Nuclear structure studies using inelastic scattering reactions: example of the pygmy resonance in $^{140}$Ce

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Introduction: How protons and neutrons contribute to the pygmy resonance?

1. Goal of the study of the PDR in $^{140}$Ce using the neutron inelastic scattering reaction
2. Experimental setup at NFS
3. Online results from the experiment performed in September 2022
4. Perspectives
Nature of a nuclear excitation

What is the nature of a nuclear excitation?
Contributions of the protons and neutrons to the excitation strength?

Tool
scattering reaction

Observables
Excitation energy, $E_\gamma$ and cross section

Interpretation
Comparison to microscopic calculations

$M_{p(n)} = \int \rho_{fi}^{p(n)}(r) r^{L+2} \, dr$

Transition density

Multipole moment
Multipolarity of the transition

Complementarity of the scattering experiments

\[ M = b_n \, M_n + b_p \, M_p \]

M transition multipole matrix element

\( b_{n,p} \) interaction strengths between the external field and \( n,p \) of the nucleus

\[ A. \, Bernstein, \, V. \, Brown \, and \, V. \, Madsen, \, PLB \, 103, \, 255 \, (1981) \]
The pygmy dipole resonance (PDR)

- oscillation of a neutron skin against a symmetric proton/neutron core
- additional E1 strength at lower energy

GDR (Giant Dipole Resonance)
- oscillation of neutrons against protons
- exhausts ~ 100% E1 strength

PDR plays important role:
- as a constraint of the Equation of State
- for the nucleosynthesis r process

Figure extracted from A. Bracco *et al.* Prog. Part. Nucl. Phys. 106 (2019)
If several models are able to reproduce E1 strength at lower energy than the GDR, they do not agree on the fine structure. New probes are necessary to resolve the complexity of the isospin character of the PDR.

- Isoscalar probes $\rightarrow$ 4-6 MeV
- Proton probe $\rightarrow$ selected states
- Electromagnetic probe $\rightarrow$ 4-8 MeV

If these probes agree on the structure, it will allow study of the PDR in $^{140}$Ce using $(n,n')$.
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Motivation of the proposed experiment

WHY?

(n,n’) is an elementary probe:
• which does not require Coulomb correction
• complementary to (p,p’) and to other reactions

M = b_n M_n + b_p M_p

M transition multipole matrix element

b_{n,p} interaction strengths between the external field and n,p of the nucleus

EM

Coulex

1/3

1

0

b_n / b_p

Goal of the experiment

**HOW ?**

1. Detect $n'$ and $\gamma$ in coincidence

   ![Image of 140Ce(p,p'\gamma) spectrum]


   **BUT :**
   - $E_x = E^*(140\text{Ce})$ reconstructed using the $n'$ TOF. Few MeV energy resolution
   - PARIS scintillators instead Ge detector. 2-3% energy resolution in the PDR energy region
     More difficult!

2. Measure the $n'$ and $\gamma$ angular distributions of a given excitation energy range to assess the $1^-$ strength.

   ![Graph of $d\sigma/d\Omega$ vs $\theta_{c.m.}$ for different $\gamma$ levels]

   $^{140}\text{Ce}(n,n')^{140}\text{Ce}^*$
   $E_n = 28$ MeV
   $E(^{140}\text{Ce}^*) = 9-11$ MeV

3. For each $1^-$ excited state/energy range: extract the $(n,n')$ cross section

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Goal of the experiment

**HOW ?**

**ANALYSIS of the cross sections for E1 states and INTERPRETATION**

1. Compare the measured \((n,n')\) to theoretical cross sections
2. Compare the \((p,p')\) data of the literature to the calculations

The comparison exp. vs theory for \((n,n')\) and for \((p,p')\) will **pin down the role of protons and neutrons in the PDR**

Example of calculations: QRPA transition densities (Gogny D1M interaction) + DWBA calculations using a microscopic density-dependent potential model approach

**Example of calculations:**

- QRPA (S. Péru) + DWBA-JLM (M. Dupuis)
- QRPA S. Péru et al., CEA DAM EPJA 55:232 (2009)
- DWBA with JLM M. Dupuis et al., PRC100, 044607 (2019)
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Experimental setup

\[ {^{140}\text{Ce}}(n, n') {^{140}\text{Ce}^*} (\gamma) {^{140}\text{Ce}} @ \text{NFS} \]

- 48 MONSTER modules at 3m from the Ce target
- 8 PARIS clusters at 23cm from the Ce target

- Experimental setup:
  - 1.5 mm-thick Li converter
  - \(^7\text{Li}(p, n){^7}\text{Be}
  - \(33\text{ MeV, 20 }\mu\text{A}\)
  - \((31\text{ MeV, 9.6 x }10^4 \text{ n/cm}^2/\text{s})\)

- Natural Ce target \((^{140}\text{Ce} - 89\%)\) at 5 m from the converter

Use of FASTER acquisition for PARIS and MONSTER
Experimental setup
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Beam size on target

To check the neutron beam size at the Ce target position, a photographic plate has been placed at the entrance.

Neutron beam spot at the target place
\( (\varnothing = 4 \text{ cm}) \)

Intensity

- Intensity extracted with uncertainty < 5%
- How clean the tail?
Use Time of Flight between PARIS and HF to select gammas coming from 30.7 MeV neutron interaction on the Ce target.

**ToF for all Paris detectors**

- Counts/0.1ns

- **γ from the Li converter**
- **γ from the Ce target in coincidence with 30.8 MeV neutrons**
- **γ from the Ce target in coincidence with slower incident neutrons + scattered neutrons**

**PRELIMINARY**

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Elastic reaction channel \(^{12}\text{C}(n,n)^{12}\text{C}\)

- Experimental points
  - Extracted differential cross-section without any normalization, assuming 8% intrinsic efficiency at 30.7 MeV for each

Theoretical calculations follow well the experimental angular distribution

Reconstruction validation of the scattered neutron with MONSTER

Elastic reaction channel \(^{140}\text{Ce}(n,n)^{140}\text{Ce}\)

- DWBA calculations using the microscopic JLM folding model (validated on experimental data available at other neutron energies)
PARIS and MONSTER Collaborations

1. CEA Saclay DRF/Irfu/DPhN (France)
2. IJCLab (France)
3. CEA Bruyères le Chatel DAM/DIF (France)
4. GANIL (France)
5. LPC Caen (France)
6. CIEMAT (Spain)
7. Institut of Nuclear Physics PAN Krakow (Poland)
8. Université de Strasbourg, Institut Pluridisciplinaire Hubert Curien
9. KVI-CART (The Netherlands)
10. IP2I Lyon (France)
11. IFIN-HH, Bucharest (Romania)
12. Milano University and INFN (Italy)

Thank you for your attention!

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