Experimental Research on the Reactions and Decays of Exotic Nuclei

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54th ASRC International Workshop Sakura-2019
"Nuclear Fission and Structure of Exotic Nuclei"
Japan Atomic Energy Agency, Tokai, Japan, 25-27 March 2019
Research Activities in NRG

Heavy-Ion Reaction

NRG

Exotic Nuclei

Exotic Structure

Eva.

EI

\( ^{152}\text{Sm} \), \( ^{170}\text{Er} \), \( ^{174}\text{Yb} \)

\( ^{27}\text{P} \) (Z=15)

\( ^{28}\text{S} \) (Z=16)

\( ^2\text{He} \) ~20%
1. Potentials of exotic nuclear systems
2. Reactions with weakly-bound nuclei
3. $2p$ emissions from excited states
4. Decays of extremely $p$-rich nuclei
Optical Model is a successful model to explain the nuclear scattering and reaction, which resembles the case of light scattered by an opaque glass sphere.

Optical Model Potential (OMP):

\[ U = V(r) + iW(r) \]

- **attractive**
- **absorptive**

★ phenomenological potential, independent on energy.

★ A basic task in nuclear reaction study is to understand the nuclear interaction potential.

Threshold Anomaly (TA)

A universal phenomenon within the Coulomb barrier energy region

\[ U(r; E) = V(r; E) + iW(r; E) \]

\[ V(r; E) = V_0(r; E) + \Delta V(r; E) \]

Dynamic polarization potential:

\[ \Delta V(r; E) = \frac{P}{\pi} \int_0^\infty \frac{W(r; E')}{E' - E} dE' \]

Dispersion relation (results from the causality)


tightlly-bound nuclear systems

Space

Time

Nonlocality

Dispersion relation

Abnormal TA: weakly-bound nuclei

- Exotic nuclei: weakly-bound & having specified structures (cluster, halo/skin)
- Reactions: easily breakup, strongly coupling to continuum, complex mechanisms

**Cluster**
- $^6\text{Li} (\alpha+d)$
  - $S_\alpha = 1.47 \text{ MeV}$
- $^7\text{Li} (\alpha+t)$
  - $S_\alpha = 2.47 \text{ MeV}$
- $^9\text{Be} (\alpha+n+\alpha)$
  - $S_n = 1.66 \text{ MeV}$

**Halo**
- $^11\text{Be} (^{10}\text{Be}+n)$
  - $S_n = 0.50 \text{ MeV}$
- $^6\text{He} (\alpha+2n)$
  - $S_{2n} = 0.98 \text{ MeV}$

Abnormal Threshold Anomaly

- $^9\text{Be}+^{208}\text{Pb}$
- $^9\text{Be}+^{209}\text{Bi}$

JPG 371, 075108 (2010).
Abnormal TA: unstable nuclei

OMPs are usually extracted from the elastic scattering.

\[ \Delta \theta = 6 - 11^\circ \]
\[ \Delta E = 1.2 - 1.5 \text{ MeV} \]

★ Rather difficult to extract an effective OMP at low energies.

Transfer Method

\[ a = b + x \quad \rightarrow \quad b + x \]

\( b \) \(-\rightarrow\) \( A \) 

\( A \) \(-\rightarrow\) \( b \)

\[ B = A + x \]

Transition reaction \( A(a,b)B \)

Transition amplitude:

\[ T = J \int d^3 r_b \int d^3 r_a \chi^{(-)}(\vec{k}_f, \vec{r}_b) \ast \langle bB|V|aA\rangle \chi^{(+)}(\vec{k}_i, \vec{r}_a) \]

4 wave functions are needed,

\( \ast \) two bound states: \( b+x \) & \( A+x \) (single-particle potential model)

\( \ast \) two scattering states: incoming & outgoing (optical potentials)

**Proposed:** C. J. Lin et al., AIP Conf. Proc. 853, 81 (2006), presented at the FUSION06.


\( ^{63}\text{Cu}(^{7}\text{Li},^{6}\text{He})^{64}\text{Zn} \): Phys. Rev. C 95, 034616 (2017).
Two experiments have been done at HI-13 tandem accelerator @ CIAE

Exp1: $E_{\text{beam}} = 42.55, 37.55, 32.55, 28.55, 25.67$ MeV – high energies  
【2004.8】

Exp2: $E_{\text{beam}} = 28.55, 25.67, 24.3, 21.2$ MeV -- low energies  
【2016.4】

★ Angular distributions of both elastic scattering and transfer were measured.

2 Telescopes: SSSD(20\(\mu\)m) + DSSD(60\(\mu\)m) + QSD(100\(\mu\)m)
Results: OMPs of $^6\text{He}+^{209}\text{Bi}$

- OMPs of the $^6\text{He}+^{209}\text{Bi}$ system are determined precisely for the first time;
- The decreasing trend in the imaginary part is observed, and the threshold energy is about 13.73 MeV (~0.68 $V_B$);
- The behavior of real part looks normal, i.e. like a bell shape around the barrier;
- The dispersion relation does NOT hold in this system.

L. Yang, C.J. Lin*, H.M. Jia et al., Phys. Rev. Lett. 119, 042503 (2017);
Discussions

★ Dispersion relation results from causality, connecting real and imaginary part;
★ Any wave/particle should follow this relation when it passes through a media;
★ The dispersion relation is not applicable for exotic nuclear systems.

Possible reasons:

• Causality → dispersion relation
  stable systems: causality ↔ analyticity

• Cauchy integration
  infinity poles (breakup) & off-axis (multi-process)

• Negative Index of Refraction
  causality based criteria must be used with care

• Locality vs. non-locality
  equivalent local potential in Schrödinger equation

$$\text{Cauchy's residue theorem}$$

Negative Index of Refraction?
Topics

1. Potentials of exotic nuclear systems
2. Reactions with weakly-bound nuclei
3. $2p$ emissions from excited states
4. Decays of extremely $p$-rich nuclei
Reactions with Exotic Nuclei

RIBs experiments

♠ Elastic scattering
3-body, 4-body
CDCC ...

♠ Fusion/Reaction
TF = ICF + CF ...

♠ Breakup/transfer
Effects & mechanisms

Reaction mechanism

How to identify the different reaction process?

complete-kinematics measurement

2-body kinematics

3-body kinematics

Same products
Experiments

★ Complete-kinematics measurement ;  ★ Reactions induced by $^7\text{Be}$, $^8\text{B}$, $^{17}\text{F}$ ...

RIBLL: $^{17}\text{F}+^{89}\text{Y},^{208}\text{Pb},^{7}\text{Be}+^{209}\text{Bi}$

CRIB: $^{17}\text{F}+^{12}\text{C},^{58}\text{Ni},^{8}\text{B}+^{120}\text{Sn}$

RIBLL separator at IMP

CRIB separator at CNS

40% of $4\pi$

8% of $4\pi$

40/60 μm DSSD

300 μm QSD

1-1.5 mm QSD

2019/5/2

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Angular distribution of quasi-elastic scattering.
(OMP & CDCC by Lei Jin)
Preliminary Results: $^{17}\text{F}^+{}^{58}\text{Ni}$

Angular distribution of **breakups/transfer**
[Cf. Lei Jin & A. M. Moro, PRL 122, 042503 (2019)]

**Preliminary conclusions:**

- The non-elastic breakups are dominant;
- Fusions are suppressed at energies above the barrier but enhanced below the barrier.
★ Exclusive breakup \(^{16}\text{O}-p\)

Our result: \(\sigma \sim 1.2 \text{ mb} @ 63 \text{ MeV}\);
Liang’s result: \(\sigma \sim 15.6 \text{ mb} @ 170 \text{ MeV}\).  

[J.F. Liang et al., PLB 681, 22 (2009).]

Why are the breakup cross sections so low?

• Screen effects due to the dynamic polarization?

• Transfers are dominant?

• …

\(^8\text{B}+^{120}\text{Sn}\) experiment will be performed at CNS/RIKEN (2 - 16 Apr., 2019)

\(^{17}\text{F} (S_p = 0.601 \text{ MeV}), \quad ^8\text{B} (S_p = 0.136 \text{ MeV})\)
1. Potentials of exotic nuclear systems
2. Reactions with weakly-bound nuclei
3. \(2p\) emissions from excited states
4. Decays of extremely \(p\)-rich nuclei
Exotic decays of $p$-rich nuclei

Bound states: $\beta$-delayed particle emissions
Unbound states: directly particle emissions

- Structures of $p$-rich nuclei close to/beyond the drip-line
- Effective interaction – pairing, isospin non-conserving (INC), three-body force
- Initial state interaction (ISI), final state interaction (FSI), quantum entanglement
- Nuclear astrophysics – ($p,\gamma$), (2$p,\gamma$), ($\alpha,\gamma$) ... processes
Overview of our research

- Started from 2004
- RIBLL@HIRFL (Lanzhou)
- **In-flight** decay
  (Ex. states 2p emissions)
  \[28,29\text{S}/27,28\text{P};\]
  \[17,18\text{Ne}.\]
- **Implantation** decay
  (G.S. \(\beta p, \beta 2p...\))
  \[36,37\text{Ca};\]
  \[27\text{S}/26\text{P}/25\text{Si};\]
  \[22\text{Si}/20\text{Mg};\]
  \[23\text{Si}/22\text{Al}/21\text{Mg};\]
  \[24\text{Si}/23\text{Al}.\]
In-flight decays

\(2p\) emissions from high-lying excited states and related topics

AIP CP 961, 117 (2007); NPA 805, 403 (2008); AIP CP 1165, 106 (2009); CPL 26, 032301 (2009); PRC 80, 014310 (2009); PRC 82, 064316 (2010); NPA 834, 450c (2010); AIP CP 1409, 98 (2011); SCPMA 54(S1), S73 (2011); PST 14, 317 (2012); PLB 727, 126 (2013); JPS CP 1, 013026 (2014); NPR 33, 160 (2016).

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Exp. setup 1

RIBLL Experimental Setup 2007

Note:
Collimators: PPAC1: φ30 mm; PPAC2: φ20 mm.
ΔE: 300μm Si ΔE detector, combined with TOF (150 μs).
$^{197}$Au: target, 200-250 μm, φ28 mm.
D1,D2,D3: 300μm Si, 48mm×48mm.
D4: 1000μm Si detector with 4 segments, 50mm×50mm.
X1,Y1,X2,Y2: 300μm Si strip detectors, each of 216 segments.
CSI: CSI(Tl)+PIN detectors, 20 mm length, total length 1500 mm.

Complete-kinematics measurements

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Exp. setup 2

Detector array for $^{28,29}$S experiment

Secondary target: $^{197}$Au, 100 µm

SD: Silicon detectors, 325, 1000 µm

SSSD: Single sided Silicon Strip Detectors with 2 mm in the width and 0.1 mm in the interval for the construction of the particle trajectories

CsI(Tl) array: 6 × 6 lattices, each 15 × 15 × 20 mm, read out through PIN photodiodes.
2p-decay modes

$2p$ emission – three extreme decay modes

$^2$He decay  3-body simultaneous decay  2-body sequential decay

Relativistic-kinematics reconstruction for $^{29}$S $\rightarrow$ $^{27}$Si+$p$+$p$ events

$q_p^{cm}$ (MeV/c) vs. $\varphi_p^{cm}$ (deg)

$E_x$ (MeV) vs. Counts

$^{27}$Si+$p$+$p$

7.4  10.0
Diproton emissions were observed in $^{29}\text{S}$ but not in $^{28}\text{P}$.

$^{29}\text{S}$: C.J. Lin, X. X. Xu, H. M. Jia et al., PRC 80, 014310 (2009);

$^{28}\text{P}$: X. X. Xu, C.J. Lin, H.M. Jia et al., PRC 81, 054317 (2010).
2p emission: $^{28}\text{S}/^{27}\text{P}$

⭐ Diproton emission is enhanced by 2p halo-like states.

2p emission & 2p halo

2p halo/skin in proton-rich S isotopes

Decay scheme of $^{29}$S

Ground state

6Be, $^{12}$O, $^{16}$Ne, $^{19}$Mg, $^{45}$Fe, $^{48}$Ni, $^{54}$Zn .......

Beyond 1p drip-line

2p resonance state

Excited state:

14O, 17,18Ne, 28,29S, .......

2p valence pair

above 2p emission threshold

2p correlated emission

weak link with core (decoupled)

2p halo/skin
Momentum correlation functions & HBT analyses

\[ \langle r_{pp}^2 \rangle^{1/2} = 5.17 \text{ fm} \]
\[ \langle r_{c-pp}^2 \rangle^{1/2} = 3.4 \text{ fm} \]
\[ \Theta_{pp} = 74.5^\circ \]

BCS-BEC crossover

Hagino's results (theory): 76.64°

cf: T. Oishi et al., PRC 82, 024315 (2010).

Question: How to describe $2p$ emission in precise?

Initial state (3-body model) [T. Oishi et al., PRC 82, 024315 (2010).]

Tunneling → Propagation

Diagram:
- Corresponds to the energy-distance model
- Depicts correlated and free protons

Discussions 2019/5/2
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1. Potentials of exotic nuclear systems
2. Reactions with weakly-bound nuclei
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Implantation decays

$\beta$-decay spectroscopy of nuclei close to the proton drip line

Exotic decays: $\beta\gamma$, $\beta p$, $\beta 2p$ ...

$^{23}$Al, $^{24}$Si: NIMA 804, 1 (2015).
$^{22}$Si: PLB 766, 321 (2017).
$^{20}$Mg: PRC 95, 014314 (2017).
$^{22}$Al: NST 29, 98 (2018); PLB 784, 12 (2018).

2012

2013

2014

2015

2016

2017

2018

2019
A detector array for $2p$-decay study by **implantation** method
for lifetime $> 10 \, \mu s$

1p efficiency: 66%; 2p efficiency: 20%
• 150 um + 60 um DSSDs for ion implantations and $\alpha/2\alpha$-decay measurements.
• Others for $\beta$-decay measurements and background rejection.

- Implanted close to the back edge of the 150 um DSSD.
- $1\alpha$ efficiency: >90%; 2$\alpha$ efficiency: 20%

[L.J. Sun et al., NIMA 804, 1 (2005).]
Results 1: $^{22}\text{Si}/^{20}\text{Mg}$

Primary beam: $^{28}\text{Si}$, 75.3 MeV/u @ 40 enA.

- $^{22}\text{Si}$: $4 \times 10^{-3}$ pps @ $8 \times 10^{-4}\%$
- $^{20}\text{Mg}$: 0.72 pps @ 0.15\%

PID of the secondary beam

$\beta p$ precursors

$N = 8$

$T_z = -3$

$T_z = -2$

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$^{20}\text{Mg}$

$\beta$-spectrum

\[ p - \text{spectrum} \]

\[ \gamma - \text{spectrum} \]

Counts per 20 keV

Counts per 4 keV

Counts per keV

Decay curve

$T_{1/2} = 90.0 \pm 0.6 \text{ ms}$

$\chi^2/\text{ndf} = 1.14$

The most precise!

L. J. Sun et al., PRC 95, 014314 (2017).

Decay scheme

$^{15}\text{O} + \alpha + p \rightarrow ^{19}\text{Ne} + p$

$S_2 = 3528.5(5) \text{ keV}$

$^{15}\text{O} + \alpha + p$

$S_1 = 3528.5(5) \text{ keV}$

$^{19}\text{Ne} + p$

$S_2 = 2190.1(11) \text{ keV}$

$^{20}\text{Na}$

$\beta$-spectrum

$\gamma$-spectrum

$\beta$-coincident spec.

$\beta$-coincident spec.

$\beta$-coincident spec.

$\beta$-coincident spec.

$\beta$-coincident spec.

$\beta$-coincident spec.

$\beta$-coincident spec.

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$\beta$-coincident spec.

$\beta$-coincident spec.

$\beta$-coincident spec.
### Peak Energies and BRs

<table>
<thead>
<tr>
<th>Peak</th>
<th>Energy (keV)</th>
<th>BR (%)</th>
<th>Decay Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>230(50)</td>
<td>2.9(10)</td>
<td>$2p$</td>
</tr>
<tr>
<td>2</td>
<td>680(50)</td>
<td>6.8(14)</td>
<td>$\beta p$</td>
</tr>
<tr>
<td>3</td>
<td>1710(50)</td>
<td>1.9(7)</td>
<td>$\beta p$</td>
</tr>
<tr>
<td>4</td>
<td>1950(50)</td>
<td>52.0(74)</td>
<td>$\beta p$</td>
</tr>
<tr>
<td>5</td>
<td>2110(50)</td>
<td>10.9(21)</td>
<td>$\beta p$</td>
</tr>
<tr>
<td>6</td>
<td>2180(50)</td>
<td>6.5(15)</td>
<td>$\beta p$</td>
</tr>
<tr>
<td>7</td>
<td>2330(50)</td>
<td>5.1(13)</td>
<td>$\beta p$</td>
</tr>
<tr>
<td>8</td>
<td>3550(50)</td>
<td>2.5(9)</td>
<td>$\beta p$</td>
</tr>
<tr>
<td>9</td>
<td>5600(70)</td>
<td>0.7(3)</td>
<td>$\beta 2p$</td>
</tr>
</tbody>
</table>

#### Mass of $^{22}\text{Si}$

- $\Delta(^{22}\text{Si}) = \Delta(^{22}\text{Al IAS}) + \Delta E_c - \Delta n_H$
  \[ \rightarrow S_{2p} = -108 \pm 125 \text{ keV}; \]
- $\Delta(^{22}\text{Si}) = \Delta(^{22}\text{O}) - 2b(A,T)T_Z$
  \[ \rightarrow S_{2p} = -15 \text{ keV} \]

The first experimental mass data. The first $\beta 2p$ precursor found in Asian Lab.
Discussions on $^{22}$Si/$^{20}$Mg

Mirror asymmetry $\rightarrow$ INC interaction

$$\delta = \frac{ft^+}{ft^-} - 1$$

<table>
<thead>
<tr>
<th>$^{20}$Mg $\rightarrow$ $^{20}$Na</th>
<th>$^{20}$O $\rightarrow$ $^{20}$F</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{20}$Na $E^*$ (keV)</td>
<td>$J^\pi$</td>
</tr>
<tr>
<td>983.9(22)</td>
<td>1$^+$</td>
</tr>
<tr>
<td>2998(13)</td>
<td>1$^+$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$^{22}$Si $\rightarrow$ $^{22}$Al</th>
<th>$^{22}$O $\rightarrow$ $^{22}$F</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{22}$Al $E^*$ (keV)</td>
<td>$br$ (%)</td>
</tr>
<tr>
<td>1170(50)</td>
<td>5.1(3)</td>
</tr>
<tr>
<td>2400(50)</td>
<td>60.6(65)</td>
</tr>
</tbody>
</table>

Mass $\rightarrow$ Three-Body Force

PRL110,022502(2013).

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>$NN + 3N$</td>
<td>$NN + 3N$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$N = 8$</td>
<td>[IMME]</td>
<td>$sd$</td>
<td>$sdf_{7/2}p_{3/2}$</td>
</tr>
<tr>
<td>$^{18}$Ne</td>
<td>3.92</td>
<td>4.05</td>
<td>3.76</td>
</tr>
<tr>
<td>$^{19}$Na</td>
<td>$-0.32$</td>
<td>$-0.32$</td>
<td>$-0.26$</td>
</tr>
<tr>
<td>$^{20}$Mg</td>
<td>2.66</td>
<td>2.83</td>
<td>2.98</td>
</tr>
<tr>
<td>$^{21}$Al</td>
<td>$[-1.34]$</td>
<td>$-2.52$</td>
<td>$-1.83$</td>
</tr>
<tr>
<td>$^{22}$Si</td>
<td>$[1.35]$</td>
<td>0.90</td>
<td>1.71</td>
</tr>
</tbody>
</table>

Ground State Energy (MeV) vs Mass Number A

N=8

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Results 2: $^{27}\text{S}$

24 $\beta p$ & $1\beta 2p$ decays

decay scheme

$T_{1/2} = 16.3(2)$ ms  
$T = 2$  
$5/2^+$

$\beta^+$  
$\Delta = 17678(77)$ keV

$Q_{EC}=18337(78)$ keV

$E'(keV)$  
$F$  
$br(\%)$

The most precise!
Daughter: $^{27}$P

$\beta p$ & $\beta\gamma$ were measured simultaneously for the first time.

- **Branch ratios pinned down**
- **Precise energy & mass data**

- $T_{1/2} = 16.3(2)$ ms
- $5/2^+$
- $\Delta = 17638(96)$ keV
- $\beta^+$
- $Q_{EC} = 18297(97)$ keV
- $E_p = 318(8)$ keV
- $I_{p1} = 23.1(21)\%$
- $E_{p2} = 762(8)$ keV
- $I_{p2} = 8.9(10)\%$
- $5/2^+$
- $1569(12)$
- $8.9(10)$
- $3/2^+$
- $1125(2)$
- $54.2(88)$
- $^0_+\rightarrow \gamma_1$ $1125(2)$
- $\Delta = -7141.0(1)$ keV
- $\gamma_1$ $I_{\gamma 1} = 31.1(86)\%$
- $1/2^+$
- $27^P$
- $\Delta = -659(9)$ keV
The Galactic $^{26}\text{Al}$ puzzle

The $^{26}\text{Si}(p,\gamma)^{27}\text{P}$ reaction competes with the $\beta$ decay of $^{26}\text{Si}$ to $^{26}\text{Al}^m$, and the latter can produce $^{26}\text{Al}^g$ via thermal excitations. Thus, the production and destruction of $^{26}\text{Si}$ by proton capture should be influential in determining the amount of the $^{26}\text{Al}^m$ and $^{26}\text{Al}^g$ produced by the equilibrium.

Explosive hydrogen burning scenarios

Comparison of the calculated thermonuclear reaction rates from the $3/2^+$ resonance contribution.

Collaborators

Thanks to all the collaborators

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... ...
Thank you for your attention.