E1 excitations in atomic nuclei: From Giants, Pygmies and Octupoles

Andreas Zilges
Institut für Kernphysik
Universität zu Köln
MAGNETIC and ELECTRIC dipole excitations

Isovector Magnetic Scissors Mode
(A. Richter, 1984)

Isovector Electric Giant Dipole Resonance
(W. Bothe and W. Gentner, 1937)

Proton-Neutron Symmetry Breaking
Electric dipole response in Ca isotopes

$^{40}\text{Ca}$
Z=20, N=20

$^{48}\text{Ca}$
Z=20, N=28

Half life: M1 vs. E1 at $E_x = 3$ MeV

Typical strengths for dipole excitations at 3 MeV:

\[ B(M1) \uparrow \approx 1 \mu_N^2 \approx 100 \text{ meV} \approx 5 \text{ fs half-life} \]

\[ B(E1) \uparrow \approx 10^{-2} e^2 fm^2 \approx 100 \text{ meV} \approx 5 \text{ fs half-life} \]
E1 excitations in atomic nuclei: From Giants, Pygmies and Octupoles

• Overview

• Studies of the Pygmy Dipole Resonance
  - completeness of \((\gamma,\gamma')\) measurements
  - systematics
  - structure

• Octupole Modes
The E1 response of spherical atomic nuclei

- Two Phonon Excitation: $E_x \sim 3$ MeV, $B(E1) \sim 10^{-2}$ W.u.
- Giant Dipole Resonance: $E_x \sim 18$ MeV, $B(E1) \sim 10$ W.u.
- Pygmy Dipole Resonance: $E_x \sim 7$ MeV, $B(E1) \sim 10^{-1}$ W.u.
The E1 response of deformed atomic nuclei

- Octupole vibrational bandheads: 
  \( E_x \sim 2 \text{ MeV}, B(E1) \sim 10^{-2} \text{ W.u.} \)

- Splitted Giant Dipole Resonance: 
  \( E_x \sim 13 \text{ MeV and 18 MeV}, B(E1) \sim 10 \text{ W.u.} \)
E1 response in spherical nuclei studied in photon scattering experiments

by courtesy of D. Savran
E1 distribution in the N=82 isotones from $(\gamma,\gamma')$

A. Zilges et al., PLB 542 (2002) 43
S. Volz et al., NPA 779 (2006) 1
Open questions on the Pygmy Dipole Resonance

• How complete are photon scattering experiments?

• Does the PDR show a N/Z dependence?

• What is the underlying excitation structure?

• What is the connection to the PDR in exotic nuclei?
$^{136}$Xe: Experimental fragmentation

\[ \sum B(E1)^\uparrow \ [10^{-3}e^2fm^2] \]

D. Savran et al., PRL 100 (2008) 232501
Fragmentation in the Quasiparticle Phonon Model

- $B(E1)$ nearly completely carried by 1ph part
- Coupling to complex configuration produces fragmentation
- 1ph, 2ph, 3ph up to 8.5 MeV
  $\Rightarrow$ Model space nearly complete up to 8.5 MeV
N=82 isotones: Experiment vs. QPM


V. Yu. Pomonarev
$^{136}\text{Xe}$: Experiment vs. QPM

$\Sigma B(E1) [10^{-3} e^2 f m^2]$ vs. Energy [keV]

- **Exp.**
- **QPM (including 3ph)**

- **Experiment**
- **QPM**
- **QPM$_L$**

(With experimental sensitivity limit)

Sensitivity limit

$S_n$

*D. Savran et al., PRL 100 (2008) 232501*
$^{136}\text{Xe}$: Experimental fragmentation

$\Sigma B(E1)$ [10^{-3} e^2fm^2]

B(E1)\uparrow$ strength of a single transition [10^{-3} e^2fm^2]
$^{136}$Xe: Experiment vs. QPM

$\Sigma B(E1)^\uparrow$ [10$^{-3}$e$^2$fm$^2$]

D. Savran et al., PRL 100 (2008) 232501
How complete are photon scattering experiments?

- Increasing fragmentation from $^{136}\text{Xe}$ to $^{144}\text{Sm}$ in experiment and QPM
- Impact of experimental sensitivity limit more important with increasing proton number
- Missing strengths can vary from a few percent to a factor of three

*D. Savran et al., PRL 100 (2008) 232501*
Open questions concerning the PDR

• How complete are photon scattering experiments?
  → Depending on the nucleus 10% to 300% of the total strength are missing.

• Does the PDR show a N/Z dependence?
Summed E1 strength vs. N/Z ratio

$E_X < 8.02 \text{ MeV}$

\[
\Sigma B(E1) [\text{MeV}^2 \text{fm}^2] \quad \text{vs.} \quad \frac{N}{Z}
\]
Summed E1 strength vs. N/Z ratio

$E_x < 8.02$ MeV

$\Sigma B(E1) [e^2f_{m^2}]$

$\frac{N}{Z}$
Open questions concerning the PDR

• How complete are photon scattering experiments?
  → Depending on the nucleus 10% to 250% of the total strength are missing.

• Does the PDR show a N/Z dependence?
  → No direct evidence.

• What is the underlying excitation structure?
Exhaustion of isovector E1 sum rule

A. Tonchev et al., NIM B 241 (2005) 170

What is the underlying excitation structure?

N. Paar, Y.F. Niu, D. Vretenar, and J. Meng, PRL 103 (2009) 032502
B(E1) strength distribution

\[ \begin{align*}
\text{N}=82 & \quad \text{\(^{140}\text{Ce}(\gamma,\gamma')\)} \\
\text{N}=82 & \quad \text{\(^{138}\text{Ba}(\gamma,\gamma')\)} \\
\text{Z}=50 & \quad \text{\(^{124}\text{Sn}(\gamma,\gamma')\)} \\
\text{Z}=42, \text{N}=52 & \quad \text{\(^{94}\text{Mo}(\gamma,\gamma')\)}
\end{align*} \]

Energy [keV]

\[ B(\text{E1}) \uparrow \quad [10^{-3} \text{e}^2\text{fm}^2] \]

J. Endres, to be published
A splitting of the PDR?

F. Iachello, priv. comm.
A complementary probe: $\alpha$ scattering

- Isoscalar probe
  → Complementary structure information

- Problem:
  - 30-100 keV energy resolution
    → Single excitations not resolved
  - Excitation of higher multipolarities
    → Difficult separation from other excitations

⇒ **No detailed spectroscopy of PDR possible with ($\alpha,\alpha'$)**
The solution: \((\alpha,\alpha'\gamma)\) experiments

- Coincident measurement of \(\gamma\)-decay
  \[\Rightarrow (\alpha,\alpha'\gamma)\]

- Selection of decays to the ground state
  \[\Rightarrow \text{Selectivity to E1 decays}\]
  
  \(T.D. \ Poelhekken \ et \ al., \ Phys. \ Lett. \ B \ 278 \ (1992) \ 423\)

- Use of HPGe detectors
  \[\Rightarrow \text{High energy resolution}\]
  
  \(D. \ Savran \ et \ al., \ Nucl. \ Instr. \ and \ Meth. \ A \ 564 \ (2006) \ 267\)

- Experimental parameters:
  \[\Rightarrow E_\alpha = 136 \text{ MeV and forward angle}\]
Realization at the BBS/EUROSUPERNova setup

2 Super-Clover detectors (GSI)
2 Clover detectors (KVI)
3 Coaxial detectors with BGO
2 Coaxial detectors
(about 100% rel. efficiency each)
→ 0.5% absolute photo-peak efficiency

Realization at the BBS/EUROSUPERNOVA setup
Realization at the BBS/EUROSUPERNOVA setup
The $\alpha-\gamma$ coincidence matrix for $^{140}$Ce

Angular distribution

\[ \theta_\gamma = 202^\circ \]

\[ \theta_\gamma = 264^\circ \]

Comparison: $(\alpha,\alpha'\gamma)$ and $(\gamma,\gamma')$

$^{138}\text{Ba}(\alpha,\alpha'\gamma)$

$^{138}\text{Ba}(\gamma,\gamma')$

Comparison: $(\alpha,\alpha'\gamma)$ and $(\gamma,\gamma')$

$^{140}\text{Ce}(\alpha, \alpha'\gamma)$

$^{140}\text{Ce}(\gamma, \gamma')$

$J. \text{ Endres et al., Phys. Rev. C 80 (2009) 034302}$
A splitting of the PDR?
A splitting of the PDR!

- Splitting of the PDR:
  - Two groups of states with different structure

- Two different probes:
  - Isospin character
  - Interaction with nucleus

J. Endres et al., to be published
E1 strength in the relativistic QRPA

N. Paar, Y.F. Niu, D. Vretenar, and J. Meng, PRL 103 (2009) 032502
E1 strength in the relativistic QRPA

\[ ^{140}\text{Ce} \]

\[ 1^- \]

N. Paar, Y.F. Niu, D. Vretenar, and J. Meng, PRL 103 (2009) 032502
Open questions concerning the PDR

• How complete are photon scattering experiments?
  → Depending on the nucleus 10% to 300% of the total strength are missing.

• Does the PDR show a strong N/Z dependence?
  → No direct evidence.

• What is the underlying excitation structure?
  → An isoscalar surface excitation at low energies plus an isovector part at higher energies.

• What is the connection to the PDR in exotic nuclei?
PDR in neutron rich Sn isotopes observed in $(\gamma, n)$ transitions.

- For $^{130}$Sn, the transition at 10.1 MeV.
- For $^{132}$Sn, the transition at 9.8 MeV.

PDR in neutron rich $^{68}$Ni observed in $\gamma$ decay

Open questions concerning the PDR

• How complete are photon scattering experiments?
  ➔ Depending on the nucleus 10% to 250% of the total strength are missing.

• Does the PDR show a strong N/Z dependence?
  ➔ No direct evidence.

• What is the underlying excitation structure?
  ➔ An isoscalar surface excitation at low energies plus an isovector part at higher energies.

• What is the connection to the PDR in exotic nuclei?
The E1 response of deformed atomic nuclei

Do we understand the octupole structures?
Open questions concerning octupole structures

- What is the systematics of octupole excitations concerning energies, strengths, branching ratios?

- What is the influence of the K quantum number?

- How do the excitations evolve in a shape transition from spherical to well deformed?

- Are octupole excitations enhanced in exotic nuclei?

One needs **selective** and **sensitive** experiments yielding as much observables as possible!
An ideal setup for such experiments

HORUS array at University of Cologne:
- 14 HPGe detectors (in close geometry)
- Photopeak efficiency at 1332 keV: up to 2%

- adequate efficiency
- high energy resolution
- angular resolution
- auxillary particle detectors
- coincidence techniques
- robust ion beam
(d,d'γ) experiments on $^{172}$Yb

 photon spectrum with gate $4 \, \text{MeV} \leq E_d \leq 8 \, \text{MeV}$
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Not only spin-isospin excitations are interesting...
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Institut für Kernphysik, Universität zu Köln
Institut für Kernphysik, TU Darmstadt
KVI, University of Groningen
Department of Physics, University of Liverpool,
Physik-Department E12, TU München,
I.N.P. NSCR Demokritos, Athens

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