Nuclear Experiments with Radioactive Isotope Beams II

Hiroyoshi Sakurai
RIKEN Nishina Center / Univ. of Tokyo
Radioactive isotope productions and particle identification

In-beam gamma spectroscopy
Decay spectroscopy

Mass spectroscopy

Invariant mass spectroscopy
Missing mass spectroscopy
Others
RI Beam Factory

5 cyclotrons + 2 linacs
3 inflight separators
Experimental devices coupled with BigRIPS have been completed in FY13

113\textsuperscript{th} Nh “Nihonium”

“SHE”

“Exotic Nuclei”
Shell Evolution: magicity loss and new magicity

Neutron Correlation in the vicinity of the Drip-line

R-process path: Synthesis up to U

EOS: asymmetric nuclear matter
SN explosion, neutron-star, gravitational wave
Nuclear Magic Numbers and Shell Evolution

Stable nuclei

Neutron-rich nuclei

Mayer & Jensen
Nobel Prize 1963

Shell Structure
One-body potential
Large LS term
(surface contribution)

Magic numbers ->
2, 8, 20, 28, 50 …
Magicity and its loss through determining $E(2^+)$
The 1st in-beam gamma experiment

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GAMMA RAYS FOLLOWING ($\alpha$, xn) REACTIONS

H. MORINAGA† and P.C. GUGELOT

Instituut voor Kernphysisch Onderzoek, Amsterdam, Netherlands

Received 14 January 1963

Fig. 2. Experimental set-up for the detection of gamma rays from thin targets bombarded by 27 to 52 MeV alpha particles.
Spectroscopy via reactions with in-beam gamma method

Secondary target: H$_2$, C, Pb, ...
Gamma-detectors: DALI2 NaI array to measure de-excited gamma rays

S. Takeuchi et al., NIM A 763, 596-603 (2014)

PID at ZeroDegree

Doornenbal, Scheit et al.
PRL 103, 032501 (2009)
Achievements with DALI2 at ZD

2+ and 4+ for Even-Even Light n-rich nuclei

Magicity at N=82 and Z=50?
$^{126}$Pd: Wang, PRC 88, 054318 (2013)
$^{136}$Sn: Wang, PTEP 023D02 (2014)

Magicity at Z=50 and N=50?
$^{104}$Sn: Corsi, PLB 743, 451 (2015)
$^{104}$Sn: Doornenbal, PRC 90, 061302 (2014)

New Magicity N=32, 34

Shape transition

Halo Nuclei

Island-of-inversion region and beyond (N=20-28)

$^{29}$Ne: Kobayashi, PRC 93, 014613 (2016)
$^{32}$Ne: Doornenbal, PRL 103, 032501 (2009)
$^{31,32,33}$Na: Doornenbal, PRC 81, 041305R (2010)
$^{33,34,35}$Na: Doornenbal, PTEP 2014, 053D01 (2014)
$^{36,38}$Mg: Doornenbal, PRL 111, 212502 (2013)
$^{32}$Mg: Li, PRC 92, 014608 (2015)
$^{42}$Si: Takeuchi PRL 109, 182501 (2012)
$^{40}$Mg: Crawford PRC 89, 041303 (2014)
$^{31}$Ne: Nakamura, PRL 103, 262501 (2009), PRL, 112, 142501 (2014)
$^{37}$Mg: Kobayashi PRL 112, 242501 (2014)

"SEASTAR" project (MINOS+DALI2)

$^{66}$Cr, $^{72}$Fe: Santamaria, PRL 115:192501 (2015)

$^{80,82}$Zn: Shiga, PRC 93, 024320 (2016)

PRL 114, 252501 (2015)
A large deformation at $Z=10-12$ in spite of $N=20$
A pilot-region for nuclear structure
Interplay of three ingredients:
  - Weakly-bound natures
  - Tensor forces
  - Pairing

Doornenbal, Scheit, et al.
Ne-32 1st excited states: PRL 103, 032501 (2009)
New states in $^{31,32,33}$Na: PRC 81, 041305R (2010)
Mg-36,-38: PRL111, 212502 (2013)
F-29: in preparation
Takeuchi et al.
Si-42 : PRL109, 182501 (2012)
P.Fallon et al.
Mg-40 : PRC 89, 041303 (2014)
Collectivity of the neutron-rich Mg isotopes

P. Doornenbal, H. Scheit et al. PRL111 212502 (2013)

Excitation Energy of $2^+$ and $4^+$ in Mg

$^{A}\text{Al} + C \rightarrow ^{A-1}\text{Mg}$

For $A=34$ to 38
$E(2^+)$~700 keV
$E(4^+)/E(2^+)$~3.1

At $N=22$, 24, 26 the nuclei are well deformed

No increase of $E(2^+)$ at $N=26$
$N=28$ for Mg is not magic?

B(E2)?
Mn/Mp?
$E(2^+)$, $E(4^+)$ in $^{40}\text{Mg}$?
Energy of single particle states?
Well developed deformation of $^{42}\text{Si}$

Confirmation of $2^+$ energy observed at GANIL

High statistic data allows gamma-gamma coincidence

$^{44}\text{S} + \text{C} \rightarrow ^{42}\text{Si} + X$

$E(4^+)/E(2^+) \sim 3$ for Si-42
Island-of-inversion and beyond

A large deformation at $Z=10-12$ in spite of $N=20$
A pilot-region for nuclear structure
Interplay of three ingredients:
  Weakly-bound natures
  Tensor forces
  Pairing

What is the next “magic”?

Dodatak

Ne-$^{32}$ 1$^{\text{st}}$ excited states: PRL 103, 032501 (2009)
New states in $^{31,32,33}$Na: PRC 81, 041305R (2010)
Mg-$^{36,38}$: PRL111, 212502 (2013)
F-$^{29}$: in preparation
Takeuchi et al.
Si-$^{42}$ : PRL109, 182501 (2012)
P.Fallon et al.
Mg-$^{40}$ : PRC 89, 041303 (2014)
New “Magicity” of N=34 in the Ca isotopes

D. Steppenbeck et al., Nature 502

Zn-70 primary beam (100 pnA max)
Ti-56  120 pps/pnA, Sc-55  12 pps/pnA

Zn-70 -> Ti-56, Sc-55
Ti-56, Sc-55 + Be -> Ca-54 + X
“Magicity” in the Ar isotopes: Ar-50 (N=32)


Sum of the reaction channels
\[ ^{9}\text{Be}(^{54}\text{Ca},^{50}\text{Ar}+\gamma)X \]
\[ ^{9}\text{Be}(^{55}\text{Sc},^{50}\text{Ar}+\gamma)X \]
\[ ^{9}\text{Be}(^{56}\text{Ti},^{50}\text{Ar}+\gamma)X \]

\[ 1.18(2) \text{ MeV} \]
\[ 2^+ \rightarrow 0^+ \]

\[ 1.58(4) \text{ MeV} \]
\[ 4^+ \rightarrow 2^+ \]

N=32 gap in Ar is similar at that in Ca and Ti...

How about Ar-52 (N=34)?
Ca-56 (N=36)?

Robustness of N=34?
MINOS (100-mm thick Liq.H₂ target and TPC system, Δβ = 20%)

-> high luminosity and vertex position determination

DALI2 -> high efficiency
to access very neutron-rich nuclei
MINOS: Magic Numbers Off Stability

In-beam knockout experiments

Position sensitive detector: X,Y
Drift time: Z beam-axis direction

Vertex resolution: < 5 mm FWHM
Detection efficiency > 85%

http://minos.cea.fr
SEASTAR : The First Campaign May 2014

(1) Extension of the N=40 Island-of-Inversion towards N=50 Spectroscopy of $^{66}$Cr, $^{70,72}$Fe

Santamaria, Louchart, Obertelli et al,
PRL 115, 192501 (2015)

(2) First spectroscopy of $^{78}$Ni

Taniuchi, Doornenbal, Yoneda et al., in preparation
Lifetime measurement for excited states

Introduction of several works at the old facility RIPS
Such lifetime measurement activities should be re-encouraged/re-organized at the new facility RIBF
B(E2) measurement for the light mass region

B(E2) | lifetime
Coul. Ex. | stable nuclei | unstable nuclei

Situation in 2002

No data for the neutron-rich Be and C isotopes
In-beam Gamma Spectroscopy at the RIPS facility

Lifetime measurements of first excited states in C-16 and C-18
Neutron-dominant quadrupole collective motion in C-16
Lifetime measurements of excited states in C-17
First lifetime measurements of 2+ state in Be-12

Lifetime measurements developed
Recoil Shadow Method
Doppler Shift Attenuation Method
Recoil Distance Method
to measure B(E2)
For light nuclei to which CEX is not applied.
E(2+) and B(E2) systematics for Carbon isotopes


\[ B(E2)_{sys} = (5140 \pm 900)E^{-1}Z^2A^{-2/3} \]

S. Raman et al, ADNDT 78,1(2001)

significant discrepancy from Raman’s systematics
Excited states in even-even C isotopes

\[ 1^{4}\text{C} \text{ double magic ??} \]

N=8 gap
Z=6 gap

GANIL, Eur. Phys. J.A 20, 95 (04)
New data for transition strengths in $^{16, 17, 18}$C based on an upgrade setup for recoil shadow method

$^{18}$C: Ong et al. PRC  \quad  ^{17}$C: Suzuki et al. PLB

- Increased detectors
  - improved statistics
  - Various combinations
  - increased sensitivity towards lifetime

- Measurement with/without lead shield
  - $R_{wPb}/R_{woPb}$
  - NO uncertainty due to angular distribution of $\gamma$-ray
Excited states in the odd C and O isotopes

\[ \text{Neutron-dominant collective states?} \]

\[ \text{d}_{5/2} - \text{s}_{1/2} - (\text{d}_{3/2}) \]

\[ \begin{align*}
\text{N=7} & \quad \text{N=9} & \quad \text{N=11} & \quad \text{N=13} \\
\end{align*} \]
Life-time measurements of excited states in $^{17}$C

D. Suzuki, et al., PLB

$B$(M1; $(1/2^+)$ → $3/2^+$) = $(1.0 \pm 0.1) \times 10^{-2} \ [\mu_N^2]$  

$B$(M1; $(5/2^+) \rightarrow 3/2^+$) = $(8.2 +3.2/-1.8) \times 10^{-2} \ [\mu_N^2]$
Comparison between $^{17}$C and $^{21}$Ne

- $(5/2^+)$: Almost identical excitation energy and M1 strength
- $(1/2^+)$: Low excitation energy and small M1 strength

⇒ Drastic change in the structure of the $1/2^+$ state
s-wave dominance in the $1/2^+$ state?

- $3/2^+$; the $[d_{5/2} \times 2^+]^{3/2^+}$ configuration is dominant.

$\Rightarrow$ The $1/2^+$ state of $^{17}\text{C}$ may have a large amount of the $[s_{1/2} \times 0^+]^{1/2^+}$ configuration since the M1 transition between the $s_{1/2}$ and $d_{5/2}$ orbitals is forbidden.

The $1/2^+$ state of $^{17}\text{C}$ may be a halo state ?.
Next Generation Gamma-ray Array

DALI2 (present)
NaI crystals
dE/E ~ 8%

SHOGUN (future)
LaBr3 crystals
dE/E ~ 2%

Asia-Ball (5-10 years)
Ge crystals
dE/E ~ 0.2%
+ SHOGUN

Doppler corrected gamma energy spectra of Mg-33 (real data)
Inelastic scattering with GRETINA at NSCL (K. Wimmer)

Neutron knockout with DALI2 at RIBF (D. Bazin)
Decay Spectroscopy Setup

Beta-delayed gamma
  -> Ge detectors
HI implanted and beta-rays
  -> active stopper (DSSSD)

U-238 Acceleration
at Super-Conducting Cyclotron

Be production target
fission

U-238 beam
345A MeV

Super-conducting Inflight
Separator to deliver intense
RI beams

1st decay spectroscopy 2009 Dec.
U beam intensity
  0.1-0.2 pnA on average
2.5 days for data accumulation

Exotic Collective-Motions
at A~110 and Their Applications
to the R-process

S. Nishimura et al., PRL 106, 052502 (2011)
T. Sumikama et al., PRL 106, 202501 (2011)
Exotic Collective-Motions at A~110 and Their Applications to the R-process Nucleosynthesis

New Half-life data for 18 new isotopes
S. Nishimura et al., PRL 106, 052502 (2011)

Deformed magic N=64 in Zr isotopes
T. Sumikama et al., PRL 106, 202501 (2011)

Low-lying level structure of Nb-109: A possible oblate prolate shape isomer

Development of axial asymmetry in neutron-rich nucleus Mo-110
First decay spectroscopy in 2009

U-beam intensity ... $\times 50$ times
- 0.2 pnA $\rightarrow$ 10 pnA

Gamma-ray efficiency ... $\times 10$ times
- 4 Clover detectors (Det. Effi. $\sim 1.5\%$ at 0.662 MeV)
  $\rightarrow$ 12 Cluster detectors (Det. Eff. $\sim 15\%$ at 0.662 MeV)

Beam time $\times 40$ times
- 2.5 days (4 papers) $\rightarrow$ 100 days ... (160 papers)
EURICA Project at RIBF

EUROBALL-RIKEN Cluster Array (EURICA) 2012-16

Euroball Cluster detectors
Support structure
Readout electronics used for GSI-RISING

RIKEN RIBF (Japan)

2011 Nov.
EURICA Installation

Nov.02, 2011

Jan.10, 2012

Jan.05, 2012

Feb.04, 2012

Ivan Kojouharov

Nick Kurtz

Henning Schaffner
EURICA
EUroball-RIKEN Cluster Array 2012-2016

Beta-delayed gamma / Isomer Spectroscopy

12 Euroball Cluster detectors
Support structure
Electronics used for RISING

RIBF: decay station
Active stopper: DS-SSD (WAS3ABi)
Liq. N$_2$ system, other infrastructures

+Additional detectors (LaBr$_3$, Plastic ...)

230 collaborators from 19 countries
About 100 days were approved for physics run

Commissioning March 2012
Physics Run June 2012 – June 2016

Publication at this time (August 2016)
23 papers (8 PRL, 5 PLB, 3 PRC(R), 7 PRC)
9 PhD Thesis + 1 Master Thesis
31 proceedings
8 technical articles
β-Decay Half-Lives of Co76,77, Ni79,80, and Cu81: Experimental Indication of a Doubly Magic Ni78

NP0702-RIBF10: S. Nishimura
Decay study for 75-78Co, 77-80Ni, 80-82Cu, and 82-83Zn near the N=50 shell closure

Isotope dependence of T1/2

Isotone dependence of T1/2
FIG. 2 (color online). Time distribution of the $\beta$-decay events correlated with implanted $^{79}$Ni. The fitting function (solid red line) considers the activities of parent nuclei (dashed-dotted black line), $\beta$-decay daughter nuclei (fine-dashed blue line), $\beta n$-decay daughter nuclei (dashed green line), a constant background (solid pink line), and other decay products (granddaughter nuclei, etc.), which are not drawn in the figure.
Isomers in $^{128}\text{Pd}$ and $^{126}\text{Pd}$: Evidence for a Robust Shell Closure at the Neutron Magic Number 82 in Exotic Palladium Isotopes

H. Watanabe et al., PRL 111, 152501 (2013)

Typical seniority-isomer observed in Pd-128
→ No evidence of shell-quenching ....
EURICA Achievements in 2014-2016 (July) - New Isotopes/ Isomer/ Beta-delayed gamma

New isotopes, magicity and deformed regions

- $^{96}\text{In}$, $^{94}\text{Cd}$, $^{92}\text{Ag}$, $^{90}\text{Pd}$ : Celikovic et al., PRL 116, 162501(2016)
- $^{138}\text{Te}$: Lee et al., PRC 92, 044320(2015)
- $^{136}\text{Sb}$: Lozeva et al., PRC 91, 024302(2015)
- $^{140}\text{Sb}$: Lozeva et al., PRC 93, 014316 (2016)
- $^{129}\text{Cd}$: Taprogge et al, PLB 738, 223 (2014)
- $^{129}\text{In}$: Taprogge et al., PRC 91, 054324 (2015)
- $^{104,106}\text{Zr}$: Browne et al., PLB 750, 448(2015)
- $^{132}\text{In}$: Jungclaus et al, PRC 93, 041301(R) (2016)
- $^{126}\text{Pd}$: Watanabe et al, PRL 113, 042502 (2014)
- $^{63}\text{Se}$, $^{67,68}\text{Kr}$ : Blank et al., PRC 93, 061301(R) (2016)
- $^{76}\text{Co}$, $^{76}\text{Ni}$: Soderstrom et al., PLB 750, 448(2015)
- $^{72}\text{Ni}$: Morales et al., PRC 93, 034328 (2016)
- $^{164}\text{Sm}$, $^{166}\text{Gd}$: Patel et al., PRL 113, 262502 (2014)
- $^{160}\text{Sm}$ : Patel et al., PLB, 753, 182 (2016)

Protons and neutrons with magic number have bands arising from $r$-process path (prediction).

- Proton Magicity $Z=28$
- Neutron Magicity $N=50$
- Neutron Magicity $N=82$
Shell Evolution

Magicity Loss at N=20, 28
New magic number N=34
Double magicity of $^{78}\text{Ni}$ (Z=28, N=50)
Magicity at N=82 with Z>46…

$^{32}\text{Ne}$: Doornenbal, PRL 103, 032501 (2009)
$^{31,32,33}\text{Na}$: Doornenbal, PRC 81, 041305R (2010)
$^{33,34,35}\text{Na}$: Doornenbal, PTEP 2014, 053D01 (2014)
$^{32}\text{Mg}$: Li, PRC 92, 014608 (2015)
$^{36,38}\text{Mg}$: Doornenbal, PRL 111, 212502 (2013)
$^{42}\text{Si}$: Takeuchi PRL 109, 182501 (2012)
$^{50}\text{Ar}$: Steppenbeck, PRL 114, 252501 (2015)
$^{40}\text{Mg}$: Crawford PRC 89, 041303 (2014)
$^{54}\text{Ca}$: Steppenbeck, Nature 502, 207 (2013)
$^{50}\text{Ar}$: Steppenbeck, PRL 114, 252501 (2015)
$^{66}\text{Cr}$, $^{72}\text{Fe}$: Santamaria, PRL 115:192501 (2015)
$^{126}\text{Pd}$: Wang, PRC 88 054318 (2013)
$^{136}\text{Sn}$: Wang, PTEP 023D02 (2014)
$^{106,108}\text{Zr}$: Sumikama, PRL 106, 202501 (2011)
$^{126,128}\text{Pd}$: Watanabe, PRL 111, 152501 (2013)
$^{78}\text{Ni}$: Xu, PRL 113, 032505 (2014)
Mass measurements for shell evolution

Yamaguchi (Saitama U.), Wakasugi (RIKEN), Uesaka (RIKEN), Ozawa (Tsukuba U.), et al.

Neutron shell gap

Proton shell gap

Key technologies:
- Isochronous ring
- $\Delta T/T < 10^{-6}$ for $\delta p/p = \pm 0.5\%$
- Individual injection triggered by a detector at BigRIPS
- Efficiency $\sim 100\%$
even for a “cyclotron” beam

Schedule:
- 2015 Commissioning run
- 2016- Mass measurements of RI
The r-process nucleosynthesis

William A. Fowler
1983 Nobel Prize Physics

© The Nobel Foundation

The r-process path
rapid neutron-capture vs beta-decay

Mass -> path location
Half-life -> matter flow

1st peak
N=50

2nd peak
N=82

3rd peak
N=126

Supernova explosion?
NS merger?
Or both?

Isotopes found at RIBF

N=50
N=82
N=126

N=50
N=82
N=126

r-process path

Solar r-process abundance

Stability line

20 28

(He) 2

(2)
“Revolution” in the r-process research

Bunch of T1/2 data for A~100
A standard model assuming (n,gamma) equilibrium reproduces the r-abundance up to rare-earth region

Mass, beta-delayed neutron emission probability measurement in future

G. Lorusso, S. Nishimura et al. PRL. 114, 192501 (2015)
S. Nishimura et al., PRL. 106, 052502 (2011)

Next step should be towards the 3rd peak
BRIKEN: beta-delayed neutron detection (He-3)

AIDA (Edinburgh, UK)

He-3 detector system

ORNL-JINR-GSI-UPC-RIKEN
182 counters

Very high efficiency neutron detector →
Survey of beta-delayed multi-neutron & T1/2
2016-

Table 1: $^3$He tubes available within the BRIKEN Collaboration.

<table>
<thead>
<tr>
<th>Owner</th>
<th>Pressure (atm)</th>
<th>Diameter (inch/cm)</th>
<th>Eff. Length (inch/mm)</th>
<th>Number of Counters</th>
</tr>
</thead>
<tbody>
<tr>
<td>GSI</td>
<td>10</td>
<td>1 / 2.54</td>
<td>23.62 / 600</td>
<td>10</td>
</tr>
<tr>
<td>JINR</td>
<td>4</td>
<td>1.18 / 3.0</td>
<td>19.69 / 500</td>
<td>20</td>
</tr>
<tr>
<td>ORNL</td>
<td>10</td>
<td>2 / 5.08</td>
<td>24 / 609.6</td>
<td>67</td>
</tr>
<tr>
<td>ORNL</td>
<td>10</td>
<td>1 / 2.54</td>
<td>24 / 609.6</td>
<td>17</td>
</tr>
<tr>
<td>RIKEN</td>
<td>5.13</td>
<td>1 / 2.54</td>
<td>118.1 / 300</td>
<td>26</td>
</tr>
<tr>
<td>UPC</td>
<td>8</td>
<td>1 / 2.54</td>
<td>23.62 / 600</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total 182</td>
</tr>
</tbody>
</table>

Neutron Detection Efficiency (%)

Neutron Energy (MeV)
New Method for Spin Aligned RI-beam Production

Production of spin-controlled rare isotope beams

Yuichi Ichikawa1, Hideki Ueno1, Yuji Ishii2, Takeshi Furukawa3, Akihiro Yoshimi4, Daisuke Kameda1, Hiroshi Watanabe1, Nori Aoi1, Koichiro Asahi7, Dimitri L. Balabanski5, Raphaël Chevrier6, Jean-Michel Daugas6, Naoki Fukuda1, Georgi Georgiev7, Hironori Hayashi2, Hiroaki Iijima2, Naoto Inabe1, Takeshi Inoue2, Masayasu Ishihara1, Toshiyuki Kubo1, Tsubasa Nanao2, Tetsuya Ohnishi1, Kunifumi Suzuki2, Masato Tsuchiya2, Hiroyuki Takeda1 and Mustafa M. Rajabali8

Key 1:

Two step PF
→ Maximize spin alignment

Key 2:

Dispersion matching
→ Maximize yield of two-step PF
Halo: low density nuclear (neutron) matter in the lab.
Multi-neutron correlation on and beyond the drip-line?
Element Number Zero: Tetra-neutron system

“Nucleus made only of neutrons”
Benchmark for ab initio calculations
NN, NNN, NNNN... interactions
high T interactions
Multi-body resonances

A high statistics experiment was conducted June 2016.

Clear strength with 4.9σ significance level
\[ E_{4n} = 0.83 \pm 0.65 \text{ (stat.)} \pm 1.25 \text{ (syst.)} \text{ MeV} \]
Upper limit of \( \Gamma = 2.6 \text{ MeV (FWHM)} \)
Cross section: 3.8 nb
(integrated up to \( \theta_{CM} < 5.4 \text{ degree} \))
Energy resolution: 1.2 MeV
Uncertainty of calibration: ± 1.3 MeV
Background : 0.02 events/2MeV

Kisamori, Shimoura et al., PRL 116, 052501 (2016)
Superconducting Analyzer for MULTI-particle from RAdio Isotope Beam

Kinematically Complete measurements by detecting multiple particles in coincidence


**Large momentum acceptance**

\[ \frac{B\rho_{\text{max}}}{B\rho_{\text{min}}} \sim 2 - 3 \]

**Good Momentum Resolution**

\[ \Delta p/p \sim 1/700 \] (designed value)

(5\sigma separation for A=100)

**Large angular acceptance for n**

20 deg (H) x 10 deg (V)

(~100% coverage < \(E_{\text{rel}}\) ~ 2 MeV,

~ 30% coverage at \(E_{\text{rel}}\) ~ 10 MeV)

**Stage: Rotatable (-5 -- 95 degrees)**

**Versatile Usage**

Invariant mass for n+HI

Invariant mass for p+HI

(p,n), (p,p'), (p,pn), (p,pp) etc.

Heavy Ion Collision

polarized deuteron, etc.
Day-One Campaign Experiments at SAMURAI: Explore Neutron Drip Line (May 2012)

- Established only up to Z=8 (O)
- Halo Structures
- New/Lost Magic Numbers
- Exotic Unbound Resonances
--- Physics at the bound limit

Coulomb Breakup of $^{19}$B and $^{22}$C, Nakamura et al.
Study of $^{18}$B, $^{21}$C, and excited states of $^{19}$B, $^{22}$C, Orr et al.
Structure of Unbound Oxygen Isotopes $^{25}$O, $^{26}$O, Kondo et al.
Ground state
5 times higher statistics than previous study
\[ E_{\text{decay}} = 18 \pm 3 \text{(stat)} \pm 4 \text{(syst)} \text{ keV} \]
Finite value is determined for the first time

\[ E_{\text{decay}} = 1.28^{+0.11}_{-0.08} \text{MeV} \]
Observed for the first time

N=16 shell closure is confirmed
USDB cannot describe \( 2^+ \) energy at \( ^{26}\text{O} \)

\[ \rightarrow \text{effect of pf shell? and/or continuum? Or other effects? (such as 3N forces, 2n correlation)} \]
Y. Kondo et al., PRL 116, 102503 (2016)
Go much beyond the dripline: Extension to $^{28}\text{O}$
(SAMURAI21 (Y. Kondo) in Nov-Dec 2015)

Successfully done with SAMURAI
+MINOS
+NeuLAND
+DALI2
high intense beam ($^{29}\text{F}$: ~100 pps)
88 participants from 25 institutes
SCRIT Facility for e+RI scattering

SCoP: UCx Target in FEBIAD ion source

Electron beam ~2000°C

ERIS

SR2 (SCRIT-equipped RIKEN Storage Ring)
- Energy: 100 - 700 MeV
- Stored current: 300 mA (current operation)
- Lifetime: ~1 AH
- Circumference: 21.946 m
- Tunes: 1.62 / 1.58
- β-max: 10.36 / 4.09 m

Luminosity of $10^{27}/(\text{cm}^2\text{s})$ was achieved at the e-beam current of 250mA.

Efficiency improvement
- More high power beam 10W->1kW -> $10^{29}/\text{cm}^2/\text{s}$
SLOWRI Device for Trap Experiments

Wada, Sonoda et al.

1) Optical spectroscopy

HFS of $^{11}$Be$^+$

Takamine et al, PRL 112(2014)162502

2) Mass measurements of short-lived nuclei

Ito, Schury et al, PRC 88(2013)011306R

3) Resonance Ionization Spectroscopy

Parasitic RI beam production, spin, moments, radii..
RI Beam Factory

5 cyclotrons + 2 linacs
3 inflight separators
Experimental devices coupled with BigRIPS have been completed in FY13

113th Nh Nihonium

“SHE”

“Exotic Nuclei”
Program for nuclear structure and matter at RIBF

\[ E = mc^2 \]

\[ A Z \]

\[ A(Z+1) \]

\[ A-1Z + n \]

**EOS (SAMURAI)**

**invariant mass spectroscopy (SAMURAI)**

**missing mass spectroscopy**

(ZeroDegree, SHARAQ)

**in-beam gamma spectroscopy**

(ZeroDegree)

**beta spectroscopy /isomeric states**

(BigRIPS/ZeroDegree)

**matter radii (BigRIPS)**

**matter distribution (ZeroDegree)**

**charge radii (SLOWRI)**

**charge distribution (SCRIT)**

**mass (SLOWRI, RING)**

\[ T_{1/2} (\text{BigRIPS}) \]

**electromagnetic moments**

(RI Spin Lab./SLOWRI)
Experimental Devices (1) : spectrometer

ZeroDegree (2008-)
Beam line spectrometer
low-\(p\) (E) transfer reactions
\(p/\Delta p \sim 2000\text{--}4000\)
PID for ejectiles with \(A<200\)
In-beam gamma spectroscopy for bound excited states
missing mass with detectors for target recoiling

SAMURAI (2012-)
Versatile spectrometer with a super. dipole magnet
high-\(p\) (E) transfer reactions
\(p/\Delta p \sim 700\) at \(Z\sim8\)
Invariant mass spectroscopy for unbound states
Neutron corr. in halo, O-26, GDR, alpha-cluster,
EOS in HIC (2015-), 3NF...

SHARAQ (2009-)
high-resolution spectrometer
\(p/\Delta p \sim 15000\)
missing mass spectroscopy with RI beams
Exotic modes such as IVSMR, DGTR
Experimental Devices (2) : unique device

**SCRIT (2012-)**

- e- + RI scattering for charge density distribution
- U-238 photo-fission by 150-MeV e-beam (10W->1kW)
- Electron beam 150-700 MeV 300mA
- high-res. Spectrometer
- Luminosity ~ 10^27 /cm2/s for stable isotopes
- 2015- data production
  - skin-thickness via p-elastic and e-elastic

**Rare-RI Ring (2013-)**

- Isochronous mass measurement ~ O(1) ppm
  - C=60.3m, p/Δp = +/- 0.5%
- Trans. Emittance 20pi/10pi mm mrad
- 2013- Commissioning
- 2016- data production

**SLOWRI (2014-)**

- Gas-catcher system to slow down RI beams
- mass, laser spec., decay studies
- 2014 commissioning
- 2015 day-one exp.
Nuclear transmutation facility dedicated for nuclear waste of FP?  
FP is dominant in nuclear waste

Partitioning technique + deep geological disposal are being considered...

MA -> ADS
FP -> ??
Possible FP transmutation? to minimize FP activities neutron induced transmutation with an accelerator system or others?
-> almost no reaction data...
Transmutation for LLFP : The First Challenge

April, 2014

<table>
<thead>
<tr>
<th>Beam species</th>
<th>Beam energy [MeV/u]</th>
<th>Intensity [/s/10pnA]</th>
<th>Purity [%]</th>
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<td>137Cs</td>
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<td>1200</td>
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<tr>
<td>90Sr</td>
<td>187</td>
<td>7100</td>
<td>28</td>
</tr>
</tbody>
</table>

U-238 Acceleration at Super-Conducting Cyclotron

2ndary target
C, CH₂, CD₂

(n, Xn) Fragmentation
Charge exchange for p, d(n), C targets

Inflight Separator to deliver intense RI beams: Cs-137, etc

ZeroDegree Spectrometer

PID for reaction products to determine reaction channels.

PID at BigRIPS

PID at ZeroDegree

Be production target

RIKEN, UT, Miyazaki, Kyushu ...