1. Introduction of gamma-ray spectroscopy study of nuclear structure by measuring $\gamma$-rays

2. Recent results by our group using RI beams

(1) Study of change of shell structure to collective mode in neutron-rich Mg nuclei using polarized Na beam (produced by laser) at TRIUMF, Canada

(2) Study of nuclear shape change using isomers (excited levels with $T_{1/2} \sim \text{nsec}$) at RCNP, Osaka Univ.
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We could not watch nuclei by our eyes.

\[
\text{nucleus : } 10^{-15} \text{ m} \quad \leftrightarrow \quad \text{atom : } 10^{-10} \text{ m}
\]

nuclear deformation, nuclear motion and so on …

mesoscopic system  quantum many body system

nucleus (proton + neutron) $1 \sim$ hundreds of nucleons
stable nuclei 262
unstable nuclei observed one ~3000
prediction ~7000

magic number
2, 8, 20, 28, 50, 82, 126 ...

nuclear chart
Study of nuclear structure

(1) nuclear deformation

- Shape of small number of nuclei
  - oblate (pancake) [orange]
  - $\beta < 0$

- Nuclei with number of proton and/or neutron is magic number
  - spherical

- Shape of many nuclei
  - prolate (cigar) [lemon]
  - $\beta > 0$

\[ R(\theta', \varphi') = R_0 \left( 1 + \beta Y_2^0(\theta') \right) \]  
$\beta$: deformation parameter
Study of nuclear structure

(2) nuclear motion --- rotation

- Rotation of nuclei with prolate shape along the rotation axis perpendicular to the symmetry axis.

- Prolate (cigar) [lemon]

- Super deformation: long : short axes = 2 : 1
  [shape of ball used by rugby football]
Study of nuclear structure

(3) nuclear motion --- vibration

beta vibration  gamma vibration  octupole vibration
By measuring $\gamma$ rays, we can study nuclear shape, nuclear motion and so on.

(1) Single-particle motion of spherical, oblate nuclei

(2) Vibration of nuclei

(3) Rotation of prolate nuclei

Study of nuclear structure

Gamma-ray spectroscopy method

$\gamma$-ray spectra

level scheme
151Tb super deformed band

Level energy: \( E(I) = I(I+1)/2J \)

\( J \): moment of inertia

\( \gamma \)-ray energy: \( E_\gamma = 4I + 6 \)

Difference of \( \gamma \)-ray energy: \( \Delta E_\gamma = 4 \) const.

Yrast super deformed band

Energy [ keV ]

Counts

Level scheme

\( E(I) \)

\( E_\gamma \)
expected exotic nuclear shapes and rotations in high-spin region

super deformation (2:1)

hyper deformation (3:1)

oblate super deformation (1:2)

banana shape

pear shape

tetrahedral (pyramid)

octahedral (diamond)
exotic nuclear shapes in light nuclei

- large deformation ($^{32}\text{Mg}$)
- neutron skin
- neutron halo
- cluster nuclei
- neutron number
- proton number

RIKEN HP
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Shimoda group
Department of Physics, Osaka University
Study of Nuclear Structure using RI beam

Shimoda group

polarized RI beam study of nuclear structure of exotic nuclei

TRIUMF (Canada)

disappearance of \( N=20 \) magic number

prolate deformation

neutron halo

\( ^{10}\text{Be} \) \( ^{11}\text{Be} \)

OSAKA beam line

high-spin shape isomer in \( N=83 \) isotones oblate deformation

RI beam study of nuclear structure of high-spin isomers

RCNP RI beam line (EN course)
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Shimoda group
Department of Physics, Osaka University
Study of exotic nuclear structure in neutron-rich nuclei using polarized RI beam

1. Neutron halo in neutron-rich nucleus $^{11}$Be studied by $\beta$ delayed neutron decay using polarized $^{11}$Li RI beam

2. Disappearance of magic number $N=20$ in neutron-rich Mg isotopes studied by $\beta$ delayed $\gamma$ decay using neutron-rich polarized Na beam
Beta-decay spectroscopy with spin-polarized radioactive nuclei at TRIUMF, Canada

\[ \beta - \gamma\text{ coincidence} \]

\[ \beta - \gamma - \gamma\text{ coincidence} \]

\[ \text{very effective method to assign spin-parity of daughter states} \]

\[ \text{polarized polarization} \]

\[ \text{polarized} \]

\[ \beta - \gamma\text{ coincidence} \]

\[ \beta - \gamma - \gamma\text{ coincidence} \]
**β-decay from a spin-polarized nucleus**

**β-decay angular distribution**

\[ W(\theta) \sim 1 + AP \cos \theta \]

**A**: asymmetry parameter of allowed β-decay

**P**: polarization of the parent nucleus

\[ \theta = 0 \] for \( I_f = I_i + 1 \)

\[ \theta = \tau \] for \( I_f = I_i - 1 \)

\[ \tau = CV \langle 1 \rangle / CA \langle \sigma \rangle \sim 0 \]

A takes very different values depending on the final state spin.

<table>
<thead>
<tr>
<th>( I_i ) (Na)</th>
<th>( I_f ) (Mg)</th>
<th>( A(I_i, I_f) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1+</td>
<td>1+</td>
<td>-0.5</td>
</tr>
<tr>
<td>0+</td>
<td>0+</td>
<td>-1.0</td>
</tr>
<tr>
<td>5/2+</td>
<td>3/2+</td>
<td>0.6</td>
</tr>
<tr>
<td>3/2+</td>
<td>1/2+</td>
<td>-0.4</td>
</tr>
<tr>
<td>2+</td>
<td>3+</td>
<td>0.67</td>
</tr>
<tr>
<td>1+</td>
<td>2+</td>
<td>-0.33</td>
</tr>
<tr>
<td>4+</td>
<td>3+</td>
<td>0.8</td>
</tr>
<tr>
<td>4-</td>
<td>3-</td>
<td>-0.2</td>
</tr>
<tr>
<td>3-</td>
<td>4-</td>
<td>-1.0</td>
</tr>
<tr>
<td>4-</td>
<td>2-</td>
<td>0.75</td>
</tr>
<tr>
<td>3-</td>
<td>2-</td>
<td>-0.25</td>
</tr>
<tr>
<td>2-</td>
<td>2-</td>
<td>-1.0</td>
</tr>
</tbody>
</table>
$P$ can be evaluated from $AP$ value for a transition to the known spin state.

$AP = \frac{\sqrt{R} - 1}{\sqrt{R} + 1} \left( R = \frac{N_R^+}{N_L^+} / \frac{N_R^-}{N_L^-} \right)$

$p$ can be evaluated from $AP$ value for a transition to the known spin state.

$A \rightarrow \text{spin assignment}$
A polarized beam produced by optical pumping was used. By pumping the two ground-state hyperfine levels, high polarization was achieved. The laser frequency was 905 MHz. The 905 MHz EOM was used for optical pumping.

\[ \overrightarrow{F} = \overrightarrow{J} + \overrightarrow{I} \]

The 673 nm D1 line was used for optical pumping.

\[ {^2}P_{1/2} \rightarrow {^2}S_{1/2} \]

\[ F = 2 \quad 104 \text{MHz} \]

\[ F = 1 \]

\[ M_F = -2, -1, 0, 1, 2 \]

\[ \text{Polarization} \]

\[ {^{11}}\text{Li}(I = 3/2^-) \]
TRIUMF ISAC (Isotope Separator / Accelerator)

The ISAC - II Accelerator Floor

- Na beam
- 18 Plastic Scintillators
- 9 Ge detectors
- B~830 gauss
- Plastic scintillators (1.5 mm)

Scintillator telescope

β- and γ-rays
Spin assignments of the levels in $^{28}\text{Mg}$

<table>
<thead>
<tr>
<th>$I_i^\text{Na}$</th>
<th>$I_f^\text{Mg}$</th>
<th>$A(I_i, I_f)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2^+$</td>
<td>$1^+$</td>
<td>$+0.5$</td>
</tr>
<tr>
<td>$1^+$</td>
<td>$1^+$</td>
<td>$-0.5$</td>
</tr>
<tr>
<td>$0^+$</td>
<td></td>
<td>$-1.0$</td>
</tr>
</tbody>
</table>

$\beta$-ray energy spectrum

$AP = -0.283(5)$

$\Rightarrow P = 0.283(5)$

$1^+ \rightarrow 0^+ : A = -1.0$

uncorrected for spin-relaxation

2389 keV $\gamma$-ray peaks (3862 $\rightarrow$ 1473) coincident with $\beta$-rays

$AP = -0.25 \pm 0.01 \Rightarrow A = -0.89 \pm 0.05 \Rightarrow I^\pi = 0^+$
Revised Decay Scheme of $^{28}$Na and New Levels in $^{28}$Mg

Levels and gamma rays
- Red: newly observed ones
- Blue: previously observed in (t, p) reaction and newly observed in $^{28}$Na $\beta$ decay

Spins and parities
- Red: newly assigned
- Green: previously reported, and confirmed by present work
- Black: previously reported
Revised Decay Scheme of $^{29}$Na and Spin-Parity Assignments of $^{29}$Mg Levels

These two levels are associated with large log $ft$ values.

Shell model calculations with sd shell configurations do not predict no more levels around 1.0 - 1.5 MeV region.
Experimental systematics of negative parity levels

Z = 12
N = 17

Prediction by AMD calculations (Kimura)

single-particle levels

negative parity

positive parity

prediction by AMD calculations (Kimura)
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Shimoda group
Department of Physics, Osaka University
Study of nuclear shape change using isomers

Isomers are caused by the nuclear structures. Isomers are good probe to obtain information of large change of nuclear structure.

Shape isomer: caused by the sudden shape change

We are studying high-spin shape isomers with oblate shape.

Exotic shape and/or motion are expected to be observed in high-spin states in nuclei.
High-spin shape isomers in $N=83$ isotones

$^{152}$Er: \([\nu(f_{7/2}h_{9/2}i_{13/2})\pi(h_{11/2}^4)]_{61/2}^+\)

$^{151}$Ho: \([\nu(f_{7/2}h_{9/2}i_{13/2})\pi(h_{11/2}^3)]_{28}^-\)

Odd
\([\nu(f_{7/2}h_{9/2}i_{13/2})\pi h_{11/2}^2]_{49/2}^+\)

Odd-odd
\([\nu(f_{7/2}h_{9/2}i_{13/2})\pi(h_{11/2}^2d_{5/2})]_{27}^+\)

Oblate
\[\beta \sim -0.19\]
Study of nuclear structure using fusion reaction

High angular momentum can be produce in compound nuclei.

beam (heavy ion) → target → compound nucleus

proton → neutron → alpha → high-energy $\gamma$ rays (~ 5 – 10 MeV)

low-energy $\gamma$ rays (up to ~3 MeV)

ground state
Study of nuclear structure of the coldest high-spin state for each angular momentum

Exotic shape and/or motion are expected to be observed in high-spin states in nuclei.

We can study the coldest state for each angular momentum in nuclei.

- High-energy $\gamma$ rays ($\sim 5 – 10$ MeV)
- Low-energy $\gamma$ rays (up to $\sim 3$ MeV)
Development of RI beam for the experiment using fusion reaction

Nuclear Chart:
Experimental maximum spins reported in NNDC

\[ \frac{\text{proton number}}{\text{neutron number}} \]

- Experimental data reported in NNDC
- Development of RI beam for the experiment using fusion reaction

- High-spin shape isomers
- \( \beta \)-stability line
- \( N-Z \approx 0.006xA^{5/3} \)

- \( N=83 \) isotones

- \( Z = 45 \leq Z \leq 82 \)
- \( N = 45 \leq N \leq 130 \)

- Except for SD with spins which are not confirmed

by A. Takashima
Gamma-ray spectroscopy at RCNP, Osaka University

1. direct beam provided by the AVF cyclotron
2. new ECR ion source for heavy ion beam

In-beam $\gamma$-ray experiment using fusion reaction
Heavy ion beam with proper beam energy

since 2005
EN beam line

Maximum rigidity 3.2 Tm
Energy acceptance $\Delta E/E = 16\%$
Angular acceptance $\Delta \theta = 40\ mrad$
$\Delta \phi = 28\ mrad$
Path length 16.8 m

RCNP secondary beam line

Ge array : 14 Ge + 6 BGOACS
total efficiency 1.2 % at 1.3 MeV
Dep. of Phys. & RCNP Osaka Univ.
Dep. of Phys. Tohoku Univ.
SUNY
Search for high-spin shape isomers in $^{142}_{59}$Pr$_{83}$ using $^{17}$N RI beam fusion reaction

low-energy RI beam ($<10$ MeV/u) for fusion reaction

primary reaction : $^9$Be($^{18}$O, $^{17}$N)$^{10}$B 9.2 MeV/u, 0.8 pμA

secondary reaction : $^{130}$Te + $^{17}$N 4.3 MeV/u, 2x10$^4$ pps, ~60%

Gamma-rays correlated to the secondary fusion reaction were selected by using the information time difference between PPAC and Ge detectors.
Gamma-Ray Correlating with $^{17}$N RI Beam ($\gamma$-Singles)

- Live time: 86 h 40 min.
- Background
- Fusion products

Graph showing correlation of $\gamma$-rays with $^{17}$N RI beam (time difference $\pm 50$ ns)

- $^{141}$Pr [272.7, 273.7]
- $^{142}$Pr [268, 358, 373, 452, 454, 509, 563]
- PPAC-Ge detectors
We can newly observed the $\gamma$-rays associated with the isomer by using PPAC-Ge time difference.
Summary

1. Nuclear structure (various shapes, motions and so on) can be studied based on the gamma-ray spectroscopy.

2. Recent results using RI beams

   (1) Study of change of shell structure to collective mode in neutron-rich Mg nuclei using polarized Na beam (produced by laser optical pumping) at TRIUMF, Canada

   Nuclear structure of $^{28}\text{Mg}_{16}$ and $^{29}\text{Mg}_{17}$ was studied. Disappearance of $N=20$ magic number was discussed in $^{29}\text{Mg}$.

   (2) Study of nuclear shape change using isomers (excited levels with $T_{1/2}>\sim\text{nsec}$) EN beam line (secondary beam line) at RCNP, Osaka Univ.

   Study for high-spin states of $^{142}\text{Pr}$ was performed by low-energy (<10MeV/u) RI beam induced fusion reaction.
TRIUMF Experiment S1114


Osaka Univ., KEK\(^A\), TRIUMF\(^B\)
Study of high-spin states in $^{142}$Pr by RI beam induced fusion reaction