Study of cluster structures in $^{10}$Be and $^{16}$C neutron-rich nuclei via break-up reactions

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Exotic structures in light nuclei

- Clustering in non self-conjugated nuclei;
- The state of art of $^{10}$Be and $^{16}$C nuclei structure;

Exotic structures in light nuclei

- Exotic beam production and tagging at INFN-LNS: The FRIBs facility;
- The $4\pi$ CHIMERA multi-detector array;
- Helium break-up of self-conjugated nuclei as experimental test;

Experimental results

- $^4$He-$^6$He correlations: the $^{10}$Be structure;
- $^6$He-$^{10}$Be correlations: the $^{16}$C structure;

Conclusions and future perspectives
Exotic structures in light nuclei: an interesting scenario

Complexity of nuclear force → **dominant** phenomena of nucleon-nucleon **correlations** which determine a spatial re-organization of the nucleons in bounded **sub-units** → the **constituent clusters**.
**The $^{10}\text{Be}$ case**

**AMD+VAP calculations → high deformation in GS → [1] → $K^\pi=0^+$ rotational band [2]**

High $\alpha-\alpha$ cluster distance [3] → strong **molecular structure** → $K^\pi=0^+$ **molecular band** built on the 6.1793 MeV [4] state

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The $^{10}$Be case

Rotational band in dimeric structure $\rightarrow$ very interesting case

<table>
<thead>
<tr>
<th>J</th>
<th>J(J+1)</th>
<th>$E_x$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>6.18</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>7.54</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>10.15 [4]</td>
</tr>
</tbody>
</table>


possible cluster configurations $\rightarrow$ AMD calculations Ref. [1]

molecular states predicted $\rightarrow$ possible rotational bands $\rightarrow$ $^6$He+$^{10}$Be powerful disintegration channel to explore this region $\rightarrow$ confirmations needed.

no experimental evidence on $^{16}$C molecular nature still provided [2,3] $\rightarrow$ very low statistic measurements

Expected nuclear reactions

- $^{16}$C disintegration
- $^4$He+$^{12}$Be
- $^8$He+$^8$Be
- $^2n+^{14}$C
- $^{n+15}$C
Beam production $\rightarrow$ IFF (In Flight Fragmentation) technique $\rightarrow$ FRIBs (Flight Radioactive Ion Beams) facility @ INFN-LNS:

- $^{18}\text{O}^{7+}$ at 56 MeV/u (superconducting cyclotron K800);
- $^{9}\text{Be}$ (1,5 mm thickness) production target;
- LNS-FRS (Fragment-Recoil Separator) $B\rho \approx 2.8 Tm$;

**Tagging system** [1] (particle by particle identification):

- MCP large area detector;

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Identification ($\Delta E$-ToF) plot FRIBs cocktail beam → good performances.
High exotic beams intensity:
- $^{16}$C (49.5 MeV/u) $10^5$ pps;
- $^{13}$B (49.5 MeV/u) $5 \cdot 10^4$ pps;
- $^{10}$Be (56.0 MeV/u) $4 \cdot 10^4$ pps;

CHIMERA (Charged Heavy Ion Mass Energy Resolving Array) [1,2]


- 1192 ΔE-E telescopes (∼300 µm Si + CsI(Tl) scintillator);
- 9 forward rings (1° ≤ θ ≤ 30°);
- 17 rings sphere (30° < θ ≤ 176°);

First 3 forward rings → 144 telescopes (1° ≤ θ ≤ 7°) complete azimuthal coverage → ΔE-E identification technique.

Good $^4$He – $^6$He separation → beryllium line mainly dominated by $^{10}$Be
As a starting check → **correlations** between helium break-up fragments from self-conjugated nuclei

- **2α correlations** → the $^8\text{Be}$ spectroscopy:
  - MonteCarlo simulation → good agreement with the experimental data for the 91.8 keV peak ($^8\text{Be}_{\text{gs}}$) → good consistency of the procedure.
  - Possible contaminations of $^9\text{Be}$ neutron decay → **ghost peaks**?

- **3α correlations** → the $^{12}\text{C}$ spectroscopy:
  - 3 body correlations → good agreement with the literature → $^{12}\text{C}$ Hoyle state.

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**Note:** The diagrams illustrate the experimental data and MonteCarlo simulation results for $^8\text{Be}$ and $^{12}\text{C}$, respectively, highlighting the peaks and energy levels.
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- **3α correlations** → the **12C** spectroscopy:

**3 body correlations** → good agreement with the literature → **12C Hoyle state**.

Interesting study of **sequential de-excitation** for the Hoyle state → **12C**

**C**: **12** → **α + Be gs** (green spectrum)
Possible new state in $^{10}\text{Be}$

**6He+$^4\text{He}$ channel: the $^{10}\text{Be}$ structure**

Found **bumps** corresponding to **excited states** known in literature (vertical arrows) $\rightarrow$ interesting peak at about **13.5 MeV**.

**Smooth efficiency** for both the possible target nuclei ($^{12}\text{C}$ and $^1\text{H}$ from the polyethylene CH$_2$ target used) $\rightarrow$ **MonteCarlo simulation** with exponential angular distribution in the anelastic scattering center of mass frame:

$$\frac{d\sigma}{d\Omega_{cm}} \propto e^{\frac{\theta_{cm}}{\alpha}}$$

$\alpha$ fall-of factor 12°-16°

Flat **spurious background** contribution $\rightarrow$ **event mixing** procedure.

Possible **evidence** of a new excited state at about **13.5 MeV** not reported in literature.
Angular correlation analysis on 13.5 MeV state → high spin contributions → possible 6+ assignment → agreement with the recent R-matrix calculation in resonant elastic scattering 6He+4He experiment [1]

Angular correlation analysis on 13.5 MeV state $\rightarrow$ high spin contributions $\rightarrow$ possible 6$^+$ assignment $\rightarrow$ agreement with the recent R-matrix calculation in resonant elastic scattering $^6\text{He}+^4\text{He}$ experiment [1]

Possible 6$^+$ further member of the K=0$^+$ molecular band $\rightarrow$ low statistics $\rightarrow$ new experiments are needed.
As a **final test** → complete MonteCarlo simulation with the **13.5 MeV** state (shadowed histogram) → nice **agreement** with the experimental data (black points)

**Table:**

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<th>$E_x$ (MeV)</th>
<th>$J^\pi$</th>
<th>$\Gamma_{tot}$ (MeV)</th>
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<tr>
<td>9.51</td>
<td>$2^+ [1,2,3]$</td>
<td>0.14 [4,5]</td>
</tr>
<tr>
<td>10.6 [5]</td>
<td></td>
<td>0.20 [8,4]</td>
</tr>
<tr>
<td>11.8</td>
<td>(4$^+$) [5,6]</td>
<td>0.12 [5,6]</td>
</tr>
<tr>
<td>$\approx 13.5$</td>
<td>$6^+ [9]$, this work</td>
<td>$\approx 0.15$ this work</td>
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[5] Brookhaven National Laboratory, National Nuclear Data Center
$^{16}\text{C}$ 2 body disintegration $\rightarrow$ $^{6}\text{He} + ^{10}\text{Be}$ break-up channel $\rightarrow$ low statistics data.

Enhancement at about 20.6 MeV $\rightarrow$ possible agreement with the previous low statistics measurements $^{[1]} [^{[2]}$$^{[3]}$$^{[4]}$ more statistics required to confirm the suggestion.

Future perspectives: the CLIR experiment @ LNS

CLIR (Clustering in Light Ion Reactions) February–June 2015 → new investigation of cluster structures in nuclear reactions induced by FRIBs beams at INFN-LNS

**FARCOS** array [2] coupled to **CHIMERA** device → improved energy and angular resolution → **DSSSD+CsI** detectors.


FARCOS array [1] more info in E.V. Pagano’s talk
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$\Delta E-E$ identification plot with **FARCOS**

**DSSSD** (1500 $\mu$m) vs **CsI** fast

$^{16}\text{O}+\text{C} @ 55$ MeV/u
We have performed a spectroscopic investigation of $^{10}$Be and $^{16}$C via cluster break-up reactions at intermediate energies at INFN-LNS.

The cocktail beam was provided by the FRIBs facility → particle by particle identification → tagging system coupled to CHIMERA $4\pi$ multi-detector.

$^6$He-$^4$He correlations → structure of $^{10}$Be → new possible $6^+$ state at about 13.5 MeV excitation energy → possible agreement with a recent R-matrix calculation [1] (resonant elastic scattering data) → energetic compatibility with a $6^+$ further member of the $^{10}$Be molecular band.

$^6$He-$^{10}$Be correlations → structure of $^{16}$C → very low statistics data → agreement with previous experiment enhancement at about 21 MeV excitation energy.

Future Perspectives: