Studio della struttura a cluster dei nuclei neutron-rich $^{10}$Be e $^{16}$C attraverso reazioni di break-up

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

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

The $^{16}\text{C}$ case
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) $B\rho \approx 2.8\text{Tm}$;

**Tagging system [1]** (particle by particle identification):
- MCP large area detector;

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**Identification ($\Delta E$-ToF) plot** FRIBs cocktail beam $\rightarrow$ good performances.

High exotic beams intensity:
- $^{16}\text{C}$ (49.5 MeV/u) $10^5$ pps;
- $^{13}\text{B}$ (49.5 MeV/u) $5 \cdot 10^4$ pps;
- $^{10}\text{Be}$ (56.0 MeV/u) $4 \cdot 10^4$ pps;

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


- 1192 $\Delta$E-E telescopes ($\sim 300 \mu m$ Si + CsI(Tl) scintillator);
- 9 forward rings ($1^\circ \leq \theta \leq 30^\circ$);
- 17 rings sphere ($30^\circ < \theta \leq 176^\circ$);

First 3 forward rings $\rightarrow$ 144 telescopes ($1^\circ \leq \theta \leq 7^\circ$) complete azimuthal coverage $\rightarrow$ $\Delta$E-E identification technique.

Good $^4$He – $^6$He separation $\rightarrow$ beryllium line mainly dominated by $^{10}$Be

$\Delta$E-E identification $\rightarrow$ good isotopic separation
Found **bumps** corresponding to **excited states** known in literature (vertical arrows) → interesting peak at about **13.5 MeV**.

**Smooth efficiency** for both the possible target nuclei ($^{12}$C and $^1$H from the polyethylene CH$_2$ target used) → **MonteCarlo simulation**

**Possible evidence** of a new excited state at about **13.5 MeV** not reported in literature.
Angular correlation analysis on 13.5 MeV state leads to high spin contributions, suggesting a possible $6^+$ assignment. This assignment agrees with the recent R-matrix calculation in resonant elastic scattering from the $^6\text{He}+^4\text{He}$ experiment [1].


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$\chi^2$ values for different angular momenta:

- $J = 2$: $\chi^2 = 1.15$
- $J = 4$: $\chi^2 = 1.17$
- $J = 6$: $\chi^2 = 0.62$
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 $^6\text{He}+^4\text{He}$ experiment [1]

Possible 6+ further member of the $K=0^+$ molecular band → low statistics → 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>$J^\pi$</th>
<th>$\Gamma_{\text{tot}}$ (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></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
$^6\text{He}$-$^{10}\text{Be}$ coincidences: the $^{16}\text{C}$ structure

$^{16}\text{C}$ 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] $\rightarrow$ more statistics required to confirm the suggestion.

Experimental data
- Efficiency $^1\text{H}$ target
- Efficiency $^{12}\text{C}$ target

Ref. [1]

Ref. [2]

Ref. [3]

Low statistics results $\rightarrow$ 20.6 MeV bump
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.

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ΔE-E identification plot with FARCOS DSSSD (1500 μm) vs CsI fast

\(^{16}\text{O}+\text{C} @ 55 \text{MeV/u}\)
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 4π 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:**