Study of Resonance States in Unstable Nuclei Using Low-Energy Radioactive Nuclear Beams

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Proton resonance scattering on unstable nuclei at energies below 5 MeV/nucleon
Introduction

Experimental study of unstable nuclei

Developments of secondary beams of radioactive ions

Exotic nuclear structure (Neutron halo e.g. $^{11}\text{Li}$)

Change of magic numbers in a neutron-rich region
  (e.g. disappearance of the N=20 magic number)

Nuclear astrophysics
Nucleosynthesis diagram in the nuclear chart

Unstable nuclei play important roles in explosive nucleosynthesis under high-temperature & high-density conditions (supernova, nova & X-ray burst etc.)

Neutron-rich nuclei: Mass, lifetime, \((n,\gamma)\) reaction rates \(\square\) r-process

Proton-rich nuclei: \((p,\gamma)\) reaction rates \(\square\) rp-process
Low-energy Radioactive Nuclear Beams at $E < 10$ MeV/nucleon

Recently, techniques of producing low-energy radioactive nuclear beams have been developed largely at many facilities.

Low energy nuclear reactions of unstable nuclei
   Nuclear spectroscopy
   Nuclear Astrophysics

Applied physics
   Implantation of radioactive ions into materials
   (material science, biology...)

**Production of Low-Energy Radioactive Beams**

**ISOL (Isotope Separator On-Line)**
- Reaction products stopped in the target
- Extraction & acceleration
- Good beam quality.
- Production efficiency depends on chemical properties and lifetime

**In-Flight Separator**
- Reaction products in flight are separated and used as beam particles
- Independent of chemical properties
- Beam quality not so good
- Technically simpler than ISOL

- Usually for high-energy beams (>~100 MeV/u)
- (also useful for low-energy beams)
CNS Low-energy In-flight Beam Line in RIKEN Facility

Center for Nuclear Study (CNS), University of Tokyo

RIKEN Accelerator Research Facility

RIKEN Ring Cyclotron (K=540)

From Liniac

K=70 AVF Cyclotron

AVF

CRIB

ECR

14-GHz ECR Ion Source

CNS Radioactive-Ion Beam separator (CRIB)
CRIB (CNS low-energy Radioactive-Ion Beam) separator

Primary beam from AVF cyclotron

Production Target
Gas target cell with window foils

Dipole Magnet

Momentum-dispersive focal plane
$B \rho = P/q$ selection

Secondary beam

F1

F2

Achromatic focal plane
small beam spot $\phi 5\text{mm (FWHM)}$

F3

Wien filter section
velocity selection

Final focal plane

$P/q = \text{const.} \& v = \text{const.} \Rightarrow m/q$ selection

(Z can be separated by energy-loss at degrader)
Production reactions for low-energy in-flight method

Heavy-Ion beam + light-ion target

Proton-rich nuclei: (p,n), (p,d), (d,n), (d,t), (³He,n)….
Neutron-rich nuclei: (d,p), (d,³He)…..

Light proton-rich nuclei: hot-pp, hot-CNO, early stages of rp-process

Beams developed so far: ⁸Li, ⁷Be, ¹⁰,¹¹C, ¹²,¹³N, ¹⁴O, ¹⁷N, ²¹Na, ²²,²³Mg, ²⁵Al, ²⁶Si at around 5 MeV/nucleon
Example: $^{14}$O beam

- Reaction: $p(^{14}N, ^{14}O)n$  \((p,n)\) reaction in inverse kinematics  
  \(\sigma \sim 8\) mb

- Primary beam $^{14}$N\((6+)\)  Intensity: 500 pnA \((3 \times 10^{12} \text{ particles/s})\)  
  Energy: 8.4 A MeV

- Gas target (Proton target):  
  Hydrogen-gas  
  1 atm. & 2-cm thick \((0.2 \text{ mg/cm}^2)\)  
  confined in a cell with two Havar foils

$^{14}$O secondary beam intensity: $10^6$ particles/s
<table>
<thead>
<tr>
<th>Energy Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A^{-1}(Z-1) + p )</td>
<td>Neutron-rich nucleus near the drip line</td>
</tr>
<tr>
<td>( E_x \sim 10 \text{ MeV} )</td>
<td>Proton/Neutron separation energy</td>
</tr>
<tr>
<td>( A^{-1}Z + n )</td>
<td>Stable nucleus</td>
</tr>
<tr>
<td>( E_x \sim&lt; 1 \text{ MeV} )</td>
<td>Almost no bound excited states → observed as resonances</td>
</tr>
</tbody>
</table>

Study of unbound states in unstable nuclei
Proton Elastic Resonance Scattering

\[ A + p \rightarrow B^* \text{ (resonance)} \rightarrow A + p \]

- Resonance observed in the low-energy proton elastic scattering
- Recently applied to unstable nuclei
- Low-energy beams are good for this process
- Large cross sections

- For proton-rich nuclei: low-lying excited states
- For neutron-rich nuclei: highly excited states (with \( T = T_z + 1 \))
Study of proton resonances in proton-rich unstable nuclei

A(p, γ)B

A & B are proton-rich unstable nuclei

Resonance level in nucleus B near the A+p threshold

- the (p,γ) reaction rates may be enhanced

\[ A+p \rightarrow B^* \rightarrow B+\gamma \]

- Beta decay branches of parent nucleus C may be affected

\[ \text{C(β+)}B(\ast) \]
\[ \text{C(β+)}B^* \sqsubset A+p \]

beta-delayed proton emission via resonances

Important to know experimental information on resonances to understand the reaction paths in explosive hydrogen burning
Unbound nuclei outside the proton drip line

The ground state of a nucleus as a proton resonance (unbound nucleus)

c.f. $^{15}\text{F} \leftrightarrow ^{14}\text{O}+\text{p}$

- Resonance energy = mass of nucleus
  - nuclear stability, mass formula

Comparison with levels in the neutron-rich mirror nucleus
  - Charge symmetry of nuclear force
  - Effects of Coulomb force in nuclear structure
Recent experiments at CNS (2002—2005)

- **Resonance search**
  - $^{11}\text{C}(p,p)^{11}\text{C}$
  - $^{12}\text{N}(p,p)^{12}\text{N}$

(p,γ) reactions in the hot-pp chain which may bypass $3\alpha \to ^{12}\text{C}$ in metal-poor massive stars.

- **Direct measurement**
  - $^{14}\text{O}(\alpha,p)^{17}\text{F}$ breaks out from Hot-CNO into rp-process

- **Resonance search**
  - $^{13}\text{N}(p,p)^{13}\text{N}$

Hot-CNO. Structure of $^{14}\text{O}^*$

$^{13}\text{O}$  $^{14}\text{O}$  $^{15}\text{O}$  $^{16}\text{O}$  $^{17}\text{O}$  $^{18}\text{O}$

Resonance search

- $^{21}\text{Na}(p,p)^{21}\text{Na}$
- $^{22}\text{Mg}(p,p)^{22}\text{Mg}$
- $^{23}\text{Mg}(p,p)^{23}\text{Mg}$
- $^{25}\text{Al}(p,p)^{25}\text{Al}$

(p,γ) reactions make breakout from Ne-Na&Mg-Al into rp-process. Production of $^{26}\text{Al} (t_{1/2}=7\times10^5 \text{ y})$
Experiment of proton resonance scattering

\[ A + p \rightarrow B^* \rightarrow A + p \]

with a beam of unstable proton-rich nucleus “A” & a proton target

In inverse kinematics

**Experimental goals:**

- To identify resonances in the excitation function \( \frac{d\sigma}{d\Omega}(E_{\text{CM}}) \)
- To determine resonance parameters \( E_R, \Gamma (\sim \Gamma_p), \) & \( J^\pi \)

Basic data for nuclear structure and astrophysical reaction rates

However, it is unable to measure \( \Gamma_\gamma \), which is necessary to deduce astrophysical (p,γ) reaction rates.
Thick-target method for A+p in inverse kinematics

- **Thick proton target**
- Energy loss process of the beam
- Utilized to scan \( \frac{d\sigma}{d\Omega}(E) \) automatically
- Without changing the beam energy before the target

\[ \text{Proton yield} \rightarrow \frac{d\sigma}{d\Omega} \]

\[
\frac{dN}{dE} \propto \frac{d\sigma}{d\Omega} \cdot \frac{dx}{dE} \cdot \frac{d\Omega}{dE}
\]

Counts per energy-bin \( \rightarrow \) Target-thickness per energy-bin

Excitation function \( \frac{d\sigma}{d\Omega}(E) \)

Interference pattern of potential \& resonance scattering

\[ E_{\text{CM}} \propto E_p \]

Silicon Detector

Counts per energy-bin

Target-thickness per energy-bin

\( E_{\text{res}}, \Gamma \& J^\pi \)

\( \theta \sim 0^\circ \) (LAB)

\( \theta \sim 180^\circ \) (CM)
Setup for A+p

Radioactive beam A
3–4 MeV/nucleon

PPAC1
(Parallel-Plate Avalanche Counter)
Area: 100 × 100 mm²
Position (x,y) -> angle
Timing -> TOF

PPAC2

Target (CH₂)n
ϕ 3 cm
~10 mg/cm²
(C target for background subtraction)

Telescopes of ∆E-E SSD
Area 50 × 50 mm²
∆E: 75 µm thick
16(x) + 16(y) strips → (x,y)
E: 1500 µm thick

The beam stops in the target.
Recoil protons go out from the target.
Identification of Recoil Proton

$\Delta E$ vs. $E$

$E$ vs. Timing

$\Delta E$ vs. $E$

$\Delta E + E$ (MeV)

$E$ (MeV)

$\Delta E$ (MeV)
Reconstruction of CM Energy

\[ E_{\text{CM}} = \frac{1}{4 \cos^2 \theta_p} \frac{A+1}{A} E_p \]

\( A \): mass number of projectile
\( E_p \): proton energy (LAB)

By SSD
Resolution of 80 keV (FWHM)

\( \theta_p \): angle of proton (LAB)

By PPACs & SSD (double-sided strips)
Resolution of 0.5 deg (FWHM)

\( E_{\text{CM}} \) is deduced from \( E_p \) & \( \theta_p \) on an event-by-event basis
(energy loss in the target taken into account)

\( E_p \) resolution of 80 keV
\[ \rightarrow E_{\text{CM}} \text{ resolution of } \sim 20 \text{ keV (FWHM) at } \theta_p = 0 \]

Better than the invariant mass method used in radioactive beam experiments
(Contribution from energy straggling of proton in the target is small.)
11C+p experiment (for 12N resonances)

To verify known values of $E_R$, $\Gamma$ ($\sim \Gamma_p$), $J\pi$ for low-lying levels in 12N

For the astrophysical $^{11}\text{C}(p,\gamma)^{12}\text{N}$ reaction rates (Hot-PP)

$J\pi$ values for the 3.13 & 3.56-MeV levels

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>J\pi</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.14</td>
<td></td>
</tr>
<tr>
<td>3.56</td>
<td></td>
</tr>
<tr>
<td>3.13</td>
<td>$(1)^+$</td>
</tr>
<tr>
<td>2.44</td>
<td>$0^+$</td>
</tr>
<tr>
<td>1.80</td>
<td>$1^-$</td>
</tr>
<tr>
<td>1.19</td>
<td>$2^-$</td>
</tr>
<tr>
<td>0.960</td>
<td>$2^+$</td>
</tr>
</tbody>
</table>

$J\pi$ values for the 3.13 & 3.56-MeV levels

$\Gamma_p$

$^{11}\text{C} + p$
Result: $^{11}$C+p ($^{12}$N resonances)

Resonances relevant to $^{11}$C(p,$\gamma$)$^{12}$N

The resonances at 0.96 & 1.2 MeV are important for the $^{11}$C(p,$\gamma$)$^{12}$N reaction.

$J^\pi = 3^-$ newly assigned to the 3.13-MeV level
does not contribute so much to the (p,$\gamma$) reaction because of the M2 transition $3^-$ → $1^+$(g.s).

E & $\Gamma$ are consistent width known values.
13N+p experiment (for 14O resonances)

Isobaric Analog Multiplets

• T = 1 levels in A=14 nuclei (14C, 14N, 14O)
  Charge independence & Effects of Coulomb force in nuclear structure

• Experimental information on 14O is relatively poor

E_x & Γ of resonances to study the astrophysical 13N(p,γ)14O reaction rates in the Hot-CNO cycle

13N+p

14O
\(^{13}\text{N}+\text{p}\) result \((^{14}\text{O} \text{ resonances})\)

Preliminary Data

- \(E_x = 5\text{--}8\ \text{MeV}\)
- \(5.17\ \text{MeV}^{1-}\) dominates the astrophysical \(^{13}\text{N}(\text{p},\gamma)^{14}\text{O}\) reaction rates

Solid line: R-matrix

Energy resolution \(\sim 20\ \text{keV (FWHM)}\)!

cf. \(^{14}\text{N}(^{3}\text{He},t)^{14}\text{O}\) reaction
Collaborators for CRIB experiments

Kyushu-Univ., Japan
CNS, Univ. of Tokyo, Japan
RIKEN, Japan
KEK, Japan
Chung-Ang, Univ., Korea
Ewha Woman’s Univ., Korea
ATOMKI, Hungary
Sao-Paulo Univ., Brazil
Summary

Low-energy radioactive nuclear beams are useful to study resonance states near the particle threshold in unstable nuclei.

Low-energy in-flight separator method

- with intense primary beams and a large-acceptance separator
- Technically simpler than ISOL
- Complementary to ISOL

Experiments on proton-rich nuclei

$^{11}\text{C}+p$, $^{13}\text{N}+p$ ....

Other projects in near future:

- p-resonance scattering on neutron-rich nuclei
- a-resonance scattering on unstable nuclei