Studying astrophysical reactions with low-energy RI beams at CRIB

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Outline

• Introduction of low-energy RI-beam facility “CRIB” (CNS, the Univ. of Tokyo).
  ◆ Cryogenic gas target for RI beam production.
• Performed experiments
  ◆ Resonant scattering experiments using thick-target method in inverse kinematics (TTIK). $^7\text{Li}/^7\text{Be}+\alpha$ as a recent example.
  ◆ Trojan Horse Method with RI beams
   $^{18}\text{F}(p,\alpha)$ reaction cross section via $^{18}\text{F}(d,\alpha n)$. [CNS&INFN-LNS collaborated work]
  ◆ Direct measurements of $(\alpha,p)$ reactions using RI beams: with a normal gas target [$^{11}\text{C}(\alpha,p)$] or an active target
  ◆ Active target for decay measurement:
   $^{16}\text{N}$ beta-delayed $\alpha$ decay experiment performed in 2013. [CNS&INFN-LNS collaborated work]

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CNS Radio-Isotope Beam separator, constructed and operated by CNS, Univ. of Tokyo, located at RIBF (RIKEN Nishina Center).

- Low-energy (<10 MeV/u) RI beams by in-flight method.
- Primary beam from K=70 AVF cyclotron.
- Momentum (Magnetic rigidity) separation by “double achromatic” system, and velocity separation by a Wien filter.
- Orbit radius: 90 cm, solid angle: 5.6 msr, momentum resolution: 1/850.
CRIB in RIKEN RIBF

- AVF alone, operation cost ~1/10 of BigRIPS.
- Ion source / AVF/ CRIB…have been developed under CNS-RIKEN collaboration (joint venture).
Low-Energy RI beam Productions at CRIB

Direct reactions such as (p,n), (d,p) and (³He,n) in inverse kinematics are mainly used for the production....large cross section

Many RI beams have been produced at CRIB: typically $10^4$-$10^6$ pps
Intense secondary beam production using cryogenic gas target

• $\text{H}_2$ gas target of 760 Torr and 80 mm-long worked at 85K stably for a $^7\text{Li}^{2+}$ beam of 1.3 pμA. (which deposits heat of 7.4W).

• Secondary beam: $^7\text{Be}^{4+}$ at 4.0 MeV/u, purity 75% (without degrader/ WF),

  $2\times10^8$ pps was achieved.

  H. Yamaguchi et al., NIMA (2008)
Recent research projects (2010-present)

• Proton/alpha resonant scattering
  ✓$^{26}$Si+p (Collaborated with Chung-Ang, Korea) H.S. Jung et al., PRC (2012&2014).
  ✓$^7$Li/$^7$Be+α (CNS) H. Yamaguchi et al., PRC (2011&2013).
  ✓$^{21}$Na+p, $^{22}$Na+p [$^{18}$Ne(α,p), Ne-Na cycle] (IMP/CIAE, China) PRC(R) & PRC (2013).
  ✓$^{17}$F+p [Resonances for $^{14}$O(α,p)](IMP/CIAE, China) PRC(2014).

• (α,p) reaction measurement, Active target (GEM-MSTPC)
  ✓$^{18}$Ne(α,p) (Hashimoto; CNS ⇒ now at IBS)
  ✓$^{30}$S(α,p) (CNS, Daid Kahl)
  ✓$^{22}$Mg(α,p) (IOP, Vietnam , Nguyen Ngoc Duy)
  ✓$^{44}$Ti(α,p) (KEK, Ishiyama) …$^{44}$Ti beam test successful.

• (α,γ)
  $^{16}$N⇒$^{16}$O*⇒$^{12}$C+α for $^{12}$C(α,γ) (Catania, S. Cherubini) Measurement finished in Sep 2013.

• Reaction mechanism
  ✓$^8$B+Pb (Padova, C. Signorini) Measurement finished in May 2014.

• Implantation ($^7$Be)
  ✓$^{7}$Be implantation for commercial usage (RIKEN, A. Yoshida)
  ✓The Brilliant+C project…Reaction study using implanted target
INFN-CNS(CRIB) collaborated works

2007/2008:

◆ “Study of the $^{18}{\text{F}}+{p}\rightarrow^{15}{\text{O}}+{\alpha}$ reaction at astrophysical energies”

$^{18}{\text{F}}+{p}$, $^{18}{\text{F}}+{d}$, THM experiments  Spokesperson: S. Cherubini
(INFN-LNS, France, Japan)

2013 Sep:

◆ “Study of the beta-delayed alpha decay of $^{16}{\text{N}}$”, Silvio Cherubini (18 days) (LNS, and many others).

2014 May:

◆ “Dynamics of the $^{8}{\text{B}}$ interaction with $^{208}{\text{Pb}}$ at the Coulomb barrier”

Cosimo Signorini (8 days). (Padova, Napoli,+)…M. Mazzocco’s talk on Tuesday.

and many test experiments for the above projects.

- MoU on low-energy nuclear physics between INFN-LNS (Catania), SKKU (Korea) and CNS (Japan, Tokyo) was made in 2013.
- Sicily-East Asia Workshop initiated in 2014.
- Anche grazie mille per il questo invito!

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• $^7\text{Li}(\alpha,\gamma)^{11}\text{B}$ ... important at high-T, as a production reaction of $^{11}\text{B}$ (the $\nu$-process in core-collapse supernovae).

• $^7\text{Be}(\alpha,\gamma)^{11}\text{B}$ ... one of the reaction in hot $p$-$p$ chain, relevant at high-T.

• $\alpha$-cluster structure in $^{11}\text{B}/^{11}\text{C}$:
  • $2\alpha+t$ / $2\alpha+^3\text{He}$ cluster states are known to exist (similar to the dilute cluster structure in $^{12}\text{C}$.)
  • Several “bands” which have $\alpha$-cluster structure could be formed. We can study the band and cluster structure more in detail.

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\[ ^7\text{Li}/^7\text{Be}(\alpha,\gamma) \text{ experimental study} \]

- \(^7\text{Li}(\alpha,\gamma)\) and \(^7\text{Be}(\alpha,\gamma)\) were directly measured only at low-lying resonances:

\(^7\text{Be}(\alpha,\gamma)\): only two resonances at \(E_r<1\text{ MeV}\) are included in the NACRE evaluation.

<table>
<thead>
<tr>
<th>(E_r)</th>
<th>(J^\pi)</th>
<th>(\omega\gamma) (eV)</th>
<th>(\Gamma_\alpha) (eV)</th>
<th>(\Gamma_\gamma) (eV)</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.560</td>
<td>3/2^-</td>
<td>0.331 ± 0.041</td>
<td>11 ± 7</td>
<td>0.350 ± 0.056</td>
<td>HA84 I</td>
</tr>
<tr>
<td>0.877</td>
<td>5/2^-</td>
<td>3.80 ± 0.57</td>
<td>12.6 ± 3.8</td>
<td>3.1 ± 1.3</td>
<td>HA84 I</td>
</tr>
</tbody>
</table>

- Resonant reaction dominates the reaction rate. **Higher resonances** may contribute at **supernova temperature** (>1 GK).
- We studied higher-lying resonances by the resonant elastic scattering method, \(^7\text{Li}(\alpha,\alpha)\) and \(^7\text{Be}(\alpha,\alpha)\) at CRIB to obtain information on the resonances (energy, width, spin and parity).

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\( ^7\text{Be}(\alpha,\gamma) \) in supernovae

\( \nu p \)-process calculation \((T_9 > 1)\) shows considerable contribution by \(^{10}\text{B}(\alpha, p)^{13}\text{C}\) and \(^7\text{Be}(\alpha, \gamma)^{11}\text{C}\) as much as the triple-alpha process.

\[ T \quad [10^9 \text{ K}] \]

\[ dY/dt_{\text{for}} - dY/dt_{\text{inv}} \quad [\text{s}^{-1}] \]

\[ 10^3 \]

\[ 10^0 \]


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Setup for $^7\text{Li}/^7\text{Be}+\alpha$

- Thick target method with inverse kinematics ...An efficient method to measure excitation function.
  - $^7\text{Be}$ beam is monitored by a PPAC (or an MCP detector).
  - $^7\text{Be}$ beam stops in a thick helium gas target (200 mm-long, 1.6 atm).
  - Recoiled $\alpha$ particles are detected by $\Delta E-E$ counter (10 $\mu$m and 500 $\mu$m Si detectors) at forward angle.
  - Nal array for $\gamma$-ray measurement (to identify inelastic events).
• 4 excitation functions… new information on resonant widths, spin, and parity. *H. Yamaguchi et al., PRC (2013).*

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Resonant contribution to $^7$Be$(\alpha,\gamma)$

- Small but not negligible contribution compared to lower-lying states ($\sim 10\%$).

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Direct measurement of (\(\alpha\), p) reactions

- \(^{11}\text{C}(\alpha,p)@\text{CRIB}\) [S. Hayakawa et al., in preparation]

- GEM-MSTPC (active target)
  Constructed and used for several (\(\alpha\), p) reaction studies.
Experimental Setup

He (90%) + CO₂ (10%) mixture gas (160 torr)

- Acts as a He target and a detector (TPC) simultaneously
- GEM with “backgammon” type readout pad.
- 3-dimensional trajectory and energy loss can be measured ⇒ Good event identification.

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The $^{18}\text{F}(p,\alpha)$ project

- $^{18}\text{F}(p,\alpha)$... an astrophysical reaction important in novae, and other high-T environments.

- Measurement with Trojan Horse Method performed in 2008
  …The first THM+RI beam experiment.

- The RI Beam at CRIB (after development):
  Primary beam: $^{18}\text{O}^{8+}$, 4.5-5 MeVA
  Production target: $\text{H}_2$
  Production reaction: $^{18}\text{O}(p,n)^{18}\text{F}$
    - Purity nearly 100%
    - Intensity $> 5 \times 10^5$ pps

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For the star energetics, this is peanuts!
EXPERIMENTAL SETUP

ASTRHO: Array of Silicons for TRojan HORse

PPAC  MCP  TARGET

Front view of DPSSD array

DSSSD

Safety disk

CD2 target

Beam track reconstruction

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How the setup looks like in reality

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Q-VALUE SPECTRUM

Good agreement with Q-value expected position (0.658 MeV) and beam profile (exp. Sigma 0.8 MeV)

Several beam pos&timings cuts + Erel-Erel correlation + E-Theta correlation

All together

Typical Spectrum

Reaction channel identified
Assuming that a Quasi-free mechanism is dominant one can use the (PW)IA:

\[ \frac{d^3\sigma}{d\Omega_C d\Omega_D dE_{\text{cm}}} \]

**Measured at high energy**

\[ KF \cdot |\Phi(P_s)|^2 \]

**Calculated e.g. Montecarlo**

\[ \frac{d\sigma^N}{d\Omega} \]

**Indirectly Measured**

\[ E_{bx} = E_{CD-Q_{2b}} \]
THM (=barriers free) CROSS SECTION

\[ \sigma = \frac{3}{2} + \frac{1}{2} - \frac{3}{2} - \frac{7}{2} + \frac{3}{2} + \frac{11}{2} \]

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Submitted for publication!

S(E) from THM data


Smeared to THM resolution

5/2- (Laird 2013)

$^{16}$N beta-delayed alpha decay

- $^{16}$N→$^{16}$O*→$^{12}$C+$\alpha$ decay...carrying information of $^{12}$C(α,γ) reaction cross section (E1 component) at low energy.

- Tang et al. (Argonne)...measurement with 2 ionization chambers. (Low-energy events cannot be detected.)
- Using the active target for decay measurement...sensitivity at low-energy events
- Experiment at CRIB proposed and performed under a collaboration with INFN-LNS group (S. Cherubini et al.)

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- RI Beam\(\cdots^{16}\text{N}\)
  - Beam pulsing (on-off) operation by 50-ms interval.
  - 1-4 \times 10^5 \text{ pps} after the pulsing, purity 40-80%.
  - 30-MeV beam injected into the TPC, stopped in the middle of it.
- Total 16 days of beamtime, about 2 weeks of data accumulation.
- Branching ratio of \(\alpha\)-decay\(\cdots\sim10^{-5}\)
  \(\Rightarrow\) a few decay events /sec.
Typical event (preliminary)

- Signals observed in several neighboring channels...candidate of $\alpha$-decay event.
- Event selection by energy and tracking information.
- Analysis in progress.

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CRIB is a low-energy RI beam facility in RIBF operated by CNS, University of Tokyo, providing RI beams of good intensity and purity.

Manpower…Minimum to carry out experiments. We are making experiments in a worldwide collaboration with external groups.

GEM-MSTPC

Has been used in several (α,p) measurements, and recently also for alpha decay measurement of $^{16}$N.

Resonant elastic scattering

$^{7}$Li+α,$^{7}$Be+α…strong resonances were observed. The “thick target method with inverse kinematics” could be applied to many nuclides. We can study astrophysical reactions and alpha-cluster structures.

Trojan Horse experiments

$^{18}$F+d…the first RI beam+THM experiment

More to come.

We welcome new users and new ideas!

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