Pairing and giant resonances

Giant pairing vibrations
Experimental attempts to detect the GPV with stable and exotic beams

Aim: answer to the question of the GPV existence

Either detect or put an upper limit on the cross section

- Experimental requirements to detect the GPV
- Stable beam attempts (since ~ 70’s + 2009)
- Exotic beam attempt (one in ~ 2005)
- Conclusions
Giant Pairing Vibrations

- Two particles $0^+$ state ~ independent from the remaining part of the nuclei
- Harmonic vibrations
- Pairing vibrations: $L=0$, sensitive to the pairing interaction
- Giant Pairing Vibrations: collective mode in the $2n$ transfer channel analogous to a giant resonance
- Reaction model: 2 particle transfer (sequential, direct, …)
Experimental requirements

- Heavy nuclei: Sn ($E_{GPV}=14 \text{ MeV}$), Pb ($E_{GPV}=12 \text{ MeV}$)
- $L=0$ (pairing) mode

- $(p,t)$ reactions during the 70’s and 80’s, but
  - $E_p > 20 \text{ MeV}$ to excite 14 MeV mode (Coulomb barrier)
  - $E_p < 70 \text{ MeV}$ to excite $L=0$ modes (angular momentum matching)

$E^* = E_{lab} - E_t + Q$

- Stable beam + spectrometer allows high intensity and low background
Experimental attempts

- Herzog et al.: cross section optimal for $E_p = 30$ MeV
- Nakagawa et al.: $E^* > 11$ MeV; (p,d) contamination
- Gerlic et al.: $E_p = 170$ MeV; $L = 13$
- Shepard et al. NPA 322(1979)92: $E^* < 4$ MeV
- Crawley et al. PRC 22(1980)316: $E_p = 90$ MeV; $L = 6$
- Matoba et al. PRC27(1983) 2598: $E^* < 3$ MeV

Very few attempts with $E_p = 20-50$ MeV
Optimal attempt

- Crawley (PRL39(1977)23) : $E_p=42$ MeV ; $E^*<14$ MeV
Si telescopes, $\theta>8$ deg.

8 MeV peak

Spectrometer to measure $t$ with a low background, closer to 0 deg.
The deep hole states puzzle

- Crawley (PRC22(1980)316) : $E_p = 89$ MeV ; Si telescopes, $\theta > 15$ deg.

\[ ^{122}\text{Sn}(p, t)^{120}\text{Sn} \]
\[ \theta_{lab} = 25^\circ \]

8.5 MeV mode detected : not the GPV

- Bortignon et al. (Phys. Script. 34(1986) 678) : deep single particle states
The 0 deg. mode at iThemba

• Importance of (p,t) reaction for GPV at Ep=50 MeV and θ close to 0 deg.: first time
Results

Spectre Sn-target p@50MeV & k600@0

<table>
<thead>
<tr>
<th>h_ex_50_0_rm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
</tr>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>RMS</td>
</tr>
</tbody>
</table>

Counts

Energie (MeV) Manuel Remorn

B. Mougineot PhD
Attempts with exotic beams

• **Advantages**: Large Q value: $E^* = E_{\text{lab}} - E_\alpha + Q$

• **Drawbacks**: intensity: 2 particle transfer ($I=10^{11}$ pps for stable)

• **Attempt**: $^6\text{He}^{(208}\text{Pb, }210\text{Pb)}^4\text{He}$
  (GANIL ~2005), M. Assié, J.A. Scarpaci (towing mode)
  $I=10^6$ pps
  $E_{\text{lab}} = 20$ MeV/A
  No GPV, confirmed by DWBA calculations (N. Keeley)
Experimental setup with exotic beams
Recent theoretical approaches

Structure

Reaction

$^{112}\text{Sn}(p,t)$

$E_{\text{lab}} = 26 \text{ MeV}$

E. Khan, M. Grasso, J. Margueron
PRC80(2009)044328

Summary & outlooks

• **Few attempts in the appropriate energy window**: Ep=20-50 MeV
• Crawley exp: no GPV but Si detectors: observation of a 8 MeV state
• Exp search for 8 MeV state: deep hole state, no more exp. GPV search
• Present stable beam experiment with a spectrometer at iThemba (0 deg.): no GPV
• (t,p)-like reaction: 2 particles states instead of 2 holes states
• Tandem Orsay: ~ 25 MeV protons
• Recent theoretical approaches

• Exotic beam: intensity? $^6$He at EURISOL (I=$10^{10}$ pps)?
• F. Azaiez, S. Franchoo, E. Khan, B. Mougionot, A. Ramus, J.A. Scarpaci, I. Stefan - IPN Orsay

• Z. Buthelezei, S. Fortsch, H. Fujita, R. Neveling, R. Smit, I. Usman – iThemba LABS
1) Superfluidity and incompressibility
Determination of $K_\infty$

- **Microscopic method**: prediction of the GMR centroid
- Constrained-HF: $K_\infty \sim 235$ MeV with $^{208}$Pb but $K_\infty \sim 220$ MeV with $^{90}$Zr (softer)
- Relativistic approaches: $K_\infty \sim 260$ MeV

⇒ Cannot extract separately $K_\infty$, $K_{sym}$ and the density dependence of the functional (G. Colo et al, PRC70(2004)024307)
⇒ Use SEVERAL experimental constraints
The GMR on isotopic chain

- Recent measurement of the GMR in stable Sn isotopic chain  
  (T. Li et al., PRL 99 (2007) 162503)

- $K_\infty \sim 210$ MeV < Pb: Why tin are so soft?

Pairing may explain part of this softness  
(J. Li et al., PRC 78 (2008) 064304)

Interpretation: nuclear incompressibility comes from the second derivative of the energy functionnal ($\sim V_{\text{res}}$)
Shell effects on the GMR

• Pairing ⇒ shell effects on the GMR value
• Doubly magic nucleus: increase of the GMR

\[ K_\infty = 230 \text{ MeV} \]

\[ K_\infty = 216 \text{ MeV} \]

- Doubly magic nucleus: \textbf{specific} increase of the GMR

E. Khan, arXiv:0905.3335
• Tin are so soft because … $^{208}\text{Pb is doubly magic (so stiff)}$ !
• Difficult to reproduce EGMR both on doubly magic and other nuclei

• **Interpretation**: pairing effect on incompressibility in low density nuclear matter: role neutron skin in nuclei?

• **Needs for several measurements (isotopic chain)** because we cannot disentangle between the $K_\infty$, $K_{\text{sym}}$ and density dependence effects on the GMR.

• Importance to follow up the Sn chain, especially until doubly magic $^{132}\text{Sn}$

• GMR measurements requested on **Pb isotopic chain** (unstable nuclei)
GMR in unstable nuclei: a specific method

- unstable nuclei
- reverse kinematics
- low intensity beam
- low energy threshold
- thin target
- large solid angular coverage
- good detection efficiency
- thick target

Active target = target + detector

deuterium gas: 1.6 mg/cm²
(6.3 mg/cm² CD₂)

Time and Charge
Projection Chamber

deuteron kinematics

\[ ^{56}\text{Ni}(d,d') @ 50 \text{ MeV/A} \]

\[ 22 \geq E^* \geq 14 \text{ MeV} \]

\[ \theta_{\text{CM}} = 0, 2, 4, 6 \text{ deg.} \]
Experimental setup

$^{56}\text{Ni} @ 50 \text{ MeV/A}$

5.10$^4$ pps

- GANIL
- SISSI beam

Au foil

Drift chamber

Ionisation chamber

Moving flap

Si wall

CsI wall

Diamond

$^{56}\text{Ni} (5.10^4 \text{ pps})$
50 A.MeV
+ contaminants

Galette $\alpha$
Analysis with gaussian fit

\[ \theta_{\text{cm}} = 4.5 \text{ deg.} \]

Angular distributions

Reaction: DWBA with double folding using HF and RPA \(^{56}\text{Ni}\) gs and transition densities

C. Monrozeau et al., PRL\textbf{100}(2008)042501
The isospin dependence of the incompressibility modulus

\[ E(\rho, \delta) = E(\rho, 0) + a_{sym}(\rho)\delta^2 \]

: density and neutron excess

\[ \delta = \frac{N - Z}{A} \]

Determination of \( K_\infty \)

\[ K(\delta) \approx \frac{1}{2} \left. \frac{\partial^2 E(\rho, \delta)}{\partial \rho^2} \right|_{\rho=\rho_0} \]

\[ K(\delta) = K_\infty + K_{sym}\delta^2 \]

\[ K_{sym} = \frac{1}{4} \left. \frac{\partial^4 E(\rho, \delta)}{\partial \rho^2 \partial \delta^2} \right|_{\rho=\rho_0, \delta=0} \]

Multipole Decomposition Analysis

<table>
<thead>
<tr>
<th>Energy Range</th>
<th>MDA</th>
<th>$m_1/m_0$ [MeV]</th>
<th>rms [MeV]</th>
<th>% EWSR</th>
</tr>
</thead>
<tbody>
<tr>
<td>L=0</td>
<td></td>
<td>19.3</td>
<td>2.3</td>
<td>136 ± 27</td>
</tr>
<tr>
<td>L=2</td>
<td></td>
<td>16.2</td>
<td>1.7</td>
<td>76 ± 13</td>
</tr>
</tbody>
</table>
Experimental probes for isoscalar giant resonances

Inelastic scattering: \((d,d') (\alpha,\alpha')\) @ \(E \geq 25\) A.MeV

\(^{58}\text{Ni} (\alpha,\alpha')\) \(E_\alpha = 240\) MeV

GR in \(^{58}\text{Ni}\): analysis mixing 0\(^+\) and 2\(^+\)

Measurement of the GMR in exotic nuclei

• First measurement performed on unstable nucleus: $^{56}$Ni
• N=Z=28 nucleus: no $K_{sym}$, no pairing
Tool: the Giant Monopole Resonance

- GMR breathing mode $\rightarrow$ density variation around $\rho_0$ (few %)

$E_{\text{ISGMR}}$ along an isotopic chain
(stable nuclei for now)

$K_\tau = -500 \pm 50$ MeV

first (p,p') experiment in inverse kinematics!

G. Kraus et al. Phys Rev. Lett. 73 (1994) 1773

Motivations: exotic modes?

- Few measurements on GR in unstable nuclei → IVGDR
- GQR and GMR soft modes are predicted!
\[ ^{28}\text{Ni}(d,p) \text{ with } E_d=100\text{MeV at } \theta_p=6^\circ,10^\circ,15^\circ,20^\circ,25^\circ,30^\circ,40^\circ,50^\circ,60^\circ,70^\circ,80^\circ,90^\circ,100^\circ,110^\circ,120^\circ \]
from top-to-bottom
18 – Répartition en angle et en énergie des deutons détectés dans le cadre de l’expérience pour les 800 000 événements simulés.
Motivations: $K_\infty$

Microscopic method

Energy Functional $E[\rho]$

$E(\rho,\delta) = E(\rho,0) + a_{\text{sym}}(\rho) \delta^2 + ...$

$K_\infty$ in nuclear matter (analytic)
(N=Z and no Coulomb interaction)

$E_{\text{ISGMR}}$ (self-consistent CHF)

$208$Pb neutron excess nucleus

measure $E_{\text{ISGMR}}$ along an isotopic chain
(unstable nuclei)

probe the effect of the symmetry term


Skyrme & Gogny

$K_\infty = 235 \pm 12$ MeV

Relativistic MF

$K_\infty = 250 - 270$ MeV

N.B.: macroscopic method needs data on the nuclear chart
$^{56}\text{Ni(d',d')}\text{ with the active target MAYA}$

$^{56}\text{Ni unstable (10}^6\text{ pps @ GANIL)}$

A NEW EXPERIMENTAL METHOD
First measurement of isoscalar giant resonances in an unstable nucleus

• Primary: $^{58}$Ni, 75 MeV/A, 0.7 kW (July 05)
• target: C (78 mg/cm$^2$) + SISSI
• Secondary: $^{56}$Ni, 50 MeV/A, $5.10^4$ pps
Macroscopic formula for $K_{\text{sym}}$?

- Macroscopic formula of $K_A$ (Blaizot) is not adapted because it misses shell effect in the GMR: second derivative of volume, surface and asymmetry terms of LD.
- Shell effect $\sim 800$ keV on GMR $\Rightarrow \sim 10$ MeV on $K_A$

![Graph showing $\Delta K_A$ vs. $\delta$](image)

- Use only microscopic method both for $K_\infty$ and $K_{\text{sym}}$
- Or extend the demonstration of Blaizot (not only to leptodermous expansion)
- Cannot extract only $K_{\text{sym}}$ from an analysis on an isotopic chain.

H. Sagawa et al., PRC76(2007)034327
Results

$^{56}$Ni excitation energy spectrum

recoiling d kinematics