First experimental indication of the Giant Pairing Vibration in the $^{14}$C and $^{15}$C nuclei

Diana Carbone
Searching for the Giant Pairing Vibration with two-neutron transfer reactions between heavy nuclei

- Summary of the GPV features and history

- Experimental results and analysis about $^{12}\text{C}(^{18}\text{O},^{16}\text{O})^{14}\text{C}$ and $^{13}\text{C}(^{18}\text{O},^{16}\text{O})^{15}\text{C}$ reactions @ 84 MeV
- GPV signatures: energy, width, cross section, angular distributions

- Preliminary results about the new experiment: $(^{18}\text{O},^{16}\text{O})$ reactions @ 270 MeV with MAGNEX
What is the Giant Pairing Vibration?

Predicted for the first time in 1977 by Broglia and Bes starting from the *quantum symmetry between particles and holes*.

- Collective excitation of a pair across major shell
- Analogous to **Giant Resonances** (GDR, GQR)

<table>
<thead>
<tr>
<th>Giant Resonances</th>
<th>←</th>
<th>Collective p-h excitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Giant Pairing Vibrations <em>(GPV)</em></td>
<td>←</td>
<td>Collective p-p or h-h excitations</td>
</tr>
</tbody>
</table>

- $L = 0$ two-nucleon transfer reactions should populate it
GPV: an old story

Theoretical studies:
- First theoretical predictions limited to heavy nuclei (Sn and Pb isotopes)
  R.A. Broglia and D. Bes PLB 69 (1977) 129-133
- Use of weakly bound projectiles (as the \(^6\text{He},^4\text{He}\) reactions)
- Recent predictions on light nuclei (oxygen isotopes) by cQRPA calculations
  E.Khan et al. PRC 69 (2004) 014314
  B.Avez et al. PRC 78 (2008) 044318

GPV predicted features
- Excitation Energy \(\sim 20\) MeV with respect to the unperturbed nucleus
- FWHM \(\sim 1\) - \(2\) MeV (typical of giant modes)
- Cross section comparable to that of the g.s. pairing vibration
- \(L = 0\) angular momentum transfer

Experimental attempts:
- Unsuccessful attempts using \((p,t)\) or \((t,p)\) reactions on Sn or Pb
  J. R. Shepard et al. NPA 322(1979)92
  G. M. Crawley et al. PRC 22 (1980) 316
  G. M. Crawley et al. PRC 23 (1981) 589
  M. Matoba et al. PRC 27(1983) 2598
  B. Mouginot et al. PRC 83 (2011) 037302

NEVER EXPERIMENTALLY OBSERVED
Difficulties in observing the GPV

- **GPV** population requires $L = 0$ transfer
- In transfer reactions typically **large amount of angular momentum is transferred**
- **Brink’s matching conditions**
  
  $$\Delta L = (\lambda_2 - \lambda_1) + \frac{1}{2}k_0(R_1 - R_2) + Q_{eff} R/\hbar \nu \approx 0$$

- In heavy nuclei the level density is very high already at low energy, thus making the identification of such modes very hard

(\(^{18}\text{O},^{16}\text{O}\)) reactions on light nuclei: good candidates to populate the GPV

- Low $L$ transfer favoured by Brink’s matching conditions
- Compromise between the level density and the collectivity
- Preformed neutron pair in \(^{18}\text{O}\)
- Very low polarizability of \(^{16}\text{O}\) core
Experimental setup @ INFN-LNS

- $^{18}\text{O}^{7+}$ beam at 84 MeV incident energy delivered by Tandem accelerator
- $^{12}\text{C}$, $^{13}\text{C}$ thin targets
- Ejectiles detected by the MAGNEX large acceptance spectrometer
- Angular settings $\theta_{opt} = 6^\circ, 12^\circ, 18^\circ$,
  \[ 3^\circ < \theta_{lab} < 24.3^\circ \]

MAGNEX spectrometer

<table>
<thead>
<tr>
<th>Optical characteristics</th>
<th>Actual values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum magnetic rigidity (Tm)</td>
<td>1.8</td>
</tr>
<tr>
<td>Solid angle (msr)</td>
<td>50</td>
</tr>
<tr>
<td>Momentum acceptance</td>
<td>-14%, +10%</td>
</tr>
<tr>
<td>Momentum dispersion</td>
<td>3.68</td>
</tr>
<tr>
<td>First order momentum resolution</td>
<td>5400</td>
</tr>
</tbody>
</table>

Good compensation of the aberrations:

Measured resolutions:
- Energy $\Delta E/E \sim 1/1000$
- Angle $\Delta\theta \sim 0.3^\circ$
- Mass $\Delta m/m \sim 1/160$

F. Cappuzzello et al. Nova Publisher Inc (2011) 1
Particle identification

\[ Z \text{ identification} \]

\[ A \text{ identification} \]

\[ B \rho = \frac{p}{q} \]

\[ X_{foc}^2 \propto \frac{m}{q^2} E_{resid} \]

F. Cappuzzello et al., NIMA 621 (2010) 419
Energy spectra

$^{12}\text{C}(^{18}\text{O},^{16}\text{O})^{14}\text{C}$

$^{13}\text{C}(^{18}\text{O},^{16}\text{O})^{15}\text{C}$

Energy resolution $\sim 200$ keV

$9^\circ < \theta_{\text{lab}} < 10^\circ$
Projectile break-up contribution

$^{13}\text{C}(^{18}\text{O},^{16}\text{O})^{15}\text{C} @ 7^\circ < \theta_{\text{lab}} < 17^\circ$

Two independent semi-classical models

1) Removal of two independent neutrons from the projectile
   - Transfer to the continuum of the target+n+n
   - Two-step mechanism
   - No n-n correlations
   - Optical model S-matrix for the n-target interaction

   F. Cappuzzello et al., PLB 711 (2012) 347

2) Towing of a di-neutron system
   - Extreme hypothesis of the removal of a di-neutron from projectile
   - TDSE approach

   J.A. Scarpaci et al., PLB 428 (1998) 241

The $^{15}\text{C}$ bump at $13.7 \pm 0.1$ MeV is not reproduced

Similar results for $^{14}\text{C}$ case

12th international conference on Nucleus-Nucleus Collisions
June 21 – 26, 2015, Catania, Italy
Gaussian model superimposed on a linear background

$^{12}\text{C}(^{18}\text{O},^{16}\text{O})^{14}\text{C} @ 84 \text{ MeV}$

$^{14}\text{C}$  
$E_x = 16.9 \pm 0.1 \text{ MeV} \quad \text{FWHM} = 1.2 \pm 0.3 \text{ MeV}$

$^{13}\text{C}(^{18}\text{O},^{16}\text{O})^{15}\text{C} @ 84 \text{ MeV}$

$^{15}\text{C}$  
$E_x = 13.7 \pm 0.1 \text{ MeV} \quad \text{FWHM} = 1.9 \pm 0.3 \text{ MeV}$
Bump angular distributions

Clear oscillating pattern in the bump angular distributions

Resonant states characterized by a well-defined angular momentum
GPV properties

- Excitation Energy $\sim 20$ MeV with respect to the unperturbed nucleus
- FWHM $\sim 1-2$ MeV (typical of giant modes)
- Cross section comparable to that of the g.s. pairing vibration
- $L = 0$ angular momentum transfer
The excitation energy of the two resonances compared to the target ground state is the same (~ 20 MeV)

\[ E_{x} = E_{x} + M_{r} - M_{t} \]

Consistent with cQRPA predictions

E.Khan et al. PRC 69 (2004) 014314
**Width and cross section**

**Measured widths**

\[ ^{14}\text{C} \quad E_x = 16.9 \pm 0.1 \text{ MeV} \quad \text{FWHM} = 1.2 \pm 0.3 \text{ MeV} \]

\[ ^{15}\text{C} \quad E_x = 13.7 \pm 0.1 \text{ MeV} \quad \text{FWHM} = 1.9 \pm 0.3 \text{ MeV} \]

Consistent with the discussions about the GPV


**Cross section**

The GPV cross section is predicted to be similar to the \( L = 0 \) transition to the g.s.

\[ \sigma(^{14}\text{C}_{\text{g.s.}}) = 0.92 \pm 0.10 \text{ mb} \]

\[ \sigma(^{14}\text{C}_{\text{GPV}}) = 0.66 \pm 0.07 \text{ mb} \]

Consistent with theoretical predictions

\[ \left( \frac{d\sigma(\theta)}{d\Omega} \right)_{\text{tr}} = \left( \frac{d\sigma(\theta)}{d\Omega} \right)_{\text{sc}} P_{\text{tr}}(\theta)F(Q, L) \]

\[ \frac{\text{strength} \left( ^{15}\text{C}_{\text{GPV}} \right)}{\text{strength} \left( ^{14}\text{C}_{\text{g.s.}} \right)} = 3.5 \pm 0.8 \]


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12\textsuperscript{th} international conference on Nucleus-Nucleus Collisions

June 21 – 26, 2015, Catania, Italy
First $L = 0$ indication

Equal population of the $M$-states in heavy-ion reactions near the Coulomb barrier

- $L \neq 0$ transitions: featureless shape
- $L = 0$ transitions: oscillations clearly appear
Multipolarity: calculations for $^{14}$C_{GPV}

Common ingredients: a. Sao-Paulo parameter free double folding potential
   b. Extreme cluster model approximation for the two neutrons

1. Discretized continuum scheme calculations
   - Three body assumption → finer details not accurate
   - Global features: $L = 0$ cross section absolute value is found consistent with the experimental without any scaling factor

2. CRC calculations
   - Same approach used to describe transitions to bound and resonant states in $^{14}$C
     M. Cavallaro et al., PRC 88 (2013) 054601
   - Calculations for various $L$ components
   - Artificial energy value of 12 MeV (below $S_{2n}$)
   - No spectroscopic amplitudes available
   - Renormalization at $\theta_{CM} = 9^\circ$
   - Shape of the $L = 0$ calculation consistent with the experimental angular distribution

Both approaches suggest $L = 0$ transfer for the $^{14}$C resonance at 16.9 MeV
$^{14}\text{C}$ $E_x = 16.9$ MeV FWHM = 1.2 MeV
$^{15}\text{C}$ $E_x = 13.7$ MeV FWHM = 1.9 MeV

- Right energy
- Right width
- Right cross section
- $L = 0$ transfer

GPV population
Particle-hole symmetry confirmation

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Signatures of the Giant Pairing Vibration in the $^{14}\text{C}$ and $^{15}\text{C}$ atomic nuclei

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New experiment @ 270 MeV

$^{12}$C($^{18}$O,$^{16}$O)$^{14}$C @ 270 MeV
$\theta_{\text{lab}} = 4^\circ$

$^{13}$C($^{18}$O,$^{16}$O)$^{15}$C @ 270 MeV
$\theta_{\text{lab}} = 4^\circ$

Energy resolution $\sim$ 600 keV

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New experiment @ 270 MeV

@ 84 MeV incident energy

$^{14}\text{C}_{\text{GPV}} \ E_x = 16.9 \pm 0.1 \text{ MeV}$
$\text{FWHM} = 1.2 \pm 0.3 \text{ MeV}$

$^{15}\text{C}_{\text{GPV}} \ E_x = 13.7 \pm 0.1 \text{ MeV}$
$\text{FWHM} = 1.9 \pm 0.3 \text{ MeV}$
Conclusions and Outlooks

- $^{12}\text{C}(^{18}\text{O},^{16}\text{O})^{14}\text{C}$ and $^{13}\text{C}(^{18}\text{O},^{16}\text{O})^{15}\text{C}$ at 84 MeV
- Known bound and resonant states of the residual nuclei
- Unknown bumps in the continuum
- Angular distributions in wide range $6^\circ < \theta_{CM} < 60^\circ$
  - Evidence of the GPV population
- Particle-hole symmetry confirmation

New experiment:
- $^{12}\text{C}(^{18}\text{O},^{16}\text{O})^{14}\text{C}$ and $^{13}\text{C}(^{18}\text{O},^{16}\text{O})^{15}\text{C}$ at 270 MeV
- Population of the same resonances:
  - same energy
  - same width

Outlooks:
- Bumps angular distributions
- Other targets
Working group

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