Study of fusion mechanisms induced by weakly bound nuclei

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Outline

- Introduction
- Experiment and experimental results
- Summary
Introduction

$^6\text{Li}, ^7\text{Li}, ^9\text{Be}$

Transfer: direct transfer ($1n$ stripping and $1n$ pickup) and breakup transfer

The same residues
It is indicated that the sub-barrier total reaction cross section is dominantly by one and two neutron stripping. In the case of reactions with neutron-rich radioactive ion beams, the coupling to transfer is also found to be important.

The CF suppression is mostly caused by NEB modes, EBU plays a minor role. The large $\alpha$ yields can be explained as a consequence of the Trojan Horse mechanism.

$^7\text{Li} + ^{209}\text{Bi}$ at $E_{c.m.} = 38.72\text{MeV}$

Experimental setup and results
$^6\text{Li}+^8\text{Y}$ experiment at INFN-LNL in Italy
Gamma coincidence with $\alpha$ particles

### CF process
$^6\text{Li} + ^{89}\text{Y} \rightarrow ^{95}\text{Mo} \rightarrow ^{90}\text{Zr} + \alpha + n$,

### ICF process
$^2\text{H} + ^{89}\text{Y} \rightarrow ^{91}\text{Zr} \rightarrow ^{90}\text{Zr} + n, \alpha$

### Transfer process:
1n stripping: $^6\text{Li} + ^{89}\text{Y} \rightarrow ^{90}\text{Zr} + \alpha + n + 3.92\text{MeV}$,

1p stripping: $^6\text{Li} + ^{89}\text{Y} \rightarrow ^{90}\text{Zr} + \alpha + n + 3.92\text{MeV}$

1d stripping: $^6\text{Li} + ^{89}\text{Y} \rightarrow ^{91}\text{Zr} + \alpha + 11.85\text{MeV}$

### Transfer process

- **Angles (covered with Al):**
  - $^91\text{Zr}$
  - $^90\text{Y}$

- **Angles (Uncovered with Al):**
  - $^90\text{Zr}$
  - $^89\text{Zr}$

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**Trans**: $^6\text{Li} + ^{89}\text{Y} \rightarrow ^{95}\text{Mo} \rightarrow ^{90}\text{Zr} + \alpha + n \rightarrow ^{89}\text{Zr} + \alpha + 2n$
A powerful combination measurement for exploring the fusion reaction mechanisms induced by weakly bound nuclei

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Gamma coincidence with proton particles

\[ ^6\text{Li} + ^{89}\text{Y} \rightarrow (^{95}\text{Mo})^* \rightarrow ^{93}\text{Nb} + n + p \]

CF:

\[ ^6\text{Li} + ^{89}\text{Y} \rightarrow (^{95}\text{Mo})^* \rightarrow ^{92}\text{Nb} + 2n + p \]

\[ ^6\text{Li} + ^{89}\text{Y} \rightarrow (^{95}\text{Mo})^* \rightarrow ^{91}\text{Nb} + 3n + p \]

If ICF? May come from the breakup of \(^6\text{Li}\)

<table>
<thead>
<tr>
<th>breakup</th>
<th>Separation energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^6\text{Li} \rightarrow \text{d} + \alpha)</td>
<td>-1.47</td>
</tr>
<tr>
<td>(^6\text{Li} \rightarrow \text{p} + ^5\text{He} (n + \alpha))</td>
<td>-4.43</td>
</tr>
<tr>
<td>(^6\text{Li} \rightarrow \text{n} + ^5\text{Li} (\alpha + p))</td>
<td>-5.66</td>
</tr>
<tr>
<td>(\text{d} \rightarrow \text{p} + n)</td>
<td>-2.224</td>
</tr>
</tbody>
</table>

According to estimation, protons from breakup cannot go through Al and \(\Delta E\) detector.

So, \(^{91}\text{Nb}, \ ^{92}\text{Nb}\) and \(^{93}\text{Nb}\) are from CF process.
(1) The energies of protons detected by detector in the angles covered by Al are much higher than that of the other angles.

(2) The ratio of $^{92}\text{Nb}/^{91}\text{Nb}$ increases with energy at the same angle.

(3) The experimental results are consistent with that of (statistical evaporation model)
$^{89}\text{Y}+^{6}\text{Li} \rightarrow ^{90}\text{Y} + \left(^{5}\text{Li}\right)^* \rightarrow ^{90}\text{Y} + \alpha + p + 3158 \text{ keV}$

$^{90}\text{Y}$ at angles covered with Al foil comes from the $1n$ stripping reaction.

Gamma coincidence with deuteron particles

\[ ^6\text{Li} \longrightarrow \alpha + d \]

ICF:
\[ \alpha + ^{89}\text{Y} \longrightarrow (^{93}\text{Nb})^* \longrightarrow ^{92}\text{Nb} + n \]
\[ \alpha + ^{89}\text{Y} \longrightarrow (^{93}\text{Nb})^* \longrightarrow ^{91}\text{Nb} + 2n \]

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According to the calculations, a part of the deuterons from breakup can pass through the Al foil and \(\Delta E\) detector.
(1) The ratio of $^{\text{92}}\text{Nb}/^{\text{91}}\text{Nb}$ increases with energy at the same angle.

(2) By the calculation of statistical evaporation model, $^{\text{92}}\text{Nb}/^{\text{91}}\text{Nb} < 1$, which is the same as that at $148^\circ$ (uncovered with Al), but at angles with covered by Al, since the deuteron must pass through Al, it is asked for higher energy, so $^{\text{92}}\text{Nb}/^{\text{91}}\text{Nb} > 1$.
The typical γ rays (385, 949) of ⁹³Nb are different at angles (covered and uncovered with Al foils).

In α stripping reaction channel, the energy of d is higher than 11.5 MeV, through dynamical model calculation, the energy range of d is 28~34 MeV.
Gamma coincidence with triton particles

$^3$He stripping:

$^6$Li$^{^{89}Y}$$\rightarrow$$^t$$^9$Nb+$^{^{92}Nb}$($-2.12$ MeV)

(1) $E_t\approx 25$~30.5 MeV by dynamic model calculation.

$^6$Li$^{^{16}O}$$\rightarrow$$^{^{19}Ne}$$^t$+($-7.35$ MeV)

(2) $E_t\approx 8$~24 MeV by dynamic model calculation.
(1) The energies of triton are different at different angles, it is much higher at smallest angle.
(2) The ratio at smallest angle is larger than that at the other angles.
$^6\text{Li} + ^{12}\text{C} = ^{10}\text{B} + ^8\text{Be}$? $/^{10}\text{B} = ^6\text{Li} + ^4\text{He}$?
New energy levels of $^{92}$Mo

From 92mo.glis
New energy levels of $^{92}$Nb
$^6\text{Li} + ^{209}\text{Bi}$ experiment at INFN-LNL in Italy

5 days beam time
34MeV $^6\text{Li}$, 166µm Al foil
30MeV $^6\text{Li}$, 138 µm Al foil
28MeV $^6\text{Li}$, 124µm Al foil
Summary

✓ A powerful combination of gamma and light charged particles can distinguish the various reaction channels and separate the different reaction processes including CF, ICF and transfer.

✓ A powerful combination of gamma and light charged particles can correct and give new energy levels for many nuclei in the future.

✓ Particle-particle coincidence can explore the different reaction processes to study the reaction mechanisms in the future.

Not only explore the reaction dynamics of weakly bound nuclei at low energies, but also study the nuclear structure!!!
Thank you for your attention