Gamma decay of pygmy states from inelastic scattering of ions

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OUTLINE

• The pygmy dipole resonance and its excitation

• Experiments with AGATA using $^{17}$O beams

• Results for $^{90}$Zr, $^{124}$Sn, $^{208}$Pb and $^{140}$Ce

• Pygmy quadrupole resonance in $^{124}$Sn?

• Future perspectives
They are characterized by different types of excitations: question what are the probes and energy to be used to study the dipole response?
Pygmy contributes to the polarizability and thus tests the theory for the asymmetry part of the nuclear equation on states.

This is used to describe neutron stars.
Calculations of cross sections using codes based on statistical reaction models do not describe the data below the neutron separation energy if a standard Lorentzian curve is used.
Some history.....publications on PDR

The Start 1961-1971

Effect of the pigmny resonance on the calculations of the neutron capture cross section

J. S. Brzosko, E. Gierlik, A. Soltan, Jr., and Z. Wilhelmi

Three-Fluid Hydrodynamical Model of Nuclei*

R. Mohan, M. Danos, and L.C. Biedenharn,

An increasing number starting from 2000...

Neutron capture gamma rays
By G. A. Bartholomew
Nuclear Physics Branch, Chalk River Project, Atomic Energy of Canada Limited

Review papers:

D. Savran, T. Aumann, A. Zilges

A. Bracco,
F. Crespi, E. Lanza

Theory/exp = 2/1

* theory/experiment = 2/1
many more articles not using the denotation „PDR"
From A. Zilges
(γ,γ') real photons on stable nuclei
Probing the entire nuclear volume

(p,p') virtual photons at $E_{\text{beam}} > 200$ MeV on stable nuclei
Probing the entire nuclear volume
Work at Osaka RCNP

Coulomb excitation with radioactive beams virtual photons
Exotic nuclei
E1 excitation at high energy (GSI, MSU)

(α,α'γ) or ($^{17}\text{O},^{17}\text{O'}\gamma$) on stable nuclei
Probing the nuclear surface mainly

LNL
Isoscalar or isovector?

In \(^{208}\text{Pb}\n
4.3-5.5\% \text{ IS EWSR strength at 9 MeV}

Theory from Rocha-Maza, Colo’

IS nature of the PDR due to outermost nucleons (neutrons in a neutron-rich nucleus). The \(r_{np}\) is correlated with J and L.

Interesting to study the properties of the neutron skin

The low lying peaks of $1^{-}$ character have the same features:

- $n$ and $p$ transition densities are
  - in phase inside the nucleus
  - at the nuclear surface only the neutron part survives

> Interesting to use a probe interacting mainly at the surface !!!

→ different structure of Transition Densities \( \rightarrow \) Different Form Factors

→ predictions obtained with form factors from microscopic transition densities which incorporate the main features of these states
Recent measurements with $^{17}$O

Using AGATA at LNL
**The AGATA experiments**

\(^{17}\text{O} @ 20 \text{ MeV/u} \) on different targets + \(\gamma\)-rays in coincidence

- Large cross-section for the population of the giant resonance region
- \(^{17}\text{O}\) is loosely bound (\(S_n = 4.1 \text{ MeV}\))
- Clean removal of projectile excitation
Doppler Correction.....AGATA performances

Projectile-like ($^{16}$O, v/c ~20%)
- > 500 keV @ 5 MeV

Target-like recoils (v/c ~0.5%)
- ~25 keV @ 5 MeV

16O
No Dopp Corr
Crystal Centers
Segment Centers
PSA+Tracking

FWHM = 58 keV
Angular Distribution of $\gamma$'s obtained exploiting position sensitivity of AGATA and E-$\Delta$E Si telescopes (pixel type)
208Pb and 124Sn - pygmy region

208Pb

F.C.L. Crespi, et al., PRL113 (2014) 012501

\[ ^{208}\text{Pb}^{(17}\text{O}, ^{17}\text{O}'\gamma) \]
\[ E = 340 \text{ MeV} \]
Ground state decay

124Sn

L. Pellegrin, et al., PLB738 (2014)519

\[ ^{124}\text{Sn}^{(17}\text{O}, ^{17}\text{O}'\gamma) \]
\[ E_{\text{beam}} = 340 \text{ MeV} \]
AGATA energy spectrum

\[ \text{Counts / 10 keV} \]

\[ \text{Energy [keV]} \]

\[ \text{Counts / [55°-115°]} / \text{counts [15°-65°]} \]

\[ \text{Energy [keV]} \]

\[ \text{Counts / [5°-15°] / counts [15°-65°]} \]

\[ \text{Energy [keV]} \]
Excitation cross section as a function of angle of the detected scattered particles......

Start with elastic scattering and the first known excited states ...... to fix the main features of the reaction
Elastic scattering angular distribution

Optical model calculation (*) for the $^A_XX^{17}O$ elastic scattering

$\rightarrow$ ratio to the Rutherford cross section

*http://www.fresco.org.uk/

F.C.L. Crespi, et al., PRL113 (2014) 012501
L. Pellegrini, et al., PLB738 (2014) 519
F.C.L. Crespi et al, PRC 91 (2015) 024323
A. Bracco, F.C.L. Crespi and E.G. Lanza, to be published in EPJA (2015)
DWBA calculations using optical model potential parameters determined from the elastic data

In agreement with measurements at similar beam energy**

- The $B(E2)$ known from other works*

- Calculations assumed pure isoscalar excitation namely the $p$ and $n$ matrix element are related by $M_n / M_p = N/Z$

* $(e,e')$ and $(\gamma,\gamma')$ experiments, see e.g.: http://www.nndc.bnl.gov/ensdf/

**for the case of $^{208}$Pb: D.J. Horen et al. PRC44(1991)128
Not all 2+ states were excited or identified before using hadron probes and not always good agreement of data and calculation is found!!!

\[ \frac{M_n}{M_p} = 0.1 \times \frac{N}{Z}, \text{green line} \]

gray curve Coulomb excitation

this state has strong four-quasiparticle component cannot be populated by a one-step process assumed by DWBA approach!

It is excited only by Coulomb!!
**Excitation of the 3⁻ states in $^{90}$Zr, $^{208}$Pb**

**DWBA calculations using optical model from the elastic data**

In agreement with measurements at similar beam energy**

- The B(E3) known from other works*

- Calculations assumed pure isoscalar excitation namely the p and n matrix element are related by
  \[ M_n / M_p = N/Z \]

* (e,e') and ($\gamma$,\$\gamma$') experiments, see e.g.: http://www.nndc.bnl.gov/ensdf/

**for the case of $^{208}$Pb: D.J. Horen et al. PRC44(1991)128**
The splitting of the PDR region becomes even more evident if we integrate the strength in the discrete peaks measured in each experiment into two regions, 5–7 and 7–9 MeV.


L. Pellegrini, et al., PLB738 (2014)519
The calculation accounts only for a fraction of the measured yield. Why?

Calculations obtained using a standard form factor are found to be very similar to the Coulomb excitation alone.

\[ B(E1) \uparrow \text{values known from } (\gamma,\gamma)^* \]

** photon scattering experiments:
N. Ryezayeva et al. PRL 89(2002)272502,
T. Shizuma et al. PRC 78(2008)061303
Use a microscopic form factor

Transition density

Form factor

Scattering of $^{17}$O at these energies is probing mainly the nuclear surface!!

***E. G. Lanza et al., PRC 89 (2014) 041601
Some results for selected $1^-$ with high statistics in $^{90}\text{Zr}$, $^{124}\text{Sn}$ and $^{208}\text{Pb}$

Calculated transition densities:
E1 gamma-decay of an isoscalar state is possible because of the presence of isospin impurities in the state.

Determination of the isospin-mixing matrix element assuming a two-state mixing with initially unperturbed pure isovector and isoscalar states.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Mat. El. (keV)</th>
<th>R</th>
<th>Reaction</th>
<th>Energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}$Ca*</td>
<td>85(3)</td>
<td>3.67</td>
<td>$(\alpha,\alpha'\gamma)$</td>
<td>7.3, 7.6</td>
</tr>
<tr>
<td>$^{90}$Zr**</td>
<td>41.2</td>
<td>0.46</td>
<td>$(^{17}O,^{17}O'\gamma)$</td>
<td>6.30, 6.42</td>
</tr>
<tr>
<td>$^{90}$Zr**</td>
<td>73.0</td>
<td>2.76</td>
<td>$(^{17}O,^{17}O'\gamma)$</td>
<td>6.57, 6.76</td>
</tr>
<tr>
<td>$^{208}$Pb**</td>
<td>11.6</td>
<td>0.62</td>
<td>$(^{17}O,^{17}O'\gamma)$</td>
<td>7.06, 7.08</td>
</tr>
</tbody>
</table>

*V. Derya et al., PLB 730(2014)288
**F.C.L. Crespi and E.G. Lanza, to be published in EPJA(2015)
values of the isoscalar strength from the measured cross section

Consistent with what found for the IS GDR whose strength is at around 20-22 MeV

4.0 +/- 0.6 % ISEWSR
4.7 +/- 0.5 % ISEWSR
9.0 +/- 1.5 % ISEWSR

F.C.L. Crespi, et al., PRL113 (2014) 012501
L. Pellegrini, et al., PLB738 (2014)519

See also PLB278, 423 (1992)
**Experiment**

3.24 % EWSR IS

**Theory (Paar):**
4.1 % EWSR IS

Comparison of results obtained with different probes

- $^{17}\text{O}$
- alpha
- gamma

See poster of Mateusz Krzysiek
Other types of excitation of the neutron skin?

Quadrupole type?

Predictions from N. Tonseva and H. Lenske PLB695(2011)174

Transition densities
For quadrupole states in $^{120}$Sn

M1 $E_1(2^+_1 \times 3^+_1)$, $E_2(PQR)$, $E_1(PDR)$
Many Gamma –rays of E2 character!!

$^{17}$O inelastic scattering

E2 character well established by the angular distribution
Several states in $^{124}$Sn for which the multipolarity was not assigned !!!
Measured angular distribution of the Cross section for 2+ states

Comparison with DWBA Predictions

Standard 2+ form factor used for isoscalar 2+ in the FRESCO code
Pygmy quadrupole states in $^{124}$Sn

Data from gamma beam scattering

Data from $^{17}$O inelastic scattering

As compared with the data in literature for (gamma, gamma') more states are seen in ($^{17}$O,$^{17}$O')

Theory predicts even a higher fragmentation of the 2$^+$ strength

QPM model Predictions

N. Tonseva and H. Lenske

Try to get information on the transition density in the future!!

L. Pellegrini et al. PRC92 (2015)014330
Future perspectives

- Systematics on isotopic chains (mass, N/Z, exoticy to be understood)
- Decay pattern, feeding
- More on comparison of electromagnetic and hadronic excitation (CAGRA at OSAKA!)
- Strength of the PDR and asymmetry in the number of neutron and proton
- More experimental information on the transition density
- The transition region in excitation energy from pygmy to GDR; for this data also above the particle threshold are needed....

**ELI_NP is suitable for the expected small cross sections**

- Work on the PQR has just started...

Inverse kinematics using $^{13}$C targets at 15 MeV/u with measurement of gamma decay at ISOL facilities... to search for pygmy states of isoscaler character in exotic nuclei

All this will provide a very stringent test to theory....
Conclusions

• Reaction with ions followed by gamma decay such as \(^{17}\text{O},^{17}\text{O}'\gamma\) at around 20 MeV/u are a good tool for Nuclear structure for states of isoscalar character

• On the pygmy quadrupole states also from as \(^{17}\text{O},^{17}\text{O}'\gamma\) and more work has to be made!
Collaboration

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