The Electric Multipole Response of Nuclei: Pygmy Resonances and Related Structures

• Electromagnetic strengths in nuclei

• Lifetime determination with the \((p, p'\gamma)\) method

• Identification of the Pygmy Quadrupole Resonance

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Electromagnetic response of atomic nuclei

Ex [MeV]

<table>
<thead>
<tr>
<th>E1</th>
<th>OCTUPOLE COUPLING</th>
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<tr>
<td></td>
<td>α-CLUSTER</td>
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<td></td>
<td>PDR</td>
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<td>GDR</td>
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| M1 | 2QP               |
|    | GAMOW TELLER      |

| E2 | PHONON EXCITATIONS |
|    | PQR ?             |
|    | GQR               |

Strength (a.u.)

5 10 15 Ex [MeV]
From giants and pygmies

PDR

GDR

1-5% of EWSR

about 100% of EWSR

D. Savran, T. Aumann, and A. Zilges, PPNP 70 (2013) 210
Splitting of the PDR

Surface neutron oscillation mode, the „real“ PDR

$^1{}^{124}\text{Sn}(\alpha, \alpha'\gamma)$

@ 120 MeV

Isovector mode

$^1{}^{124}\text{Sn}(\gamma, \gamma')$

Janis Endres et al., PRL 105 (2010) 112503
Janis Endres et al., PRC 85 (2012) 064331
Result confirmed, e.g., in \((^{17}\text{O}, ^{17}\text{O}')\) on \(^{140}\text{Ce}\)

\[ \rightarrow \text{talks by S. Bassauer, H. Iwasaki, N. Kobayashi, J. Pei, D. Savran, P. von Neumann-Cosel} \]

\[ M. \text{Krzysiek, A. Bracco et al., PRC 93 (2016) 044330} \]
From dipole to quadrupole

Pygmy Dipole Resonance (PDR)  E1

Pygmy Quadrupole Resonance (PQR) ?  E2
Is there evidence for a **Pygmy Quadrupole Resonance (PQR)**, a quadrupole-type oscillation of the neutron skin?

*N. Tsoneva, H. Lenske, PLB 695, 174 (2011)*

- considerable E2 strength between 3-5 MeV
- dominant decay to groundstate: \( b_0 = \Gamma_0 / \Gamma > 0.5 \)

*M. Spieker et al., PLB 752, 102 (2016)*
Is there evidence for a **Pygmy Quadrupole Resonance (PQR)**, a quadrupole-type oscillation of the neutron skin?

**Important observables for the identification of the PQR:**

- B(E2) strength distribution
- branching to excited states
- single-particle structure
- isospin character (however, similar to phonon excitations)
SONIC@HORUS at the University of Cologne

- 14 HPGe detectors (+BGO)
- Target ladder
- Ion beam
- 12 Si PIPS particle detectors

S.G. Pickstone et al., NIM A (2017), in press
The proton-$\gamma$ coincidence matrix

$^{92}\text{Mo}(p,p'\gamma)$
$E_p=10.5\ \text{MeV}$

One obtains information about the **population** and **decay** of a specific level!

Example: Diagonal gates select decay to specific lower lying states, e.g., to the ground state, $2^+_1$, or $4^+_1$

*S.G. Pickstone et al., NIM A (2017), in press*
Lifetime determination using the \((p,p'\gamma)\) Doppler Shift Attenuation (DSA) coincidence method

\[
E_\gamma(\Theta,t) = E_\gamma^0 \left( 1 + F(\tau) \frac{v_0}{c} \cos \Theta \right)
\]

Determination of \(\gamma\)-energy centroid shifts due to Doppler effect

\(\rightarrow\) Emission of \(\gamma\) ray in flight while the recoil is slowing down in target+stopper

similar to \((n,n'\gamma)\) → talk by S. Yates

A. Hennig et al., NIM A794 (2015) 171
Lifetime determination via $(p,p'\gamma)$

Excitation-energy gate (SONIC)
- $v_0$ is known from kinematics
- feeding can be excluded
  → extraction of real lifetimes!

A. Hennig et al., NIM A794 (2015) 171
Comparison to existing data

A. Hennig et al., PRC 92 (2015) 064317
S. Prill et al., to be published
Many new lifetimes and $B(E2)$ values from a single experiment!
(57 lifetimes in $^{112}\text{Sn}$ and 30 lifetimes in $^{114}\text{Sn}$)

M. Spieker et al., to be published
Groundstate decay ratios \( b_0 = \frac{\Gamma_0}{\Gamma} \) in \(^{112}\text{Sn}\)

The gate on the excitation energy allows a sensitive measurement of branching ratios!
B(E2) strengths and g.s. decay ratios in Sn isotopes

\[ b_0 = \frac{\Gamma_0}{\Gamma} \]
Systematics of summed $B(E2)$ strengths in Sn

$\sum B(E2) \uparrow \left[ e^2 \text{fm}^2 \right]$ vs $A$

- Black dots: This work
- Blue dots: $(\gamma,\gamma') +$ ENSDF

A: $^{112,114,116,118,120,122,124}$

$N=64$ shell effect?

$\sum B(E2) \uparrow$ below 4 MeV

M. Spieker et al., to be published
The present experimental data does support the existence of a Pygmy Quadrupole Resonance
Probing the isospin character of the PQR

CAGRA@Grand Raiden Collaboration, RCNP, Osaka (Japan)

- $(p,p'\gamma) @ E_p = 80 \text{ MeV}$ and $(\alpha,\alpha'\gamma) @ E_\alpha = 130 \text{ MeV}$ (Oct 2016 – Dec 2016)
- **CAGRA** (12 Clover HPGe detectors and 4 large-volume LaBr$_3$:Ce detectors)
- **Grand Raiden** spectrometer (very good energy resolution)
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From quadrupole to dipole

Pygmy Dipole Resonance (PDR)

E1

Pygmy Quadrupole Resonance (PQR) ?

E2
Photons are an ideal probe to study dipole excitations

- **bremsstrahlung beams**
  (e.g., TU Darmstadt, HZDR):
  good overview, but no energy selectivity

- **photons from laser Compton backscattering, 1\textsuperscript{st} generation**
  (e.g., HIGS, New SUBARU)
  selection of an energy window, parity information
  \(\rightarrow\) talks by T. Beck, J. Isaak, A. Tonchev, H. Utsunomiya, J. Wilhelmy

- **photons from laser Compton backscattering, 2\textsuperscript{nd} generation**
  (ELI-NP)
  selective excitation of single states, parity information
  \(\rightarrow\) talk by V. Zamfir

Lifetime determination using the \((p,p'\gamma)\) Doppler Shift Attenuation (DSA) coincidence method

- Lifetimes from 10 fs to 1 ps can be measured
- Feeding from higher-lying states excluded due to \(p\gamma\) coincidences (excitation gate)
- \(\gamma\)-decay branching can be measured sensitively
- Dozens of lifetimes in one experiment
- Angular momentum transfer in \((p,p'\gamma)\): \(\Delta J = 0-5\)

→ very versatile tool for low spin nuclear structure studies
(p,p′γ) experiments at ≈10 MeV/A in Cologne yield lifetimes and branching ratios for low spin excitations

observables for some 2⁺ states agree with theoretical predictions for a Pygmy Quadrupole Resonance

further experiments on isospin and single-particle character under way for unambiguous identification of PQR

Photon beams with small bandwidth allow state selective excitation → NUCLEAR PHOTONICS
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