)

ZeroDegree: extension of beam line from BigRIPS
- Planned on RIBF design (~1997?)
- Construction completed: 2007
- First beam: 2008
- $\frac{d\delta}{\delta} = 1/1240$ (Large acceptance mode: 6%, H/V 90/60 mrad)
- $\frac{d\delta}{\delta} = 1/4000$ (Dispersive spectrometer mode: 4%, H/V 40/60 mrad)
Spectrometer on RIBF

• ZeroDegree : extension of beam line from BigRIPS
  • Planned on RIBF design (~1997 ?)
  • Construction completed : 2007
  • First beam : 2008
  • $d\delta/\delta=1/1240$ (Large acceptance mode : 6%, H/V 90/60 mrad)
  • $d\delta/\delta=1/4000$ (Dispersive spectrometer mode : 4%, H/V 40/60 mrad)

• SHARAQ : high resolution spectrometer for RI beam by CNS
  • Kick off on 2004(?)
  • TAC : 2005
  • Construction completed : 2009 (2 years earlier than SAMURAI)
  • First beam : 2010 (2 years earlier than SAMURAI)
  • $d\delta/\delta=1/15000$
SAMURAI Properties/Constituents
Typical n-HI measurement
Experimental setup

$^{26,27}$F/$^{27,28}$Ne
250MeV/u
(from BigRIPS)
SAMURAI beam line detectors

- Detectors for incoming beams: beam position (BDC), PID(Plastic and ICB), $\gamma$(DALI2) and tracking detector(FDC1) for electro-magnetic spectroscopy at SAMURAI.
SAMURAI Focal plane detectors

- Detectors for fragments: FDC2 for tracking, HODO for $\Delta E$ and TOF, ICF for $\Delta E$.
- Proton drift chamber (PDC), CsI total energy detector (TED), and total internal reflection Cherenkov (TIRC) will come in the future.
Offline analysis: much better than those of on-line phase.

- On-line: $7\sigma$ separation

\[ \downarrow \]

- $13\sigma$ separation @ $A\sim25$
- $\rightarrow 3\sigma$ separation @ $A\sim100$ (expected)

Clear Particle identification!

\[ \rightarrow \text{High resolving power of SAMURAI} \]
SAMURAI-NEBULA
Neutron-detection system for Breakup of Unstable-Nuclei with Large Acceptance

- Design
  - 240 Neutron counters
  - 48 VETO counters
  - arranged into 4 stacks
- Detection efficiency ~40% for 1n (Currently)
- Large acceptance
  - 3.6m (H) x 1.8m (V) effective area

Half (120 modules) is funded and completed.
• Neutron window: SUS 3mm\(^t\) : \(2430 \times 800\) mm\(^2\)
  • for neutrons \(\sim\) 250 MeV to pass through
  • De-dimension configuration applied
  Estimated by ANSYS calculation \(\rightarrow\) Deformation is reasonably small

CONCEPT: De-dimension
2D geometrical degree of freedom
\(\rightarrow\) approximately restricted to 1D deformation

Calculation results:
Deflection: 0.22 mm
Stress(Max.): 29 MPa

Y. Shimizu, EMIS2012 proceedings
SAMURAI Vacuum Window

- Charged particle window: $2940 \times 800 \text{ mm}^2$ for HI $\sim 250 \text{ MeV}$ to pass through
- $400\text{mm} \rightarrow 800\text{mm}$

by De-dimension concept successfully introduced on n-window

Put to the practical usage on 2013/01 for Day-2 experiments

Membrane configuration: (same)
Mylar 75 $\mu$m / Kevlar(K49) 0.28 mm$^t$
Position determination of devices upstream and downstream of the magnet

- Photo Grammetry System (PGS)
  - as RIKEN Common usage device, FY2010

1. Paste target markers on devices
2. Take pictures surrounding from the devices

Every target is identified as a green marker.

Reconstruct to 3D position by dedicated software (VStars)

Spurious reflections are noted as red markers
Establishment of position measurement by PGS unbiased by human experiences or eyes

3D reconstructed positions of each target marker

~1000 pictures
~800 targets (+288 coded targets)

Overall accuracy : 300 µm (RMS)
Results of precise position determination

Each detector position (and angle) are determined within 150μm(RMS)
→ Successfully reduce the large contribution of systematic error on momentum analysis

Absolute momentum analysis
from BDC1,2 – FDC1,2 tracking
+ B field(TOSCA calculation)

Decay energy spectrum: $^{26}\text{O}$
w/o artificial offsets/treatments

$^{27}\text{F}+\text{C} \rightarrow ^{24}\text{O}+2\text{n}$
(preliminary)

By Y. Kondo

T.Kobayashi et al.,
NIMB317(2013)294-304

Scattering Angular Resolution
→ 0.9mrad (rms)

Bρ Resolution
→ 1/700 (one-path analysis)
→ 1/1500 (sophisticated)
→ 5σ mass resolution for A=100

Utilized to other RIBF beam line
SAMURAI experimental programs
1) “Ready” programs

- **SAMURAI17** M. Sasano/R.G.T. Zegar
  Study of Gamow-Teller and spin-dipole transitions from $^{132}$Sn via the $(p,n)$ reaction at 270 MeV/u

- **SAMURAI11** M. Sasano
  Study of Gamow-Teller transitions from $^{48}$Cr (and $^{64}$Ge) via the $(p,n)$ reaction at 190 MeV

- **SAMURAI14** D. Muecher (W. Henning)
  Fission Barrier Studies of Neutron-Rich Nuclei via the $(p,2p)$ Reaction

- **SAMURAI12** D. Beaumel
  Cluster structure of Beryllium isotopes and study of multi-neutron systems

- **SAMURAI13** S. Sakaguchi
  Vector analyzing power measurement for $p$-$^6$He elastic scattering at 200 MeV/A

**WINDS**
- Only test part is ready
- Done partly on 2014/03-04

**Si tele.**
- pol-p Target
2) Programs waiting for “User Devices”

• **SAMURAI15/SAMURAI22** W. G. Lynch/T. Murakami/T. Isobe/B. Tsang
  Study of density dependence of the symmetry energy with the measurements of charged pion ratio in heavy RI collisions

• **SAMURAI20** C. Caesar(T. Aumann)
  Measurement of the neutron-decay lifetime of the $^{26}$O ground state at the SAMURAI setup at RIBF

• **SAMURAI21** Y. Kondo
  Spectroscopy of unbound oxygen isotopes II : $^{28}$O → 4n Detection

• **SAMURAI09R1** T. Kobayashi/Y. Togano
  Electric dipole response of neutron-rich Ca isotopes

• **SAMURAI18R1** A. Corsi/Y. Kubota
  Two-Neutron Momentum Correlation in Borromean Nuclei

3) Programs waiting for “SAMURAI Development”

• **SAMURAI14** D. Muecher(W. Henning)
  Fission Barrier Studies of Neutron-Rich Nuclei via the $(p,2p)$ Reaction
Submitted program on coming NP-PAC(2014/06)

4) Very new programs

- **SAMURAI23** T. Isobe/T. Murakami/W. G. Lynch/B. Tsang
  Study of density dependence of the symmetry energy with the measurements of proton to neutron ratio in heavy RI collisions

- **SAMURAI24** V. Panin(RNC)
  Investigation of proton-unbound states in neutron-deficient isotopes $^{66}$Se and $^{58}$Zn

- **SAMURAI26** N. Iwasa(Tohoku)
  Study of resonance states in $^{34}$Ca using neutron removal reactions of $^{35,36}$Ca

- **SAMURAI25** Z. Elekes(ATOMKI)
  Study of nuclear reactions relevant for type I X-ray bursts

- **SAMURAI27** N. Kobayashi (UT)
  Spectroscopy of Odd-A Nuclei in the Island of Inversion; $^{31}$Ne, $^{37}$Mg

- **SAMURAI19R1** S. Paschalls (TU Darmstadt)
  Investigation of the 4n system at SAMURAI
  by measuring p,p$\alpha$ quasi-free scattering at large momentum transfer in complete kinematics
SAMURAI TPC status

Assembly completed May 2013

Pad plane readout tested with pulsers. Testing with cosmic rays and sources are on going. Experiments will use GET (Generic Electronics for TPC’s) readout electronics. Testing with gating grid driver is on going. TPC will be shipped to RIKEN at February 2014.
CATANA
CAlorimetric deTector for rAdiation from exotic Nuclear beAms

- Study for E1 responses on medium heavy (n-rich) nuclei
  → high multiplicity $\gamma$ detection from residual nuclei

**Setup**

- Neutrons
- Charged fragments

**Beam**

**NEBULA**

**DALI** → CATANA

**15 cm$^1$/9.5 cm$^t$ CsI(Na) array**

$\varepsilon_{\gamma}(1\text{MeV})$: 25% (DALI)
→ 65% (CATANA)

Ready on 2015

*Slide from Y. Togano*
Summary

• SAMURAI Overview
• History

• Properties/Constituents
  • $d\delta/\delta \sim 1/1500$ (achieved value),
  • $dA/A \sim 1/300$ (achieved value, governed by lack of TOF resolution)
    • to be improved up to design value of $1/500$ ($5\sigma$ on $A \sim 100$)

• Experimental programs
  • Experiments with each SAMURAI configuration proposed
  • Several programs are waiting for MT assignment
  • Various user devices will be introduced coupled with SAMURAI (??? because of simplicity of SAMURAI ???)
One more thing…

- **SAMURAI ⇔ SHARAQ**
  - SAMURAI: Neutron detection but limited resolution
  - SHARAQ: high resolution but no chance on neutron

- + no chance to extend Zero degree type spectrometer downstream of SAMURAI because of limitation of building

- So, I think high resolution property coupled with neutron detection is very unique, even if it is designed on R3B-Grad magnetic spectrometer.

- QD for HI-\(p\) configuration for recovering vertical divergence.