Reaction Dynamics for the Systems $^7$Be, $^8$B + $^{208}$Pb at Energies Around the Coulomb Barrier

Marco Mazzocco

Dipartimento di Fisica e Astronomia, Università di Padova
and INFN – Sezione di Padova, Padova, Italy

26th International Nuclear Physics Conference (INPC)
Adelaide Convention Centre, Australia
11-16 September 2016
I. Introduction
Light Exotic Nuclei

The light portion of the nuclide chart is full of weakly-bound nuclei with unusual matter distributions (halo and neutron skin nuclei).

1-proton Halo

1-neutron Halo

2-neutron Halo

Neutron Skin
Near-Barrier Studies

What is the influence of the **nuclear halo** on the reaction dynamics? Depending on the treatment of the **projectile breakup process**, theoretical models predicted either the **enhancement** or the **hindrance** of the **sub-barrier fusion** cross section.

**Breakup related effects** largely increased the **sub-barrier total reaction** cross section, mainly because of **direct processes**.

---

**Elastic Scattering:** strong deviations from the Rutherford differential cross section already at **small angles**.

A. Lemasson et al., PRL 103, 232701 (2009)

M. Cubero et al., PRL 109, 262701 (2012)
II. Facility EXOTIC at INFN-LNL (Italy)
The In-Flight Facility EXOTIC

Facility at the Laboratori Nazionali di Legnaro (LNL) of the INFN for the in-flight production of light weakly-bound RIBs, employing inverse kinematics reactions with heavy projectiles impinging on gas targets ($p, d, ^3\text{He}$).

The commissioning of the facility was performed in 2004. F. Farinon et al., NIM B 266, 4097 (2008)

A substantial upgrade process was subsequently held in 2012. M. Mazzocco et al., NIM B 317, 223 (2013)

7 Radioactive Ion Beams have been delivered so far:

1. $^{17}\text{F}$ ($S_p = 600$ keV): $p^{(17}\text{O},^{17}\text{F})n$ $Q_{\text{value}} = -3.54$ MeV;
2. $^{8}\text{B}$ ($S_p = 137.5$ keV): $^3\text{He}(^6\text{Li},^8\text{B})n$ $Q_{\text{value}} = -1.97$ MeV;
3. $^7\text{Be}$ ($S_\alpha = 1.586$ MeV): $p(^7\text{Li},^7\text{Be})n$ $Q_{\text{value}} = -1.64$ MeV;
4. $^{15}\text{O}$ ($S_p = 7.297$ MeV): $p(^{15}\text{N},^{15}\text{O})n$ $Q_{\text{value}} = -3.54$ MeV;
5. $^8\text{Li}$ ($S_n = 2.033$ MeV): $d(^7\text{Li},^8\text{Li})p$ $Q_{\text{value}} = -0.19$ MeV;
6. $^{10}\text{C}$ ($S_p = 4.007$ MeV): $p(^{10}\text{B},^{10}\text{C})n$ $Q_{\text{value}} = -4.43$ MeV;
7. $^{11}\text{C}$ ($S_p = 8.689$ MeV): $p(^{11}\text{B},^{11}\text{C})n$ $Q_{\text{value}} = -2.76$ MeV;
Facility EXOTIC at INFN-LNL

1st Quadrupole Triplet
30°-Dipole Magnet
2nd Quadrupole Triplet
Wien Filter

PRIMARY BEAM
Gas Target
1st Quadrupole Triplet
30°-Dipole Magnet
Wien Filter
2nd Quadrupole Triplet

SECONDARY BEAM
4 Slit Systems
Light RIBs at EXOTIC

17F
E = 3–5 MeV/u
Purity: 93-96 %
Intensity: 10^5 pps

8B
E = 3–5 MeV/u
Purity: 30-43 %
Intensity: ~ 10^3 pps

7Be
E = 2.5–6 MeV/u
Purity: 99 %
Intensity: 10^6 pps

15O
E = 1.3 MeV/u
Purity: 97-98 %
Intensity: 4*10^4 pps

8Li
E = 2–2.5 MeV/u
Purity: 99 %
Intensity: 10^5 pps

10C
E = 4 MeV/u
Purity: 99 %
Intensity: 5*10^3 pps

11C
E = 4 MeV/u
Purity: 99 %
Intensity: 2*10^5 pps
Experiments (2006 - 2012)

$^{17}\text{F} + ^{208}\text{Pb}$ [Quasi-Elastic Scattering and Breakup]

$^{17}\text{F} + ^{58}\text{Ni}$ [Quasi-Elastic Scattering]

$^{17}\text{F} + ^{1}\text{H}$ [Elastic Scattering]

$^{8}\text{B} + ^{28}\text{Si}$ [Fusion]

$^{7}\text{Be} + ^{58}\text{Ni}$ [Elastic Scattering, Direct Processes]
Experiments (2013 - 2016)

$^{32}\text{S} + ^{48}\text{Ca}, ^{64}\text{Ni}$ [Recoil Separation (PRISMA)]
   Spokesperson: G. Montagnoli, A.M. Stefanini, M. Mazzocco

$^{7}\text{Be} + ^{208}\text{Pb}$ [Elastic Scattering, Direct Processes]
   Spokespersons: M. La Commara, L. Stroe, M. Mazzocco

$^{7}\text{Be} + ^{28}\text{Si}$ [Breakup Threshold Anomaly]
   A. Pakou et al., PRC (submitted)

$^{8}\text{Li} + ^{58}\text{Ni}$ [Elastic Scattering]
   Spokespersons: D. Torresi, M. Mazzocco

$^{8}\text{Li} + ^{90}\text{Zr}$ [Total Reaction Cross Section]

$^{15}\text{O} + ^{4}\text{He}$ [Resonant Scattering]
   D. Torresi, C. Wheldon, Tz. Kokalova et al., PRL (submitted)

$^{7}\text{Be} + ^{2}\text{H}$ [Surrogate Trojan Horse Reaction for $^{7}\text{Be}+n$]
   Spokesperons: L. Lamia, C. Spitaleri, M. Mazzocco
III. $^7\text{Be} + ^{208}\text{Pb} \@ \text{EXOTIC}$
$^7\text{Be} + ^{208}\text{Pb}$ at LNL

$^{208}\text{Pb}$ target (1 mg/cm$^2$)

EXPADIES detector array, entirely developed by our collaboration

$D$. Pierroutsakou et al., NIM A 834, 46 (2016)
$\Delta E - E_{\text{res}}$ Plots
(Quasi-) Elastic Scattering
A preliminary optical model best-fit analysis of the quasi-elastic scattering angular distributions suggests for $^7$Be ($S_\alpha = 1.586$ MeV) a behaviour more similar to $^7$Li ($S_\alpha = 2.468$ MeV) than to $^6$Li ($S_\alpha = 1.475$ MeV).
The $^4$He production yield is much larger than the $^3$He production yield, qualitatively confirming our previous result for the system $^7$Be + $^{58}$Ni.


Theoretical calculations by A.M. Moro and J.Lei (University of Seville, Spain) [unpublished]
What is the Origin of $^{3,4}$He?

$^{3}$He and $^{4}$He have significantly different yields, thus the reaction dynamics is not dominated by the breakup process.

$^{3}$He (97.5%) and $^{4}$He (99.5%) mostly come as single events, however we detected a few coincidences:

- 19 $^{3}$He+$^{4}$He (Exclusive Breakup)
- 15 $^{4}$He+$^{4}$He (n-pickup)
- 17 $^{4}$He+p (open question? Evaporation?)

![Graphs showing $^{3}$He-stripping and energy fragment distributions.]
IV. $^{8}\text{B} + ^{208}\text{Pb}$ @ CRIB
$^8\text{B} + ^{208}\text{Pb}$ at 50 MeV

$^8\text{B}$ Beam ($10^4$ pps, purity 20%)

$^{208}\text{Pb}$ Target (2.2 mg/cm$^2$)
$\Delta E - E_{res}$ Plots
$\Delta E$-ToF Plots

$4^\text{He}$, $6^\text{Li}$, $7^\text{Be}$, $8^\text{B}$
$^8\text{B} + ^{208}\text{Pb}$ Elastic Scattering

\[ \text{Ratio to Rutherford} \]

\[ \theta_{c.m.} \text{ (deg)} \]

- Tel. A
- Tel. B-C
- Tel. D-E
- Tel. F
Very preliminary optical-model best-fit analysis of the $^8\text{B} + ^{208}\text{Pb}$ elastic scattering angular distribution would suggest a total reaction cross section a factor of 3 larger than for the reaction $^7\text{Be} + ^{208}\text{Pb}$.
V. Summary

The study of the reaction dynamics induced by light weakly-bound Radioactive Ion Beams (RIBs) at near-barrier energies is currently a very active research field in Nuclear Physics. Our facility, EXOTIC, is fully operational at INFN-LNL and 7 light RIBs for reaction dynamics studies have been delivered.

Very promising results have been obtained for the system \( ^7\text{Be} + ^{208}\text{Pb} \): elastic scattering and \( ^3,^4\text{He} \) production yields. \(^4\text{He} \) ions were found to be much more abundant than \(^3\text{He} \) and we detected a few \(^3\text{He}+^4\text{He} \) (exclusive breakup), \(^4\text{He}+^4\text{He} \) (n-pickup) and \(^4\text{He}+p \) coincidence events.

The elastic scattering for the system \(^8\text{B}+^{208}\text{Pb} \) was measured at CRIB (Japan). The total reaction cross section is enhanced by a factor of 3 with respect to the reaction \(^7\text{Be}+^{208}\text{Pb} \).

Honestly speaking, I hope we will be able to answer at least one of the open questions by the FUSION17 Conference (in 5 months) 😊
EXOTIC Collaboration… & Collaborators

**Napoli**: A. Boiano, M. La Commara, G. La Rana, D. Pierroutsakou, C. Parascandolo

**Padova**: M.M., C. Signorini, F. Soramel, E. Strano


**Milano (Italy)**: C. Boiano, A. Guglielmetti

**CNS + RIKEN (Japan)**: H. Yamaguchi, S. Hayakawa, D. Kahl, Y. Sakaguchi, S. Kubono (RIKEN), N. Iwasa (Sendai), T. Teranishi (Kyushu), Y. Wakabayashi (RIKEN)

**KEK (Japan)**: H. Miyatake, S. Jeong, Y. Watanabe, H. Ishiyama, N. Imai (CNS), Y. Hirayama, Y. H. Kim, S. Kimura, I. Mukai, I. Sugai

**CIAE (China)**: H. Q. Zhang, C. J. Lin, H. Jia, Y. Yang, L. Yang, G. L. Zhang

**Ioannina (Greece)**: A. Pakou, O. Sgouros, V. Soukeras, E. Stiliaris, X. Aslanouglou

**Warsaw (Poland)**: N. Keeley, C. Mazzocchi, K. Rusek, I. Strojek, A. Trzcinska

**NIPNE (Romania)**: D. Filipescu, T. Glodariu, A. I. Gheorghe, T. Sava, L. Stroie

**Huelva (Spain)**: I. Martel, L. Acosta, G. Marquinez-Duran, A. M. Sanchez-Benitez, H. Silva

**Birmingham (UK)**: T. Kokalova, C. Wheldon
Thank You Very Much!!!
Backup
$^8B + ^{208}Pb$ Counting Statistics
$^8$B Production at CRIB

$^6$Li Primary Beam: 3 $\mu$A on target

Production Target: $^3$He gas at 90 K and 1 bar

$^8$B Secondary Beam:
   Energy: 50.0 ± 1.0 MeV (on target)
   Intensity (on target): $10^4$ pps
   Purity: 20% (main contaminant: $^7$Be and $^3$He)

Reaction Target: 2.2 mg/cm$^2$ $^{208}$Pb evaporated on 1.5 $\mu$m of Mylar.

Diameter: 25 mm
### $^6,^7\text{Li-}^7\text{Be Comparison}$

<table>
<thead>
<tr>
<th></th>
<th>$^6\text{Li+}^{208}\text{Pb}$</th>
<th>$^7\text{Li+}^{208}\text{Pb}$</th>
<th>$^7\text{Be+}^{208}\text{Pb}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breakup Thr.</td>
<td>-1.475</td>
<td>-2.468</td>
<td>-1.586</td>
</tr>
<tr>
<td>n-pickup</td>
<td>$^7\text{Li}$: -0.12</td>
<td>$^8\text{Li}$: -5.34</td>
<td>$^8\text{Be}$: +11.53</td>
</tr>
<tr>
<td>2n-pickup</td>
<td>$^8\text{Li}$: -4.82</td>
<td>$^9\text{Li}$: -8.01</td>
<td>$^9\text{Be}$: +6.46</td>
</tr>
<tr>
<td>p-pickup</td>
<td>$^7\text{Be}$: -2.40</td>
<td>$^8\text{Be}$: +9.25</td>
<td>$^8\text{B}$: -7.87</td>
</tr>
<tr>
<td>p-stripping</td>
<td>$^5\text{Li}$: -0.63</td>
<td>$^6\text{Li}$: -3.31</td>
<td>$^6\text{Be}$: -6.74</td>
</tr>
<tr>
<td>d-stripping</td>
<td>$^4\text{He}$: +4.71</td>
<td>$^5\text{He}$: -3.28</td>
<td>$^5\text{Li}$: -2.87</td>
</tr>
<tr>
<td>d-pickup</td>
<td>$^8\text{Be}$: +9.65</td>
<td>$^9\text{Be}$: +4.06</td>
<td>$^9\text{B}$: +3.86</td>
</tr>
<tr>
<td>$^4\text{He}$-stripping</td>
<td>$^2\text{H}$: -10.43</td>
<td>$^3\text{H}$: -11.42</td>
<td>$^3\text{He}$: -10.54</td>
</tr>
<tr>
<td>t-stripping</td>
<td>$^3\text{He}$: -10.73</td>
<td>$^4\text{He}$: +2.59</td>
<td>$^4\text{Li}$: -19.44</td>
</tr>
<tr>
<td>$^3\text{He}$-stripping</td>
<td>$^3\text{H}$: -10.18</td>
<td>$^4\text{H}$: -19.03</td>
<td>$^4\text{He}$: +4.03</td>
</tr>
</tbody>
</table>
Stable Projectiles - Fusion

In the Eighties a significant enhancement of the fusion cross section was observed at energies below the Coulomb barrier.

154\text{Sm}
148\text{Sm}
144\text{Sm}
64\text{Ni}^+ 64\text{Ni}
58\text{Ni}^+ 64\text{Ni}
58\text{Ni}+58\text{Ni}

Static Effect
(Target Deformation)

Dynamic Effect
(Positive Q-value Transfer Channels)

Static and dynamic effects enhance the fusion probability.

What will happen with weakly-bound/halo/neutron-skin RIBs?
Breakup related effects turned out to increase the total reaction cross section rather than the fusion probability.

\textbf{4,6}^4\text{He} + ^{209}\text{Bi}: E.F. Aguilera et al., Phys. Rev. Lett. 84 (2000) 5058


The quest has now moved towards understanding what reaction mechanisms are mainly responsible for the total reaction cross section enhancement.
Stable Projectiles - Scattering

Elastic scattering differential cross sections at near-barrier energies usually develop a peak due to the Nuclear-Coulomb interference.

\[ ^{16}\text{O} + ^{208}\text{Pb}: \text{No Strong Coupling Effects} \]

\[ ^{18}\text{O} + ^{184}\text{W}: \text{Strong Coupling Effects to Target Excitations} \]

Strong Coupling Effects may suppress the “Fresnel” peak.


What has been observed so far with weakly-bound RIBs?
Sorting the Data: Time Signal

- $^7\text{Be}$
- $^3\text{He}$
- $^8\text{B}$
$^7$Be ($S_\alpha = 1.586$ MeV)

$^7$Be: weakly-bound
$^3$He-$^4$He cluster structure
$^8$B core

$^7$Li Primary Beam
Energy: 34.2 MeV
Intensity: 100 pnA

$^1$H$_2$ Gas Target
Pressure: 1 bar
Temperature: 90 K

$^7$Be Secondary Beam
$E_{\text{lab}}$: (22.0 ± 0.4) MeV
Intensity: 2.5*10$^5$ pps
Purity: > 99 %

$^{58}$Ni Target: 1 mg/cm$^2$
$3,4^\text{He}$ Single Detection

$Q_{\text{value}} = E_{\text{He}} + E_{\text{recoil}} - E_{\text{beam}}$

$3^\text{He}$ reconstructed $Q_{\text{value}}$ spectra compatible (within 0.5 MeV) with the $Q_{\text{opt}}$ for the $4^\text{He}$-stripping process.

($Q_{\text{opt}} \sim -9$ MeV)


$3^\text{He}$-stripping and Fusion-Evaporation foresee very similar $4^\text{He}$ energy distributions.

At backward angles we have an excellent agreement with the predictions of PACE2

What’s the $^3$He/$^4$He origin?

1. **Exclusive Breakup:**
   
   $^7$Be → $^3$He + $^4$He;

   **$^3$He**

   These processes require a **coincidence event** in the reaction exit channel:

   **NO COINCIDENCE DETECTED**

   (only upper limits can be provided)

2. **$^4$He-Stripping:**
   
   $^7$Be + $^{58}$Ni → $^3$He + $^{62}$Zn

   ($Q_{gg} = +1.78$ MeV).

3. **$n$-Stripping:**
   
   → $^6$Be (= $^4$He+2p) + $^{59}$Ni

   ($Q_{gg} = -1.68$ MeV);

4. **$^3$He-Stripping:**
   
   $^7$Be → $^3$He + $^4$He;

   **$^4$He**

   → $^8$Be (= $^2^4$He) + $^{57}$Ni

   ($Q_{gg} = +6.68$ MeV);

5. **$^4$He evaporation after compound nucleus formation (Fusion).**

   **Single detection of $^3$He and $^4$He:**

   **AS EXPERIMENTALLY OBSERVED**
7Be + 58Ni: Summary

ELASTIC SCATTERING
Remarkable agreement with an earlier measurement and with DWBA calculations without free parameters.

FUSION
α-multiplicity in agreement with PACE2 predictions.

DIRECT PROCESSES

$^3$He (34.4 ± 6.3 mb) $^4$He (44.1 ± 9.9 mb)
Exclusive Breakup (10.8 mb) 1n-stripping (9.8 mb)
1n-pickup (12.1 mb) $^3$He-stripping (11.4 mb)

Remark: Higher statistical accuracy and larger geometrical efficiency for the detection of coincidences would be highly desirable.