Exotic clustering investigation in $^{13}$B and $^{14}$C nuclei using RIBs

A.Di Pietro$^1$, P. Figuera$^1$, M.Lattuada$^{1,2}$, D. Torresi$^{1,2}$, J.P. Fernandez-Garcia$^{1,2}$, M.Fisichella$^1$, M. Alcorta$^3$, M.J.G.Borge$^{4,5}$, T. Davinson$^6$, A.M.Laird$^7$, A.C.Shotter$^{3,6}$, N. Soic$^8$, O. Tengblad$^5$, M.Zadro$^7$

1-INFN-Laboratori Nazionali del Sud, Catania, Italy
2-Universita' di Catania Italy
3-TRIUMF-Canada,
4-ISOLDE-CERN,
5-CSIC-Madrid, Spain
6-University of Edinburgh UK
7-University of York UK
8-Rudjer Boskovic Institute, Zagreb, Croatia
Cluster structure is a well established feature of many light N≈Z nuclei

Weak coupling picture:
1. Clusters are formed by tightly bound nucleons (cluster is stiff, i.e. not easy to excite);
2. Weakly coupled inter-cluster motion is considered.

Threshold rule: i.e. these states appear close to the threshold for breaking-up into the cluster constituents.

Clusters in n-rich nuclei

“molecules” made of α bound together by n and/or p.

clusters where at least one component is a soft “exotic” nucleus.


Excited states of $^{13}\text{B}$ studied with AMD

AMD calculations

No known states $^{13}\text{B} E_x > 11 \text{ MeV}$

$K^\pi = 1/2^+ \text{ band}$

$^{13}\text{B}(+)$

Excitation energy (MeV)

$J(J+1)$
Inverse Kinematic Resonant Elastic Scattering Method

Elastic scattering of heavy projectiles $B$ on a light targets $b$ (protons or $\alpha$s) in order to study properties of the compound nucleus $C$ resulting from

$$B+b \rightarrow C^* \rightarrow B+b$$

Excitation function measured at $\theta_{cm} \approx 180^\circ \Rightarrow$ enhanced visibility of resonances with respect to potential and Coulomb scattering.

- thick solid
- gaseous target (H, He)
  - easy to change target thickness (changing gas pressure)
  - more homogeneous target
  - possibility to have very extended targets
Importance of Time measurement

- Background: radioactive decay of the beam, inelastic scattering and reaction events. From α or Hydrogen spectra no possibilities to discriminate different reaction processes.

Time measurement

Calculations of Time vs ΔE for a ΔE thickness=50μm. Elastic, inelastic and some reaction process are considered.
Problems with stopping power calculations.

Excitation function $^9\text{Be}+^4\text{He}$ at $E_{\text{c.m.}}<4.5\text{MeV}$

- Excitation function $^9\text{Be}+\alpha$ with resonance scattering method. M. Zadro et al, NIM B259 (2007).
- Excitation function $\alpha+^9\text{Be}$ measured with thin target method varying beam energy at small steps J. Liu [NIM B 108,(1996) 247] , J.D. Goss [PRC 7,(1973) 247]

$dE/dx$ from SRIM

$dE/dx$ measured

![Graph 1](image1.png)

![Graph 2](image2.png)
Cluster states in $^{13}$B: $^9$Li+$\alpha$ at TRIUMF

**Detectors:**
MCP : ToF measurement and beam-particle counting
3 Si-telescopes:
4 quadrant $\Delta E$ detectors: 50 $\mu$m
E- single pad: 1000 $\mu$m

$^9$Li @ 32 MeV
i=10$^5$÷10$^7$ pps

$^4$He gas
P=650÷680 Torr
Kapton window

1.5 m
TUDA chamber
Uncorrelated $\alpha$ and $\beta$ particles coming from $^9\text{Li}$ radioactive decay. Due to the large size of the detectors $\beta$ particles release large energy in both $\Delta E$ and $E$ detectors. $\alpha$–energy not sufficient to punch-through the $\Delta E$.
$^{13}\text{B}$ excitation function

- T1: $174<\theta<180$
- T2 (quad): $162<\theta<175$
- T3 (c): $140<\theta<165$
- T3 (q): $125<\theta<162$

Graphs showing differential cross section ($d\sigma/d\Omega$) vs. excitation energy ($E_{\text{exc.}}$).
Estimation of angular momentum involved
$\pi = 1/2^+$

$13\text{B}(+)$

Excitation energy (MeV):

- $J^\pi = 9/2^+$
- $J^\pi = 13/2^-$
- $J^\pi = 11/2^-$
- $J^\pi = 13/2^+$
- $J^\pi = 11/2^-$
- $J^\pi = 13/2^-$
- $J^\pi = 9/2^+$
- $J^\pi = 13/2^-$

$\sigma/d\Omega (\text{mb/sr})$ vs $E_x (\text{MeV})$:

- 0 to 0.14
- 0 to 0.02
- 0 to 0.08

$J^\pi = 11/2^-$

$J^\pi = 13/2^-$

R-matrix fit

$K^\pi = 1/2^-$

$K^\pi = 3/2^-$

(a) parity(-)

(b) parity(+)

$J(J+1)$

Excitation energy (MeV) vs $J(J+1)$:

- $K^\pi = 1/2^-$
- $K^\pi = 3/2^-$
No linear chain $\alpha$-structure nor linear chain band was found in $^{12}\text{C}$. They may exist in $^{14}\text{C}$ being stabilised by excess of neutrons. This is predicted to occur in $^{14}\text{C}$ by AMD calculations.

14C excitation function: previous results

Authors claim that inelastic excitation is negligible and that “genuine” elastic events are selected. But excitation function similar to the one of Freer et al.
Production of a $^{10}$Be radioactive beam in batch-mode at LNS

$^{10}$BeO ($^{10}$Be $T_{1/2} = 1.39 \times 10^6$ y) mixed with Ag was prepared at PSI (Zurich) and used in the source cathode of the Tandem accelerator. Several tests were done to choose the best preparation and cathode condition. Collaboration also with CIRCE laboratory.

Cathode preparation tested

<table>
<thead>
<tr>
<th>Cathode</th>
<th>Dimensions (mm x mm)</th>
<th>BeO:Ag</th>
<th>Ag ADDING</th>
<th>Q (mC)</th>
<th>$\langle i \rangle$ (nA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2X2</td>
<td>1:10</td>
<td>1/3 added bef, 2/3 after glowing</td>
<td>1.21</td>
<td>17,20</td>
</tr>
<tr>
<td>B</td>
<td>2X1</td>
<td>1:10</td>
<td>1/3 added bef, 2/3 after glowing</td>
<td>1.36</td>
<td>15.30</td>
</tr>
<tr>
<td>C</td>
<td>2X1</td>
<td>1:10</td>
<td>Ag added before glowing</td>
<td>2.41</td>
<td>27.50</td>
</tr>
<tr>
<td>D</td>
<td>2X2</td>
<td>1:10</td>
<td>1/3 added bef, 2/3 after glowing</td>
<td>2.92</td>
<td>15.90</td>
</tr>
<tr>
<td>E</td>
<td>2X2</td>
<td>1:35</td>
<td>1/3 added bef, 2/3 after glowing</td>
<td>5.59</td>
<td>23.20</td>
</tr>
<tr>
<td>F</td>
<td>2X1</td>
<td>1:35</td>
<td>Ag added before glowing</td>
<td>3.61</td>
<td>43.60</td>
</tr>
<tr>
<td>G</td>
<td>2X2</td>
<td>1:35</td>
<td>Ag added before glowing</td>
<td>5.59</td>
<td>23.20</td>
</tr>
<tr>
<td>H</td>
<td>2X1</td>
<td>1:35</td>
<td>Ag added before glowing</td>
<td>3.61</td>
<td>43.60</td>
</tr>
</tbody>
</table>

Beam current as a function of time in the tandem source

$^{10}$Be$^{4+}$ @ 47 MeV

$i \approx 10$ nAe for a few days on target, after collimation, $i \approx 1$ nAe

$^{10}$B contamination < 0.2%
$^{10}\text{Be}+\alpha$ resonant elastic scattering at LNS TANDEM

$^{10}\text{Be}+^4\text{He}$ resonant elastic scattering on thick target to investigate $\alpha$-chain-states in $^{14}\text{C}$. RIB intensity on target from $10^3$ to $10^5$ times larger than in previous experiments.

For the first time clear separation between elastic and inelastic events.

$^{14}\text{C}$ excitation function

Experimental set-up
$^{10}$Be beam LNS - results of test experiment

M. Freer et al. PRC 90, 054324 (2014)

H. Yamaguchi et al. / Physics Letters B 766 (2017) 11

Existence of molecular $\alpha$-chain configuration to be confirmed.
The hunting continues!
Existence of linear chain configuration and exotic cluster configurations are predicted by AMD calculations in n-rich C and B isotopes respectively.

Resonant scattering of light nuclei powerful tool to investigate cluster structures.

Use of extended targets + ToF allows discrimination of reaction processes.

Important precise knowledge of stopping power. Measured stopping power used in the present analysis.

$^9$Li+$^4$He excitation function shows presence of structures at high excitation energy. Possible $^{13}$B $\alpha$-cluster states? R-Matrix analysis is being performed.

$^{10}$Be radioactive beam developed at LNS with intensity typical of stable beams.

Previous measurement of $^{10}$Be+$^4$He excitation function disagree on the role of inelastic excitation of $^{10}$Be. Inelastic contribution as large as elastic at 0$^0$. Spectroscopic information need to be re-derived.
In n-rich nuclei the condition that the cluster must be a stiff particle (e.g. $\alpha$ particle) is dropped. Antisymmetrized Molecular Dynamics calculations (AMD) predicts the existence of cluster configuration of Li-He type in B isotope.