Investigation of the Pygmy Dipole Resonance in particle-$\gamma$ coincidence experiments

V. Derya$^{1*}$, J. Endres$^1$, M. N. Harakeh$^{2,3}$, D. Savran$^{4,5}$, M. Spieker$^{1*}$, H. J. Wörtche$^2$, and A. Zilges$^1$

$^1$Institute for Nuclear Physics, University of Cologne, Germany
$^2$KVI, Rijksuniversiteit Groningen, The Netherlands
$^3$GANIL, CEA/DSM-CNRS/IN2P3, Caen, France
$^4$ExtreMe Matter Institute EMMI and Research Division, GSI, Darmstadt, Germany
$^5$Frankfurt Institute for Advanced Studies FIAS, Frankfurt a.M., Germany

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The PDR in particle-$\gamma$ coincidence experiments

- Introduction
- The particle-$\gamma$ coincidence method
- Systematic study in ($\gamma,\gamma'$) and ($\alpha,\alpha'\gamma$)
- First results $^{140}\text{Ce}(p,p'\gamma)$
- Summary
- Outlook
Introduction

**E1 strength in spherical nuclei**

![Graph showing E1 strength in 140Ce]

- Isovectorial electric Giant Dipole Resonance
- Low-lying E1 strength
  - 2-Phonon \((2^+ \otimes 3^-)_1^-
  - Pygmy Dipole Resonance (PDR)

Relevance of the PDR

- Symmetry energy of the equation of state (EOS)
  \[ \leftrightarrow \text{neutron-skin thickness} \]
  \[ \leftrightarrow \text{E1 strength} \]

- Nucleosynthesis
  \[ \leftrightarrow \text{neutron-capture rates} \]
  \[ \leftrightarrow \gamma\text{-ray strength function} \]
  \[ \leftrightarrow \text{photo-absorption cross section} \]
PDR studied with \((\gamma,\gamma')\) in N=82 isotones

- Real-photon scattering for stable nuclei below the particle thresholds
- Strongly fragmented E1 strength

Accessible quantities:
- transition energy \(E_{\gamma}\)
- multipole character \(\lambda\)
- reduced transition strength \(B(E1)\)
- fragmentation
- integrated strength

## Probes for scattering experiments

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- Insight into the structure of the (dipole) excitations

- at medium particle energies ($\approx 50$-150 MeV)
The particle-$\gamma$ coincidence method

- **Reaction**: inelastic particle scattering

- **Coincident detection** of particles and $\gamma$ rays

- Performed with $\alpha$ particles at *Kernfysisch Versneller Instituut* in Groningen, The Netherlands

- $\alpha$ beam at $E_\alpha = 136$ MeV
  - AGOR cyclotron
  - Cyclotron frequency: 28 MHz
  - Particle current: 0.4-1 pnA
The PDR in particle-γ coincidence experiments

V. Derya, University of Cologne, AG Zilges

HPGe-detector array
Big-Bite Spectrometer

- QQD-type spectrometer
- Two quadrupole magnets
- One dipole magnet
- Maximum solid angle: 9.2 msr
EUROSUPERNOVA System for particle detection
- Focal Plane Detector System
  2 Vertical Drift Chambers
  $\rightarrow$ energy and particle trajectories
- scintillator layer $\rightarrow$ trigger

Big-Bite Spectrometer

Photo by S.G. Pickstone

50 cm
Excitation spectrum in $\gamma$ coincidence

Typical energy resolution: $\approx 300$ keV
The $\alpha$-$\gamma$ coincidence matrix

$$48\text{Ca}(\alpha,\alpha'\gamma)$$

Decay branching

Detector response

Excited states

$$E_X \approx E_\alpha - E_{\alpha'} \text{ [MeV]}$$

$E_\gamma \text{ [MeV]}$

Intensity
The $\alpha$-$\gamma$ coincidence matrix

$48\text{Ca}(\alpha,\alpha'\gamma)$

- Energy spectra through projection
- Selecting transitions by setting gates
Selecting transitions – Projected $\gamma$ spectra

$^{48}\text{Ca}(\alpha,\alpha'\gamma)$

Gate on $E_X \approx E_\gamma$

Gate on $E_X \approx E_\gamma + E_{2^+}$
\( \alpha - \gamma \) angular correlation from DWBA
Experimental method: \((\alpha, \alpha'\gamma)\)

- Selective excitation
  - Isoscalar probe
  - Mainly low spin from ground state
  - Natural parities

- Powerful data analysis
  - HPGe detectors with high energy resolution
  - Selection of transitions
  - Cross sections
  - Branching ratios
  - Angular distributions \(\rightarrow\) Spin assignments
The PDR in particle-\(\gamma\) coincidence experiments

Splitting:

- low-energy part \((\gamma,\gamma')\) and \((\alpha,\alpha'\gamma)\)
- high-energy part \((\gamma,\gamma')\) only

Systematic study in \((\alpha,\alpha'\gamma)\) and \((\gamma,\gamma')\) experiments

- Neutron magic (N=82) isotopes \(^{140}\text{Ce}\) and \(^{138}\text{Ba}\)
- Proton magic (Z=50) isotope \(^{124}\text{Sn}\)

![Graphs showing data for Neutron magic (N=82) isotones \(^{140}\text{Ce}\) and \(^{138}\text{Ba}\) and Proton magic (Z=50) isotope \(^{124}\text{Sn}\)]

Systematic study in \((\alpha,\alpha'\gamma)\) and \((\gamma,\gamma')\) experiments

- Neutron magic (N=82) isotones \(^{140}\text{Ce}\) and \(^{138}\text{Ba}\)
- Proton magic (Z=50) isotope \(^{124}\text{Sn}\)

Splitting is a common feature of the low-lying dipole response in semi-magic heavy neutron-rich nuclei

\[ \text{Neutron magic (N=82) isotones } \]
\[ \text{Proton magic (Z=50) isotope } \]

D. Savran et al.,

J. Endres et al.,

J. Endres, E. Litvinova et al.,
Interpretation of the splitting

Transition densities for two RQTBA states in $^{124}$Sn

- In phase
- Large neutron contribution at the surface
- Slightly out of phase
- Enhanced proton contribution

Low-lying state: Typical PDR state

High-lying state: Transitional region towards the GDR


(\(\alpha,\alpha'\gamma\)) and (\(\gamma,\gamma'\)) in \(^{94}\text{Mo}\)

- Non-magic (N=52, Z=42) isotope \(^{94}\text{Mo}\)
- Near to (sub) shell closure

\[\frac{d\sigma}{d\Omega}_\alpha\]

Sensitivity limit

\[B(E1)\uparrow\]

\(10^{-3} e2 fm^2\)

\(E\) [MeV]

\(3 \quad 4 \quad 5 \quad 6 \quad 7 \quad 8\)


C. Romig, private communication
Systematic study in $(\alpha,\alpha'\gamma)$ and $(\gamma,\gamma')$ experiments

- Neutron magic (N=82) isotones $^{140}\text{Ce}$ and $^{138}\text{Ba}$
- Proton magic (Z=50) isotope $^{124}\text{Sn}$

Splitting is a common feature of the low-lying dipole response in semi-magic heavy neutron-rich nuclei

Low-lying dipole strength in lighter nuclei

- Light-mass nuclei: halo nuclei, single-particle character excitations
- Medium-mass nuclei: development of a more collective electric-dipole excitation mode?
- Dependence on N/Z ratio in the calcium chain
Low-lying dipole strength in lighter nuclei

\[ 40\text{Ca}(\alpha,\alpha'\gamma) \]

\[ 48\text{Ca}(\alpha,\alpha'\gamma) \]

\[ \text{ISD EWSR [\%]} \]

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

\[ 40\text{Ca}(\gamma,\gamma') \]

\[ 48\text{Ca}(\gamma,\gamma') \]


V. Derya et al., to be published
J=1⁻ states in \((\alpha,\alpha'\gamma)\) and \((\gamma,\gamma')\)
J=1^- states in (α,α'γ) and (γ,γ')

- Strongest state in (γ,γ') at 7.3 MeV is missing in (α,α'γ)

\(48\text{Ca}(α,α'γ)\)

\(d\sigma/dΩ_α < 0.15 \text{ mb/sr}\)
Strongest state in \((\gamma,\gamma')\) at 7.3 MeV is missing in \((\alpha,\alpha'\gamma)\)

Strongest state in \((\alpha,\alpha'\gamma)\) at 7.6 MeV is weak in \((\gamma,\gamma')\)
Parity Measurement at HI$\gamma$S

- High Intensity $\gamma$-Ray Source (HI$\gamma$S) at the Duke Free Electron Laser Laboratory (DFELL)
- 100% linear polarized and nearly mono-energetic intense $\gamma$-ray beam ($I_\gamma \sim 10^7$ photons/sec)
- 6 HPGe detectors:
  - One for beam monitoring
  - One at backward angle
  - Four at $\theta = 90^\circ$ in the horizontal and vertical plane $\rightarrow$ Parity assignment
- Target: $^{48}$Ca
  - Amount: 1 g ($\approx$ $250,000$)
The State at 7.298 MeV

- $\gamma$-ray beam energy of 7.3 MeV
- Measured for 1.5 h

Experimental asymmetry: 

$$\varepsilon = \frac{I(||) - I(\perp)}{I(||) + I(\perp)} = q \begin{cases} +1, & \text{for } J^\pi = 1^+ \\ -1, & \text{for } J^\pi = 1^- \end{cases}$$
9 dipole excitations were observed

=> The excited dipole states do have negative parity
Comparison with theoretical results for $^{48}$Ca

- QRPA calculations:
  strong IS LED states present in all even-even Ca isotopes (N=14-40)
  P. Papakonstantinou et al. PLB 709 (2012) 270

- Character changes
  - proton-skin oscillation
  - pure IS oscillation
  - neutron-skin oscillation
  \[ \Rightarrow \text{ at } N=30 \] (Gogny interaction)

- Experimental results on $^{48}$Ca:
  - separated strong IS LED state at 7.6 MeV
  - weak in IV channel $\Rightarrow$ pure IS oscillation
  $\Rightarrow$ character changes at $N > 28$
### Probes for scattering experiments

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• at medium particle energies ($\approx 50$-$150$ MeV)

**Insight into the structure of the (dipole) excitations**
First results $^{140}\text{Ce}(p,p'\gamma)$

- performed at KVI
- beam energy: 80 MeV
- central BBS angle: 6°
- 8 HPGe detectors
- target enrichment: 99.72 %
Excitation spectrum in $\gamma$ coincidence

$^{140}\text{Ce}(p,p'\gamma)$
\( \gamma \) spectrum with gate on \( E_x = E_\gamma \)

\( \gamma \) spectrum from \(^{140}\text{Ce}(p,p'\gamma)\) with gate on \( E_\gamma = E_X \)
Comparison of the probes

\[ \frac{d\sigma}{d\Omega_\alpha} \quad [\text{mb/sr}] \]

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

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

\( (\gamma, \gamma') \)

Energy [keV]

\( \text{Sensitivity limit} \)
Comparison of the probes

\[ \frac{d\sigma}{d\Omega_\alpha} \text{[mb/sr]} \]

\[ B(E1) \uparrow \text{[}10^{-8} \text{e}^2\text{fm}^2\text{]} \]

Energy [keV]

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

\[(\alpha,\alpha'\gamma)\]

Sensitivity limit

\[(\gamma,\gamma')\]

seen in \((p,p'\gamma)\)
Summary

- Systematic study of E1 excitations in ($\gamma,\gamma'$) and ($\alpha,\alpha'\gamma$) experiments in stable and spherical nuclei
  - $A = 48$-$140$
  - $N/Z = 1.23$-$1.48$
  - semi-, doubly-, and non-magic

- ($\alpha,\alpha'\gamma$) method is appropriate tool for identifying the contribution of the PDR to the total E1 strength and strength function

- First results of $^{140}$Ce(p,p'\gamma) show qualitatively different behavior for the proton probe
Outlook: iThemba LABS

- K600 spectrometer at 0°
- Continuation of particle-$\gamma$ coincidence experiments at medium particle (p, $\alpha$, ...) energies

First feasibility test in December 2012
- Performed by R. Neveling et al.
- $\alpha$ beam of 160 MeV energy
- 2 Clover detectors, 1 big NaI detector

Outlook: SONIC & HORUS in Cologne

HORUS: $\gamma$ spectrometer
- 14 HPGe detectors
- 6 BGO shields
- Photopeak efficiency
  - with SONIC: 2% at 1332 keV
- Energy resolution
  - with digital DAQ: $\leq 2.5$ keV at 1332 keV, 6 kcps

SONIC: particle spectrometer
- Silicon Identification Chamber
- 8 $\Delta E$-$E$ detector tubes
- Solid angle coverage $\approx 4\%$
Combining $\gamma$ and particle spectroscopy

- various probes (p, d, $\alpha$, …)
- particle-$\gamma$ coincidence
Combining $\gamma$ and particle spectroscopy

- various probes ($p$, $d$, $\alpha$, …)
- particle-$\gamma$ coincidence

Excitation-energy spectrum from a very recent experiment:
$^{92}\text{Mo}(p,p'\gamma)$ at 10.5 MeV

Si detector at $131^\circ$
$\Delta E = 79$ keV @ 10.5 MeV
University of Cologne (Cologne, Germany)

V. Derya, J. Endres, A. Hennig, J. Mayer, L. Netterdon,
S. G. Pickstone, P. Scholz, M. Spieker, T.-M. Streit,
M. Weinert, and A. Zilges

Kernfysisch Versneller Instituut (Groningen, The Netherlands)

S. Bagchi, M. N. Harakeh, N. Kalantar, A. Najafi, C. Rigollet,
and H. J. Wörtche

ExtreMe Matter Institute (Darmstadt, Germany)

E. Fiori, J. Isaak, B. Löher, D. Savran, and J. Silva

TU Darmstadt (Darmstadt, Germany)

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