High-resolution measurements of absolute partial widths

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Overview

- Cluster structure in nuclear physics
- Background and motivation
- Overview of the Munich set-up
- How the measurements are made
- Results and structure: $^{16}\text{O}$ and $^{13}\text{C}$
- Summary
Threshold effect

Clustering appears close to the cluster-decay thresholds. The nucleus needs sufficient excitation energy to dissolve, e.g. into α-particles.

For heavy nuclei, the multi-α-cluster thresholds lie at very high energies.
Why? Clustering is a good test of models. 
- Significant impact on nucleosynthesis processes e.g. Hoyle state & analogues & multi-alpha states.

What? Evidence for cluster structure comes largely from decay widths & branching ratios. 
- Large partial $\alpha$-decay widths $\rightarrow$ $\alpha$-cluster structure. Preferential decay to $\alpha$-structures in daughter nuclei.

How? A method is needed for accurately measuring absolute branching ratios and decay widths with high resolution. 
- Measurement of cluster-state production & all but one of the decay/break-up particles required.
MLL Munich #1

14 MV tandem
Ejectiles of the same energy are focused to the same point on the focal plane, independent of angle.
The Q3D at Munich #1

Active length 89 cm

Horizontal wires & plastic scintillator for energy loss

255 vertical strips 3.5 mm apart for position

Q3D trigger requires plastic and horizontal wire coincidence

Each event is fitted with a Gaussian to obtain horizontal position

500 mbar isobutane


H.-F. Wirth et al., to be published.

Munich acquisition, Birmingham spy-software and discriminators
Ejectile angular information

Angle of incoming ions can be gauged by examining width of the (Gaussian) charge distribution on the strip detector.

Contaminant from reactions on oxygen in $^9$Be target.

Excitation energy in $^{13}$C

FWHM from Gaussian fitting of charge on strips
State-by-state tagging

By detecting the ejectile with sufficient resolution at the focal plane of the Q3D spectrometer, the state populated in the recoil can be established. Example show is for $^{16}$O*.

The Munich Q3D spectrometer has a world-wide unique intrinsic resolution of $\delta E/E \sim 2 \times 10^{-4}$.

$^{12}$C($^6$Li, d)$^{16}$O* at $E(^6$Li) = 42 MeV

Deuteron ejectile (trigger) 21.5°

Initial 2-body reaction

$^{16}$O recoil/$^{12}$C + $\alpha$ break-up particles

$\theta_x = 8 \rightarrow 85^\circ$, $\theta_y = -36 \rightarrow 35^\circ$
State-by-state tagging: $^{16}\text{O}$

- Results retain high-resolution of spectrometer.
- Widths of states & break-up paths can be studied together.
- Spectrometer uniquely identifies ejectile $\rightarrow$ & hence reaction.
Results – binary setting – $^{16}\text{O}$

**Identification**

Binary setting (bound states) enables verification of the detector positions and Monte-Carlo simulations.

Excitation energy = 6.230 MeV.
Results: $^{16}$O, $E_x = 14.600$ MeV #1

Catania plots: one of the two break-up particles is detected and the other is kinematically reconstructed (shown above). Labels correspond to detected particles first.
Results: $^{16}\text{O}$, $E_x = 14.600$ MeV #2

- Protons$^{15}\text{N}(\text{g.s.})$ efficiency = 41%.
- Alpha$^{12}\text{C}(\text{g.s.})$ efficiency = 40%.
- Alpha$^{12}\text{C}(2^+)$ efficiency = 37%.

Catania plot corrected for $^{15}\text{N}$. 

(Q3D-gated data)
Information from Catania plots

- Three-body Q-value
- Particle mass (identification)
- Break-up distribution (e.g. isotropic)
- Target thickness (energy loss)
- All channels at once (particle/γ)
- Efficiency
- Width of loci → angular resolution
Results comparison for $^{16}\text{O}^*$

Previous results$^1$

$^{12}\text{C}(^{13}\text{C},^{9}\text{Be})^{16}\text{O}$

(HMI Q3D)

$^{16}\text{O}^*$\,$\rightarrow$\,$^{4}\text{He}$
\,$+^{12}\text{C}(2^+)$

$^{16}\text{O}^*$\,$\rightarrow$\,$^{4}\text{He}$
\,$+^{12}\text{C}(2^+)$

- Individual states and processes are selectable.
- **Absolute** decay branches measured.
- Q3D resolution retained.


Adding silicon detector gate to select break-up
Results for $^{16}$O* by decay branch #1

- All states observed in the current work.

- As above, but additionally gated by break-up via the $^{12}$C ground-state.

- As top, but additionally gated by break-up via the $^{12}$C 1$^{\text{st}}$ excited state.
Results for \(^{16}\text{O}^*\) by decay branch \#2

- Total Q3D statistics; all.
- + gate to \(^{12}\text{C}(\text{g.s.})\); \(\alpha_0\).
- + gate to \(^{12}\text{C}(2^+)\) at 4.439 MeV; \(\alpha_1\).
- + gate to \(^{15}\text{N}(\text{g.s.})\); \(p_0\).

14.911 MeV level has 22(2)% proton0 branch.
## Results \(^{16}\text{O} – \text{branching ratios}\)

<table>
<thead>
<tr>
<th>E(level) (keV)</th>
<th>(I^\pi)</th>
<th>FWHM(^2) (keV)</th>
<th>(\Gamma_\alpha/\Gamma_{\text{tot}}) (^{12}\text{C})(g.s)</th>
<th>(\Gamma_\alpha/\Gamma_{\text{tot}}) (^{12}\text{C})(2(^+))</th>
<th>Red. wid. (\theta_\alpha^2)</th>
<th>(\Gamma_\alpha/\Gamma_{\text{tot}}) (^{12}\text{C})(gs)</th>
<th>(\Gamma_\alpha/\Gamma_{\text{tot}}) (^{12}\text{C})(2(^+))</th>
</tr>
</thead>
<tbody>
<tr>
<td>13983(2)</td>
<td>2(^-)</td>
<td>36(13)</td>
<td>&lt;0.09</td>
<td>0.87(11)</td>
<td>–</td>
<td>0</td>
<td>Large</td>
</tr>
<tr>
<td>14297(3)</td>
<td>4(^{(-)})</td>
<td>27(19)</td>
<td>&lt;0.05</td>
<td>1.04(15)</td>
<td>–</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14396(2)</td>
<td>5(^+)</td>
<td>22(18)</td>
<td>&lt;0.05</td>
<td>0.92(10)</td>
<td>–</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14566(11)</td>
<td>5(^-)</td>
<td>446(27)</td>
<td>1.14(8)</td>
<td>0.33(3)</td>
<td>0.94</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14808(3)</td>
<td>6(^+)</td>
<td>71(9)</td>
<td>0.46(6)</td>
<td>0.59(4)</td>
<td>0.05(1)</td>
<td>0.45(5)</td>
<td>0.54(5)</td>
</tr>
<tr>
<td>14911(20)</td>
<td>2(^+)</td>
<td>84(37)</td>
<td></td>
<td>0.2</td>
<td></td>
<td>0.027(2)</td>
<td></td>
</tr>
<tr>
<td>15790(5)</td>
<td>3(^+)</td>
<td>122(15)</td>
<td>&lt;0.3</td>
<td>0.88(18)</td>
<td>&lt;10(^{-3})</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Unnatural parity states can not break up via \(^4\text{He}(0^+) + ^{12}\text{C}(0^+)\) as the angular momentum coupling of the initial \(^{16}\text{O}\) and final \(^{12}\text{C}\) states must satisfy: \(I(16\text{O}^*) – l(\alpha) = I(\alpha) + I (12\text{C}^*)\) and \(I(\alpha) = 0\).

Cluster bands in $^{16}$O

<table>
<thead>
<tr>
<th>$K^\pi$</th>
<th>$E_{\text{level}}$ (keV)</th>
<th>$I^\pi$</th>
<th>$\Gamma_{\text{tot}}$</th>
<th>$\Gamma_{\alpha^0}/\Gamma_{\text{tot}}$</th>
<th>$\theta_{\alpha^0}^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0$^+$</td>
<td>6049(1)</td>
<td>0$^+$</td>
<td>Bound</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6917(0.6)</td>
<td>2$^+$</td>
<td>Bound</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10356(3)</td>
<td>4$^+$</td>
<td>26(3)</td>
<td>0.86(9)</td>
<td>0.23(3)</td>
</tr>
<tr>
<td></td>
<td>16275(7)</td>
<td>6$^+$</td>
<td>420(20)</td>
<td>0.982(48)</td>
<td>0.29(2)</td>
</tr>
<tr>
<td></td>
<td>22500(500)</td>
<td>(8$^+$)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0$^-$</td>
<td>9585(11)</td>
<td>1$^-$</td>
<td>420(20)</td>
<td>~1</td>
<td>0.57(6)</td>
</tr>
<tr>
<td></td>
<td>11600(20)</td>
<td>3$^-$</td>
<td>800(100)</td>
<td>1.00</td>
<td>0.57(8)</td>
</tr>
<tr>
<td></td>
<td>14660(20)</td>
<td>5$^-$</td>
<td>670(15)</td>
<td>1.002(42)$^1$</td>
<td>0.41(2)</td>
</tr>
<tr>
<td></td>
<td>20857(14)</td>
<td>7$^-$</td>
<td>900(60)</td>
<td>1.16(23)</td>
<td>0.33(6)</td>
</tr>
</tbody>
</table>

For states in the cluster band the larger radius reverses the usual situation and the angular momentum is carried exclusively by the $\alpha$ particle as orbital motion. Literature values are shown.

$^1$Combined with value from current work.
There are long-standing predictions of molecular bands in $^{13}$C$^1$.

**Experiment:**

α-transfer reaction: $^9$Be($^6$Li,$d$)$^{13}$C* at 42 MeV, Q3D at 20°.

Catania plots for Q3D-gated data

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13/12/2012 Ab initio workshop, Birmingham
Results for \(^{13}\)C* by decay branch

- States observed in the current work.

- As above, but additionally gated by break-up via the \(^{12}\)C 1\(^{\text{st}}\) excited state.

- As top, but additionally gated by break-up via the \(^{12}\)C/\(^{9}\)Be ground state.
Results: $^{13}$C – branching ratios

<table>
<thead>
<tr>
<th>E(level) (MeV)</th>
<th>$I^\pi$</th>
<th>$\Gamma_\text{tot}$ (keV)</th>
<th>$\Gamma_{\alpha 0}/\Gamma_\text{tot}$</th>
<th>$\Gamma_{n0}/\Gamma_\text{tot}$</th>
<th>$\Gamma_{n1}/\Gamma_\text{tot}$</th>
<th>Reduced width $\theta_{\alpha 0}$</th>
<th>Ratio to Wigner</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.753</td>
<td>7/2$^-$</td>
<td>61</td>
<td>&lt;0.05</td>
<td>0.91(11)</td>
<td>$\leq$0.13</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>10.818</td>
<td>(5/2$^-$)</td>
<td>35</td>
<td>&lt;0.02</td>
<td>0.51(4)</td>
<td>0.51(4)</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>10.996</td>
<td>1/2$^+$</td>
<td>85</td>
<td>&lt;0.08</td>
<td>0.68(3)</td>
<td>0.42(2)</td>
<td>&lt;500000%</td>
<td>&lt;421%</td>
</tr>
<tr>
<td>11.848</td>
<td>7/2$^+$</td>
<td>238</td>
<td>&lt;0.10</td>
<td>0.49(8)</td>
<td>0.71(11)</td>
<td>&lt;27%</td>
<td>–</td>
</tr>
<tr>
<td>12.13</td>
<td>5/2$^-$</td>
<td>219</td>
<td>&lt;0.17</td>
<td>0.49(8)</td>
<td>0.53(8)</td>
<td>2.2(1)%</td>
<td>–</td>
</tr>
<tr>
<td>(13760)</td>
<td>(5/2, 3/2)$^+$</td>
<td>117</td>
<td>0.54(2)</td>
<td>&lt;0.10</td>
<td>0.45(2)</td>
<td>2.2(1)%</td>
<td>–</td>
</tr>
<tr>
<td>(14.582)</td>
<td>(7/2$^+$, 9/2$^+$)</td>
<td>130</td>
<td>0.94(3)</td>
<td>&lt;0.12</td>
<td>0.13(2)</td>
<td>7.9(4)%</td>
<td>–</td>
</tr>
</tbody>
</table>

Alpha-particle threshold at 10.65 MeV. Red: proposed molecular state. Large spectroscopic factor in $\alpha$-transfer ($S_{\exp} = 24.9$)$^2$.

### Proposed molecular bands

<table>
<thead>
<tr>
<th>$K^{\pi^2}$</th>
<th>$E$(level)$^1$ (MeV)</th>
<th>$I^{\pi^1}$</th>
<th>$I^{\pi^2}$</th>
<th>$\Gamma_{tot}^1$ (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/2$^-$</td>
<td>9.897</td>
<td>3/2$^-$</td>
<td>3/2$^-$</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>10.818</td>
<td>(5/2$^-$)</td>
<td>5/2$^-$</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>12.438</td>
<td>(7/2$^-$)</td>
<td>7/2$^-$</td>
<td>140</td>
</tr>
<tr>
<td></td>
<td>14.130</td>
<td>3/2$^-$</td>
<td>9/2$^-$</td>
<td>~150</td>
</tr>
<tr>
<td></td>
<td>16.080</td>
<td>(7/2$^+$)</td>
<td>11/2$^-$</td>
<td>150</td>
</tr>
<tr>
<td>3/2$^+$</td>
<td>11.080</td>
<td>1/2$^+$</td>
<td>3/2$^+$</td>
<td>&lt;4</td>
</tr>
<tr>
<td></td>
<td>11.950</td>
<td>(5/2$^+$)</td>
<td>5/2$^+$</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>13.410</td>
<td>(9/2$^-$)</td>
<td>7/2$^+$</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>15.270</td>
<td>9/2$^+$</td>
<td>9/2$^+$</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>16.950</td>
<td>–</td>
<td>11/2$^+$</td>
<td>330</td>
</tr>
</tbody>
</table>

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Gamma-decay branches can be constrained via spatial gates as the recoil must have come from a binary reaction without break-up and has a well-defined angle. Other constraints on the Catania plots, as well as Q-value gates can be used.

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Summary

➔ Absolute measurement of decay branches in $^{16}$O and $^{13}$C for all possible decay particles.

➔ High-resolution means excitation energy region with a high density of states can be studied e.g. around the multi-alpha thresholds.

➔ Branching-ratio and width measurements can establish the cluster structure of states via reduced widths etc.
Collaborators/acknowledgements

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**Institut für Angewandte Physik & Messtechnik, Munich**
A. Bergmaier.

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1 Photo courtesy of M. Barr.
The University of Birmingham

The tallest free-standing clock tower in the world.
Test of $\gamma$-ray coincidences: $^{186}\text{Re}$ #1

- Neutron transfer reaction: $^{187}\text{Re}(p,d)^{186}\text{Re}$ at $E_{\text{beam}} = 21$ MeV.
- Target: 70$\mu$g/cm$^2$ of $^{187}$Re backed by 8.2$\mu$g/cm$^2$ carbon.
- Three Q3D settings from 0 up to $\sim$2.5 MeV.
- Q3D angle fixed at 35° to allow for a 0° beam-dump 80cm downstream.
- One miniball cluster detector (3 Ge crystals) above target chamber.
- 3nA beam-current due to high-neutron flux.
- Q3D master trigger.
- TDC module to reduce random coincidences (problems).
Test of γ-ray coincidences: $^{186}\text{Re \#2}$

- External lead shielding reduces background by factor of 3
- Recessed chamber lid
Test of $\gamma$-ray coincidences: $^{186}$Re #3

- States closer than 4 keV are resolvable.
- Accuracy better than 0.5 keV.
- 8 hrs
- 3.5 hrs
- 2 hrs
- 6 keV
Test of $\gamma$-ray coincidences: $^{186}\text{Re}$ #2

~20 hours of data

Problem: no TDC signals. Solved at end of experiment.