Reaction dynamics and exotic systems: a focus on fast processes
Motivation and outline

1. Competition between pre-equilibrium and evaporation processes in fusion reactions. \([n,\text{LCP},\gamma\text{ emission cross sections}]\)

2. Influence of Nuclear Structure on the reaction dynamics.

3. Cluster pre-formation vs Dynamical formation (coalescence)

Outline:
- \(^{12}\text{C}\) and \(^{16}\text{O}\)-induced reactions, inclusive cross sections with pre-equilibrium
- Pre-equilibrium and clustering
- The ACLUST campaigns
- Outlook with Stable beams and RIBs
Pre-equilibrium revival

PHYSICAL REVIEW C 91, 014603 (2015)

Systematic study of pre-equilibrium emission at low energies in $^{12}$C- and $^{16}$O-induced reactions

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TABLE I. Details of the system studied, including measured thickness of the samples, Coulomb barrier, and energy of interest

<table>
<thead>
<tr>
<th>Serial number</th>
<th>System studied</th>
<th>Measured thickness (mg/cm²)</th>
<th>Coulomb barrier (MeV)</th>
<th>Energy studied (MeV)</th>
<th>Reaction channels</th>
<th>T₁/₂ (h)</th>
<th>Energy ($E_γ$) (keV)</th>
<th>Branching ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$^{12}$C⁶⁺ + $^{128}$Te</td>
<td>0.92</td>
<td>42.2</td>
<td>42–80</td>
<td>$^{128}$Te($^{12}$C,3$n$)$^{137}$Ce</td>
<td>13</td>
<td>254.29</td>
<td>11.0</td>
</tr>
<tr>
<td>2</td>
<td>$^{12}$C⁶⁺ + $^{169}$Tm</td>
<td>0.50</td>
<td>51.5</td>
<td>55–85</td>
<td>$^{169}$Tm($^{12}$C,3$n$)$^{178}$Re</td>
<td>13.2</td>
<td>106.0, 237.0</td>
<td>23.4, 44.5</td>
</tr>
<tr>
<td>3</td>
<td>$^{16}$O⁷⁺ + $^{159}$Tb</td>
<td>1.80</td>
<td>63.8</td>
<td>68–95</td>
<td>$^{159}$Tb($^{16}$O,3$n$)$^{172}$Ta</td>
<td>38.8</td>
<td>214.0, 318.7</td>
<td>55.0, 49.0</td>
</tr>
<tr>
<td>4</td>
<td>$^{16}$O⁷⁺ + $^{169}$Tm</td>
<td>0.50</td>
<td>67.2</td>
<td>70–95</td>
<td>$^{169}$Tm($^{16}$O,3$n$)$^{182}$Ir</td>
<td>12</td>
<td>126.9 273.8</td>
<td>34.4, 43.0</td>
</tr>
<tr>
<td>5</td>
<td>$^{16}$O⁷⁺ + $^{181}$Ta</td>
<td>1.72</td>
<td>70.5</td>
<td>75–100</td>
<td>$^{181}$Ta($^{16}$O,3$n$)$^{194}$Tl</td>
<td>32.8</td>
<td>636.1</td>
<td>99.0</td>
</tr>
</tbody>
</table>

M. K. Sharma et al, PRC 91 (2015) 014603
Pre-equilibrium revival – H.I. reactions

Pre-equilibrium signatures:
I. Presence of a larger number of high-energy particles as compared to the spectrum predicted by the compound nucleus model (e.g. PACE4 calculations);
II. Forward–peaked angular distribution of emitted particles
III. Slowly decreasing tails of excitation functions
From our experience on pre-equilibrium emission

A. Corsi et al., PLB 679 (2009) 197

<table>
<thead>
<tr>
<th>System</th>
<th>E_{beam}</th>
<th>η</th>
<th>Comp</th>
<th>E^*</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{16}$O + $^{116}$Sn</td>
<td>130 MeV, 250 MeV</td>
<td>0.76</td>
<td>$^{132}$Ce</td>
<td>100, 206</td>
</tr>
<tr>
<td></td>
<td>15.8 AMeV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{16}$O + $^{116}$Sn</td>
<td>192 MeV, 12 AMeV</td>
<td>0.76</td>
<td>$^{132}$Ce</td>
<td>155</td>
</tr>
<tr>
<td>$^{16}$O + $^{65}$Cu</td>
<td>256 MeV, 16 AMeV</td>
<td>0.60</td>
<td>$^{81}$Rb</td>
<td>209</td>
</tr>
<tr>
<td>$^{19}$F + $^{62}$Ni</td>
<td>304 MeV, 16 AMeV</td>
<td>0.53</td>
<td>$^{81}$Rb</td>
<td>240</td>
</tr>
<tr>
<td>$^{19}$F + $^{63}$Cu</td>
<td>304 MeV, 16 AMeV</td>
<td>0.52</td>
<td>$^{82}$Sr</td>
<td>243</td>
</tr>
</tbody>
</table>

Light charged particles in coincidence with Evaporation Residues
Pre-equilibrium emission and clustering

In 1968 Ikeda suggested that $\alpha$-conjugate nuclei are observed as excited states close to decay threshold into clusters. The original idea was introduced by Hafstad and Teller in 1938.

1. In light nuclei at the neutron drip-line, clustering might be the preferred structural mode.
2. Nuclear states built on clusters bound by valence neutrons in their molecular configurations might appear.
3. These structures are mainly described by theory, but must be experimentally confirmed.

Extended Ikeda diagram

Figure 1. Different types of clustering in nuclei that have been discussed at this workshop. (Figure adapted from Ref.[1] courtesy of Catford.)

The different rotational band structures in $^{12}\text{C}$. The smaller slope of the Hoyle band curve with respect to the ground state band indicates a more extended structure. [Marín-Lambarri et al, PRL 113 (2014) 1].

$^{12}\text{C}+^{12}\text{C} @ 95 \text{ MeV}$

Experimental and calculated energy Dalitz-plot obtained from a $^{12}\text{C}+^{12}\text{C}$ peripheral scattering reaction. [Morelli et al, JoP G 43 (2016) 4]
Pre-equilibrium and clustering?

Moscow Pre-equilibrium Model (MPM)

"Exciton Clusters"
MPM A:
- Griffin Exciton Model

MPM B:
- Hybrid Exciton Model

Cluster PRE-formation
“clustering add-on” according to H.F. Zhang

MPM: O.V. Fotina, EPJ WoC 66 (2014) 03028 (and ref therein)
Experimental setup:

\[ \text{256 MeV } ^{16}\text{O} + ^{65}\text{Cu} \quad \theta_{\text{gr}} = 8.2^\circ \]

\[ \text{Ring Counter} \quad \text{IC} \quad \text{D}_{\text{gr}} = 8.6^\circ \div 17^\circ \text{ at } P = 25 \text{ mbar CF}_4 \]

\[ \text{Fast (ch), } \text{p, d, t}, \quad ^{3}\text{He, } \alpha, \quad \text{Slow (ch)} \]

Particle Identification

Neutrons: very important missing ingredient
## Experimental Campaigns

<table>
<thead>
<tr>
<th>E_beam (AMeV)</th>
<th>Comp</th>
<th>E(^*) (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16(^{\text{O}}) + 116(^{\text{Sn}})</td>
<td>8 15.8</td>
<td>132(^{\text{Ce}}) 100 206</td>
</tr>
<tr>
<td>16(^{\text{O}}) + 116(^{\text{Sn}})</td>
<td>12</td>
<td>132(^{\text{Ce}}) 155</td>
</tr>
<tr>
<td>16(^{\text{O}}) + 65(^{\text{Cu}})</td>
<td>16</td>
<td>81(^{\text{Rb}}) 209</td>
</tr>
<tr>
<td>19(^{\text{F}}) + 62(^{\text{Ni}})</td>
<td>16</td>
<td>81(^{\text{Rb}}) 240</td>
</tr>
<tr>
<td>19(^{\text{F}}) + 63(^{\text{Cu}})</td>
<td>16</td>
<td>82(^{\text{Sr}}) 243</td>
</tr>
<tr>
<td>16(^{\text{O}}) + 30(^{\text{Si}})</td>
<td>7</td>
<td>46(^{\text{Ti}}) 88</td>
</tr>
<tr>
<td>16(^{\text{O}}) + 30(^{\text{Si}})</td>
<td>8</td>
<td>46(^{\text{Ti}}) 98</td>
</tr>
<tr>
<td>18(^{\text{O}}) + 28(^{\text{Si}})</td>
<td>7</td>
<td>46(^{\text{Ti}}) 98</td>
</tr>
<tr>
<td>19(^{\text{F}}) + 27(^{\text{Al}})</td>
<td>7</td>
<td>46(^{\text{Ti}}) 103</td>
</tr>
</tbody>
</table>

- Same compound nucleus with different entrance channels
- Same projectile at different energies
- At the onset of pre-equilibrium processes
# ACLUST2 experiment

<table>
<thead>
<tr>
<th>Projectile</th>
<th>Target</th>
<th>Grazing</th>
<th>Compound Nucleus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion</td>
<td>$E_{lab}$ (AMeV)</td>
<td>Isotope</td>
<td>$\theta_{lab}$ (deg)</td>
</tr>
<tr>
<td>$^{16}O$</td>
<td>7.0</td>
<td>$^{30}Si$</td>
<td>10.1</td>
</tr>
<tr>
<td>$^{16}O$</td>
<td>8.0</td>
<td>$^{30}Si$</td>
<td>8.8</td>
</tr>
<tr>
<td>$^{18}O$</td>
<td>7.0</td>
<td>$^{28}Si$</td>
<td>9.0</td>
</tr>
<tr>
<td>$^{19}F$</td>
<td>7.0</td>
<td>$^{27}Al$</td>
<td>8.9</td>
</tr>
</tbody>
</table>
$^{16}\text{O} + ^{30}\text{Si} 128 \text{ MeV (8 AMeV)}$

$\sim 85 \text{ h Beam on tgt}$

$\sim 16.3 \text{ M residues}$
ACLUST2 experiment

$^{16}\text{O}^+\ ^{30}\text{Si}$ 128 MeV (7 AMeV) 
~ 40 h Beam on tgt 
~ 5.9 M residues

$^{18}\text{O}^+\ ^{28}\text{Si}$ 126 MeV (7 AMeV) 
~ 70 h Beam on tgt 
~ 9.9 M residues

- DC BEAM -

$^{19}\text{F}^+\ ^{27}\text{Al}$ 128 MeV (7 AMeV) 
~ 70 h Beam on tgt 
~ 10.9 M residues
ACLUST2 experiment – ER selection and target contamination

**Z vs E**: inclusive - EXP

![Graph showing Z vs E for different scenarios](image)

AN2000: EBS, EDS and SEM on $^{28}\text{Si}$ (400 $\mu\text{g/cm}^2$)

![Graph showing energy spectra with target simulation](image)

**Target Simulation:**

<table>
<thead>
<tr>
<th>Target</th>
<th>Pb</th>
<th>Si80</th>
<th>Si70</th>
<th>Si60</th>
<th>Si50</th>
<th>Si40</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO4</td>
<td>10^{-30}</td>
<td>10^{-29}</td>
<td>10^{-28}</td>
<td>10^{-27}</td>
<td>10^{-26}</td>
<td>10^{-25}</td>
</tr>
<tr>
<td>SiO5</td>
<td>10^{-29}</td>
<td>10^{-28}</td>
<td>10^{-27}</td>
<td>10^{-26}</td>
<td>10^{-25}</td>
<td>10^{-24}</td>
</tr>
<tr>
<td>SiO6</td>
<td>10^{-28}</td>
<td>10^{-27}</td>
<td>10^{-26}</td>
<td>10^{-25}</td>
<td>10^{-24}</td>
<td>10^{-23}</td>
</tr>
</tbody>
</table>

PhD work of M. Cicerchia - LNL and Unipd
Correlation between the longitudinal momentum and total collected charge

\[ \frac{q_z}{q_{\text{beam}}} \text{ vs. } \frac{Z_{\text{tot}}}{(Z_p + Z_T)} \]

\[ ^{16}\text{O}^{30}\text{Si} @ 7 \text{ MeV/u} \]

Correlation between the laboratory energy and charge

\[ \frac{q_z}{q_{\text{beam}}} < 1.3 \]

\[ Z_{\text{tot}} > 70\% Z_p + Z_T \]

PhD work of M. Cicerchia - LNL and Unipd
Experimental data and GEMINI

P in coincidence with ER – almost complete events ($Z_{tot} > 0.70\,Z_p+Z_t$): comparing the experimental energy distributions with Statistical calculation predictions

- $\theta_{lab}=8.6^\circ-150^\circ$
  - $^{16}\text{O} + ^{30}\text{Si} \, 7\text{AMeV}$
  - $^{18}\text{O} + ^{28}\text{Si} \, 7\text{AMeV}$

- $\theta_{lab}=8.6^\circ-150^\circ$
  - $^{16}\text{O} + ^{30}\text{Si} \, 8\text{AMeV}$
  - $^{19}\text{F} + ^{27}\text{Al} \, 7\text{AMeV}$
α-particles in coincidence with ER – almost complete events (Z_{tot} > 0.70 Z_p + Z_t): comparing the experimental energy distributions with Statistical calculation predictions

θ_{lab} = 8.6° - 150°

- $^{16}\text{O} + ^{30}\text{Si}$ 7AMeV
- $^{16}\text{O} + ^{30}\text{Si}$ 8AMeV
- $^{18}\text{O} + ^{28}\text{Si}$ 7AMeV
- $^{19}\text{F} + ^{27}\text{Al}$ 7AMeV

PhD work of M. Cicerchia - LNL and Unipd
Experimental data and preliminary results

\[ ^{16}\text{O} + ^{30}\text{Si} @ 111 \text{ MeV} \quad ^{16}\text{O} + ^{30}\text{Si} @ 128 \text{ MeV} \quad ^{18}\text{O} + ^{28}\text{Si} @ 126 \text{ MeV} \quad ^{19}\text{F} + ^{27}\text{Al} @ 133 \text{ MeV} \]
Multiplicity spectra

EXP MULTIPLICITY – comparison between the different reactions

FILTERED MULTIPLICITY – comparison to EXP DATA

COINCIDENCE with ER

\[ ^{16}O + ^{30}Si \ 7\text{AMeV} \quad ^{16}O + ^{30}Si \ 8\text{AMeV} \quad ^{18}O + ^{28}Si \ 7\text{AMeV} \quad ^{19}F + ^{27}Al \ 7\text{AMeV} \]

Counts (a.u.)

Counts (a.u.)

Exp Proton Multiplicity
- \( ^{16}O + ^{30}Si \) @111MeV
- \( ^{16}O + ^{30}Si \) @128MeV
- \( ^{18}O + ^{28}Si \) @126MeV
- \( ^{19}F + ^{27}Al \) @133MeV

Exp Alpha Multiplicity
- \( ^{16}O + ^{30}Si \) @111MeV
- \( ^{16}O + ^{30}Si \) @128MeV
- \( ^{18}O + ^{28}Si \) @126MeV
- \( ^{19}F + ^{27}Al \) @133MeV

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Selective channels: multiple alpha channels in coincidence with specific ER

$^{16}\text{O} + ^{30}\text{Si} \ 8\text{A}\text{MeV}$

Selected channel: $^{42-x}\text{Ar} + 3\alpha + xn$

Experimental spectra and comparison to Gemini.

Minimum, medium and maximum energy of the $3\alpha$ event by event:

PhD work of M. Cicerchia - LNL and Unipd
While at higher energy ... (ACLUST experiment):

- $^{16}\text{O} + ^{65}\text{Cu} @ 256$ MeV
  - Slow
  - Exp
  - Gemini++

- $^{16}\text{O} + ^{65}\text{Cu} @ 256$ MeV
  - Medium
  - Exp
  - Gemini++

- $^{16}\text{O} + ^{65}\text{Cu} @ 256$ MeV
  - Fast
  - Exp
  - Gemini++

- $^{19}\text{F} + ^{62}\text{Ni} @ 304$ MeV
  - Slow
  - Exp
  - Gemini++

- $^{19}\text{F} + ^{62}\text{Ni} @ 304$ MeV
  - Medium
  - Exp
  - Gemini++

- $^{19}\text{F} + ^{62}\text{Ni} @ 304$ MeV
  - Fast
  - Exp
  - Gemini++

PhD work of M. Cicerchia - LNL and Unipd
Summary

• High granularity and angular coverage allow to study pre-equilibrium processes in a detailed and exclusive way

• A link between light charged particles pre-equilibrium emission and cluster structure can be established but new observables are needed

• A systematic approach is needed, especially in terms of projectile energy

• Radioactive Ion Beams will provide a wider playground in terms of entrance channel combinations
Outlook

$^{132}\text{Sn} + ^{27}\text{Al} \ @ \ 11 \ \text{AMeV}$

$^{130-132}\text{Sn} + ^{30-28}\text{Si} \ @ \ 11 \ \text{AMeV}$

$^{114-116}\text{Sn} + ^{30-28}\text{Si}$

STABLE targets

$^{85}\text{Rb} \sim ^{87}\text{Rb} \sim ^{94-97}\text{Rb} + ^{30-28}\text{Si}$

$^{28}\text{Si} \sim ^{30}\text{Si} \sim ^{85-87}\text{Rb} + ^{30-28}\text{Si}$
One possible setup

Challenges:
- Heavy beams, dynamic range
- Beam current, Count rate
- High multiplicity
- Resolution (Energy, A, Z)

Advantages
- Low thresholds
- Angular coverage
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