Recent results on the PDR and the two-phonon 1^- state studied via $(p,p'\gamma)$ and $(\vec{\gamma},\gamma')$ reactions

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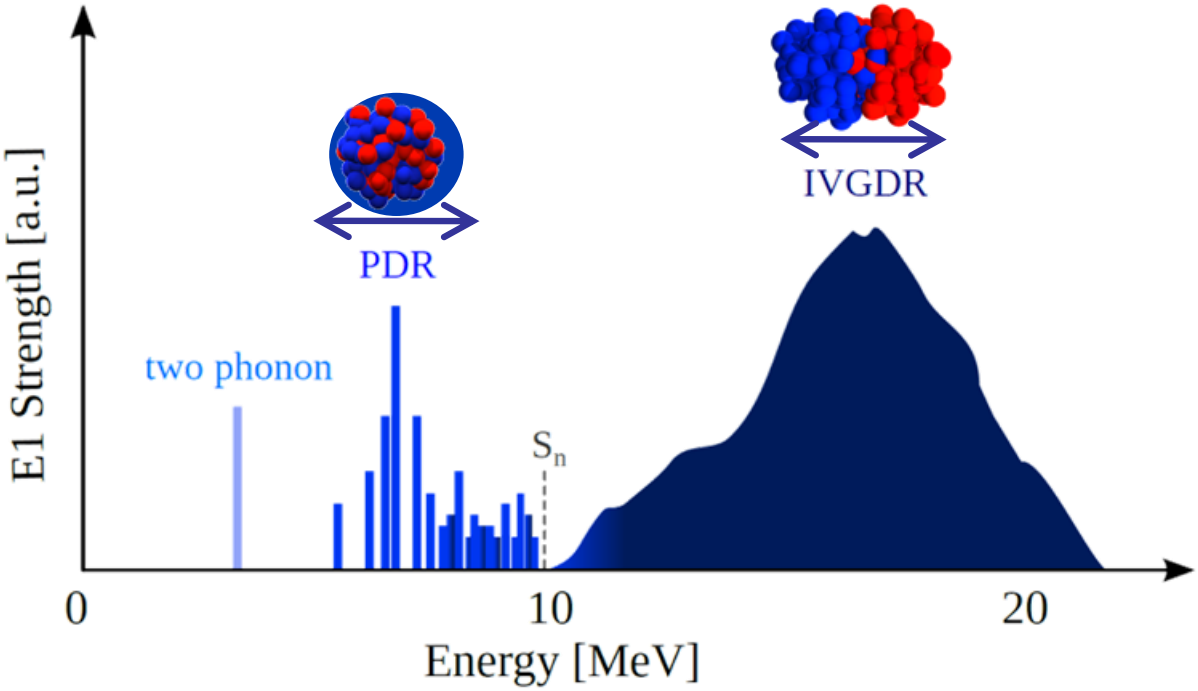
Outline

- Introduction
- The Pygmy Dipole Resonance in ^{140}Ce studied via $(\mathrm{p},\mathrm{p}'\gamma)$
- The $(2^+ \otimes 3^-)_{1^-}$ state in ^{40}Ca and ^{140}Ce studied via $(\vec{\gamma},\gamma')$
- Summary and Outlook

Introduction

E1 strength in spherical nuclei



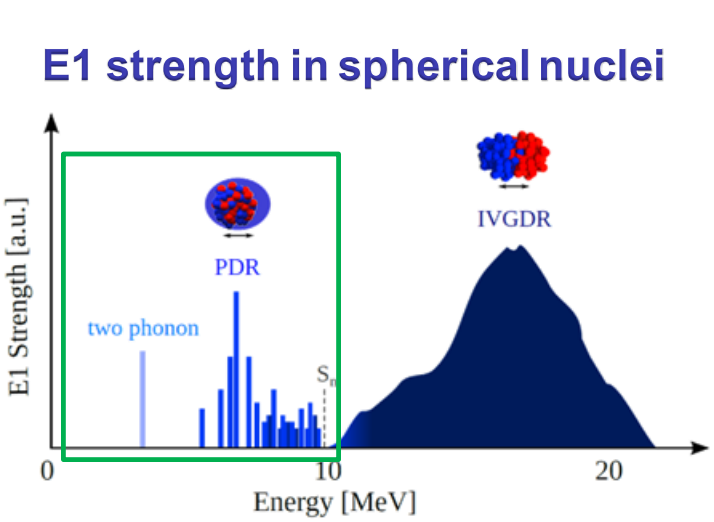
High-lying strength

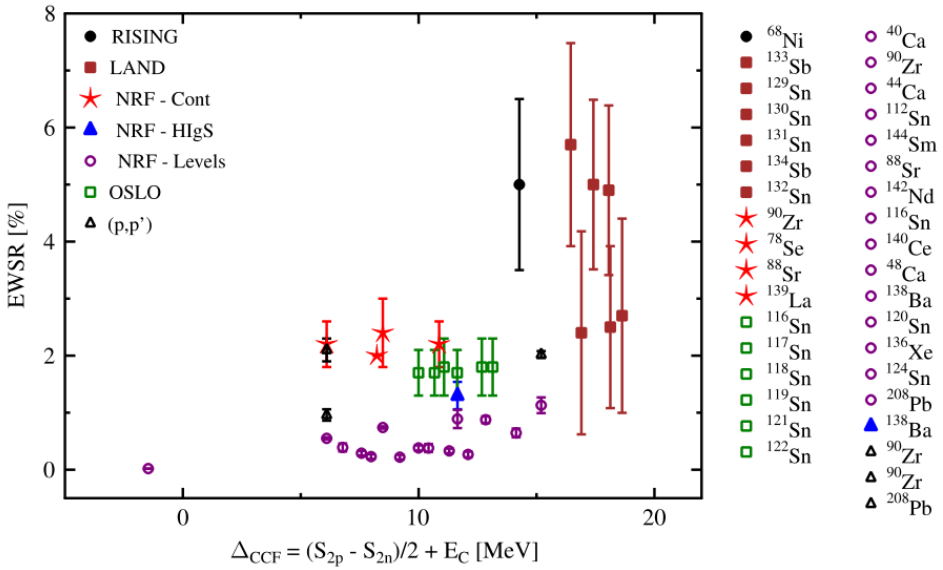
- Isovector Giant Dipole Resonance (IVGDR)

Low-lying strength

- Pygmy Dipole Resonance (PDR) → 1st part of this talk
- $(2^+ \otimes 3^-)_{1^-}$ state → 2nd part of this talk

E1 EWSR exhausted by low-lying excitations





D. Savran, T. Aumann, and A. Zilges, PPNP **70** (2013) 210

- Systematic deviations due to different approaches?
- Continuum strength and decay branching?
- Structure of E1 excitations / excitation modes?

→ **Further experimental and theoretical effort needed!**

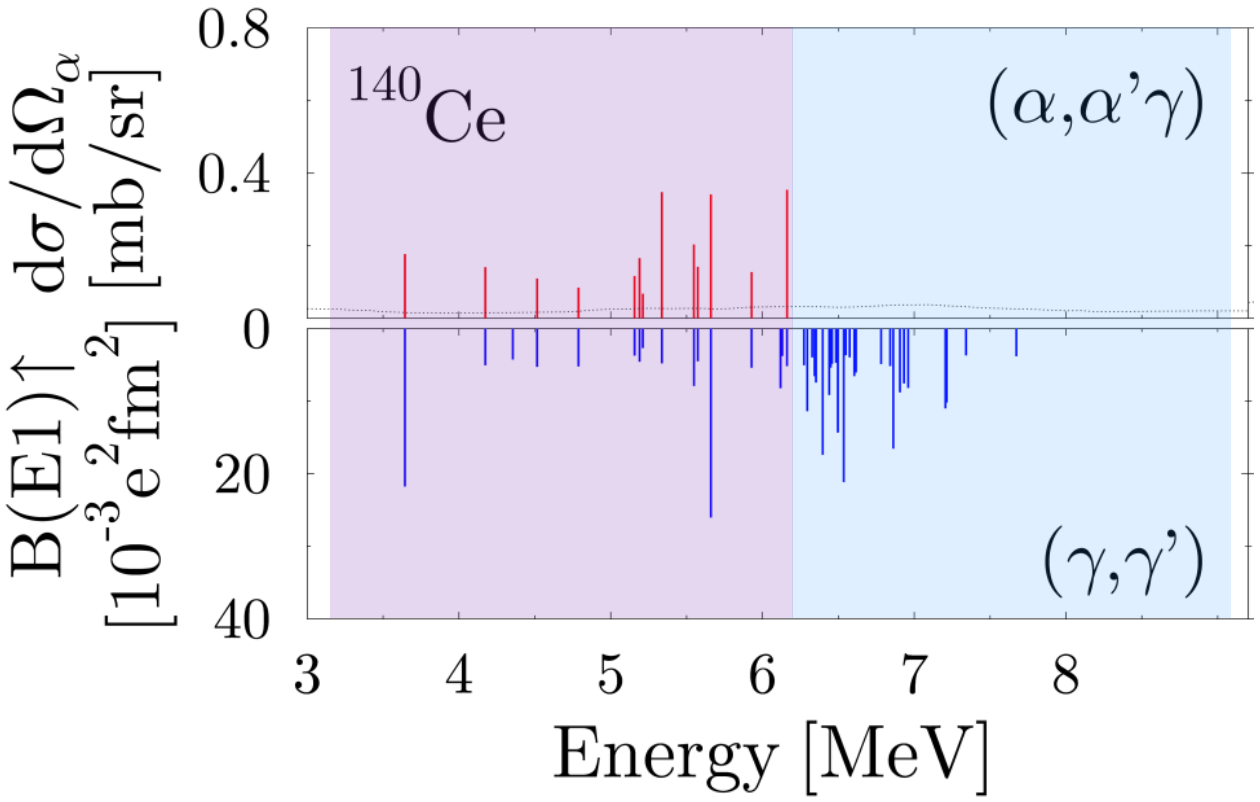
Complementary probes

Probe	Interaction (dominant)	Location of interaction	Character of interaction (dominant)
Photon	Electromagnetic	Whole nucleus	Isovector
α particle[1]	Hadronic* *at intermediate energies (≈ 20-100 MeV/u)	Surface	Isoscalar
Proton[2]			
^{17}O[3]			

[1] D. Savran et al., Phys. Rev. Lett. **97** (2006) 172502
[2] V. Derya, PhD thesis, Universität zu Köln (2014)
[3] F.C.L. Crespi et al., Phys. Rev. Lett. **113** (2014) 012501

Insight into the structure of the dipole excitations

Systematic study in (α,α′γ) and (γ,γ′) experiments



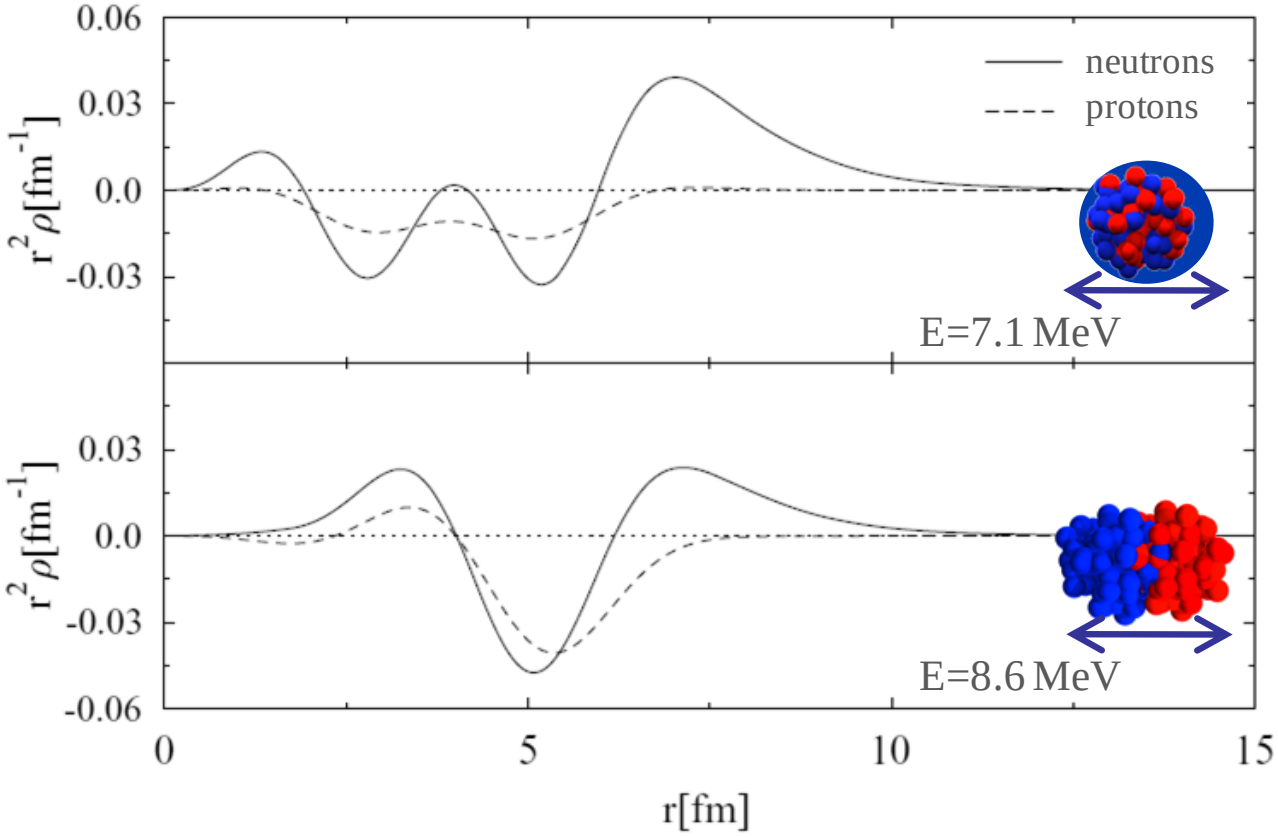
Splitting of the E1 strength:

- Low-lying part excited in (γ,γ′) and (α,α′γ)
- Higher-lying part excited in (γ,γ′)

D. Savran et al., Phys. Rev. Lett. **97** (2006) 172502

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 towards the GDR

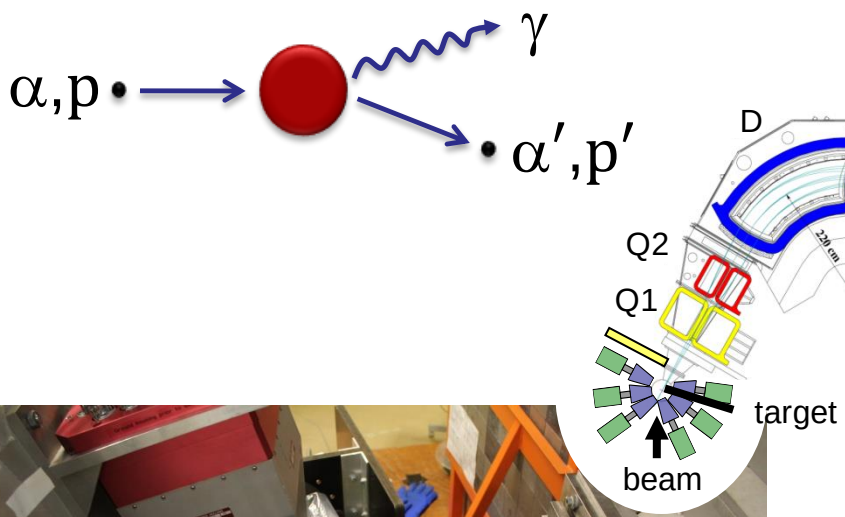
J. Endres, E. Litvinova et al., Phys. Rev. C **85** (2012) 064331

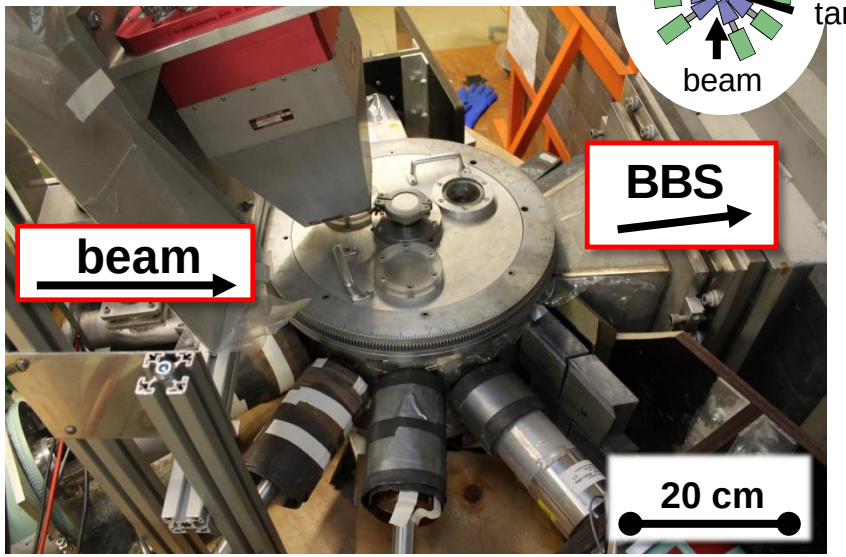
Similar conclusions in
N. Tsoneva et al., Phys. Rev. C **77** (2008) 024321

Particle-γ coincidence method

- Reaction: Inelastic particle scattering at intermediate energy performed at KVI Groningen

Big-Bite Spectrometer @ ≈ 5°

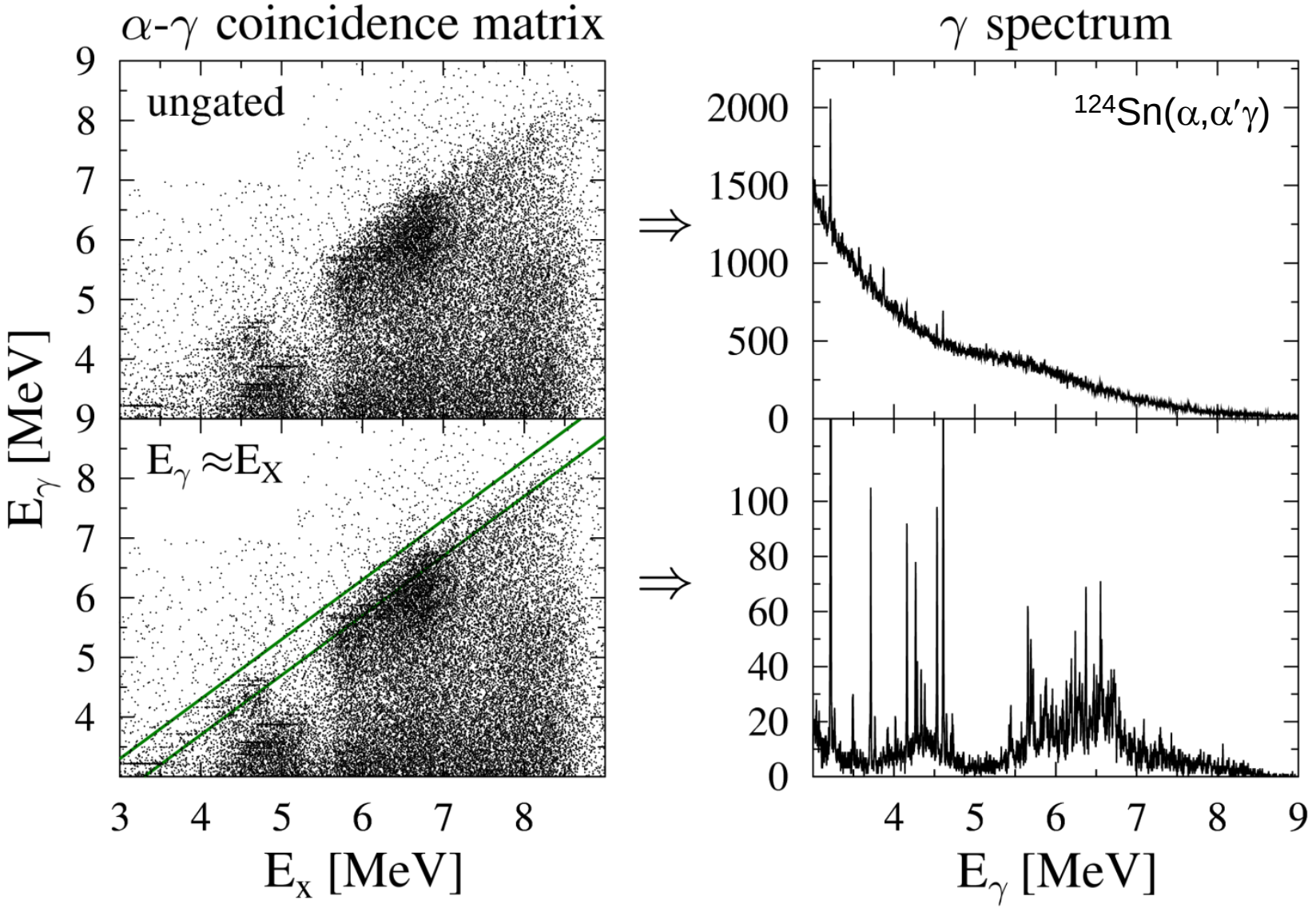




High-resolution HPGe-detector array

D. Savran et al., Nucl. Instr. Meth. A **564** (2006) 267

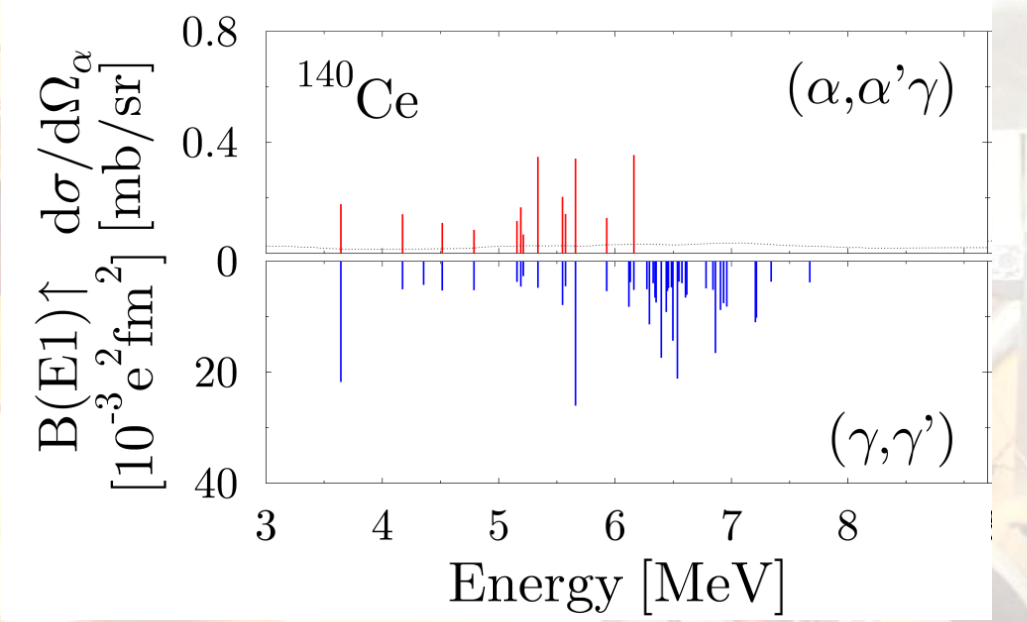
Selectivity to E1 excitations

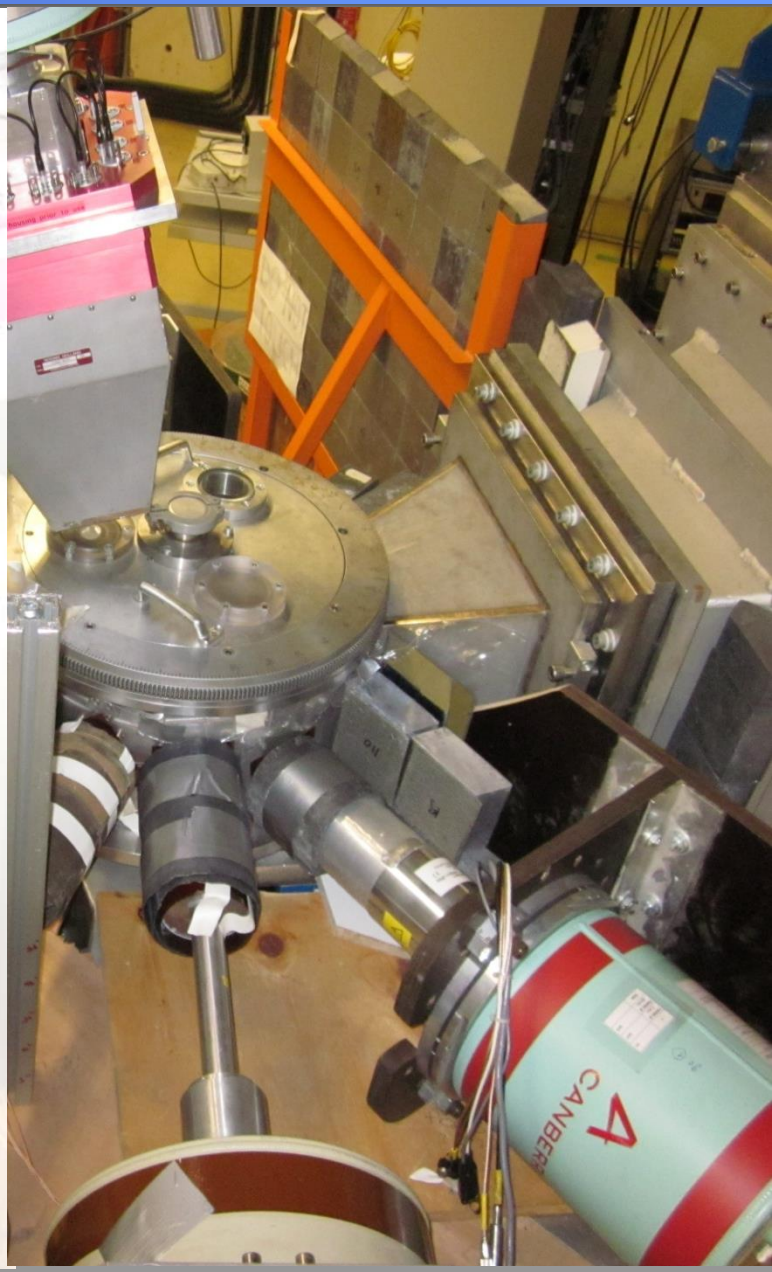


J. Endres et al., Phys. Rev. C **85** (2012) 064331

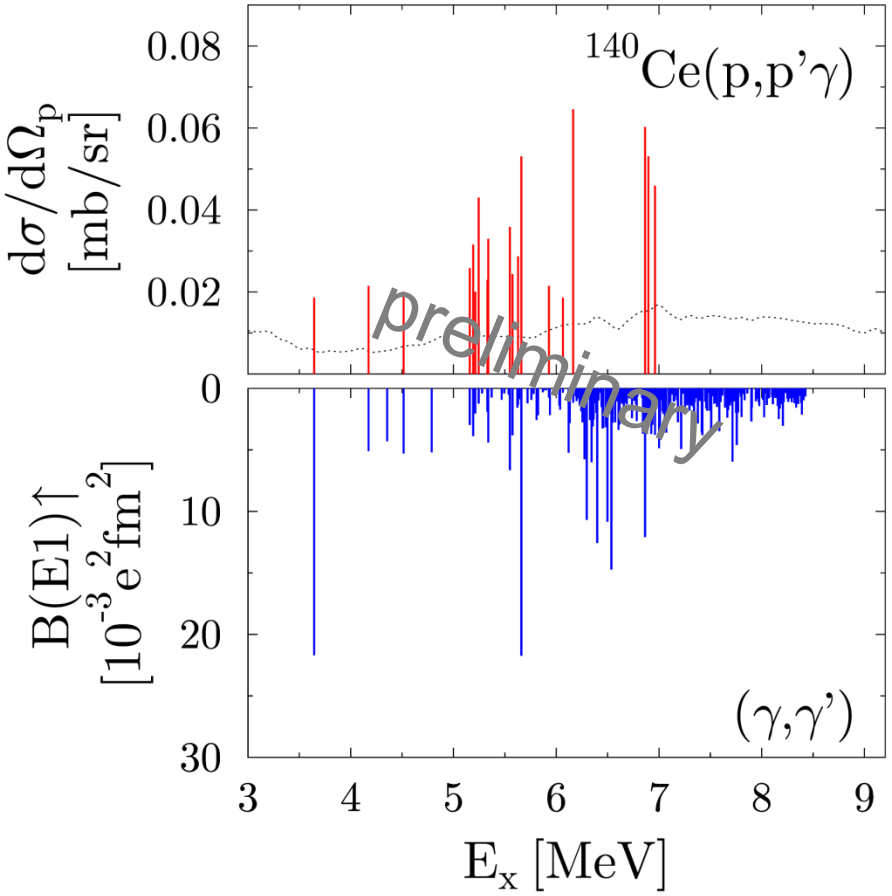
First ^{140}Ce(p,p′γ) experiment

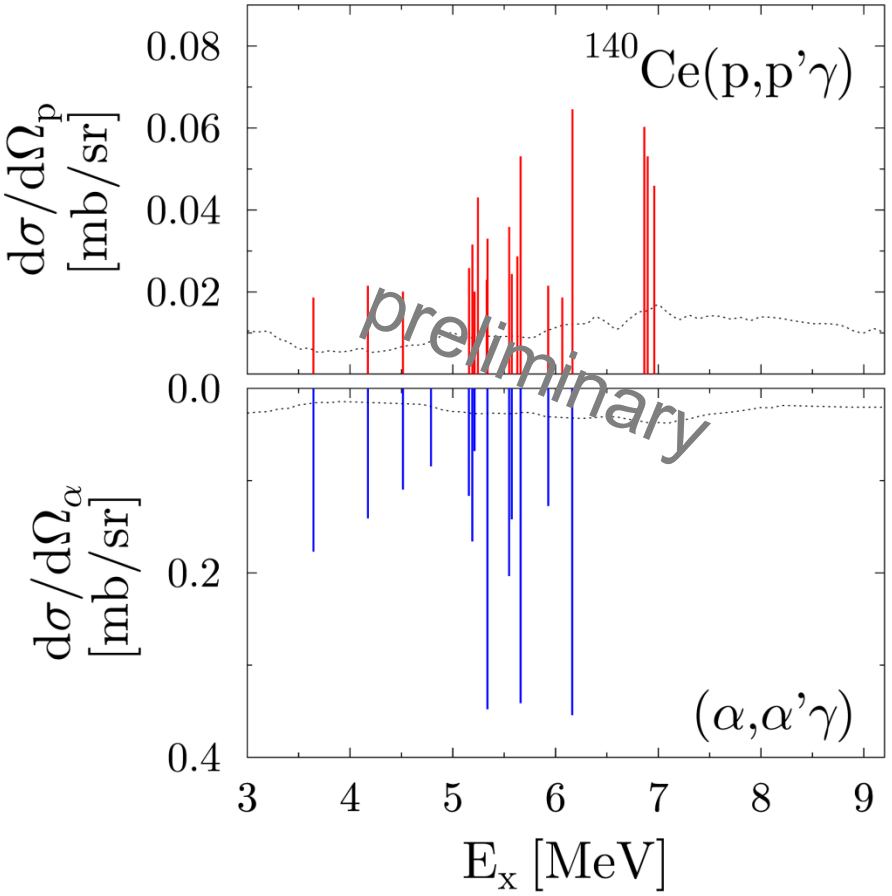
- Performed at KVI
- Beam energy: 80 MeV
- Central BBS angle: 6°
- 8 HPGe detectors
- Target enrichment: 99.72 %





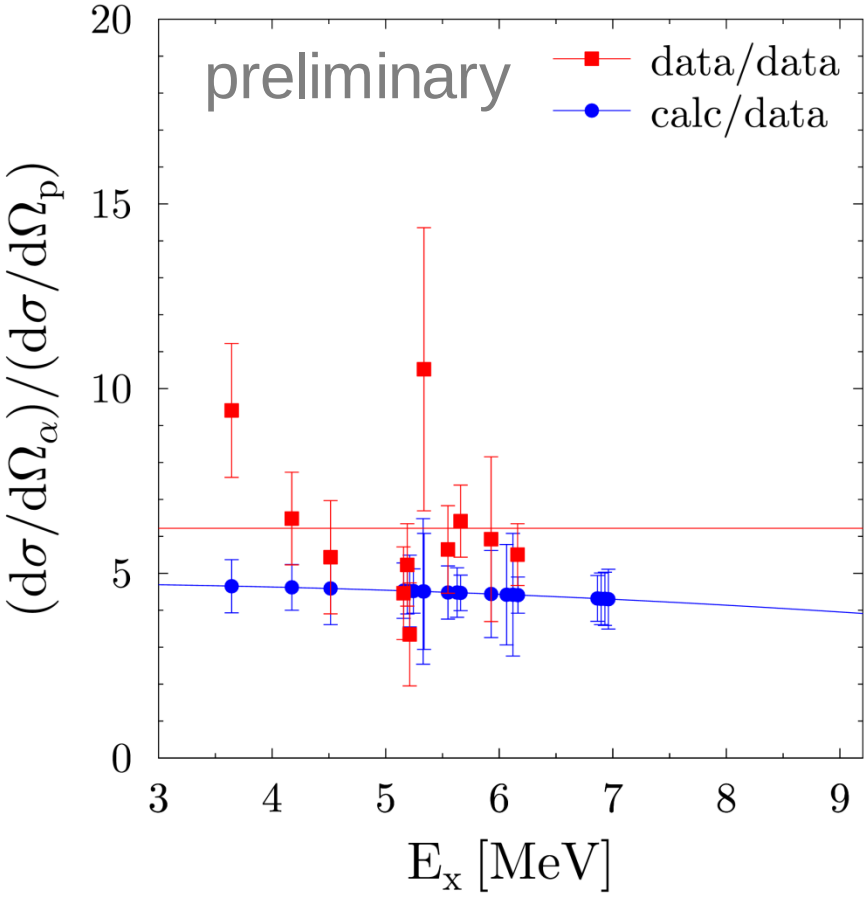
Cross sections for ^{140}Ce(p,p′γ)

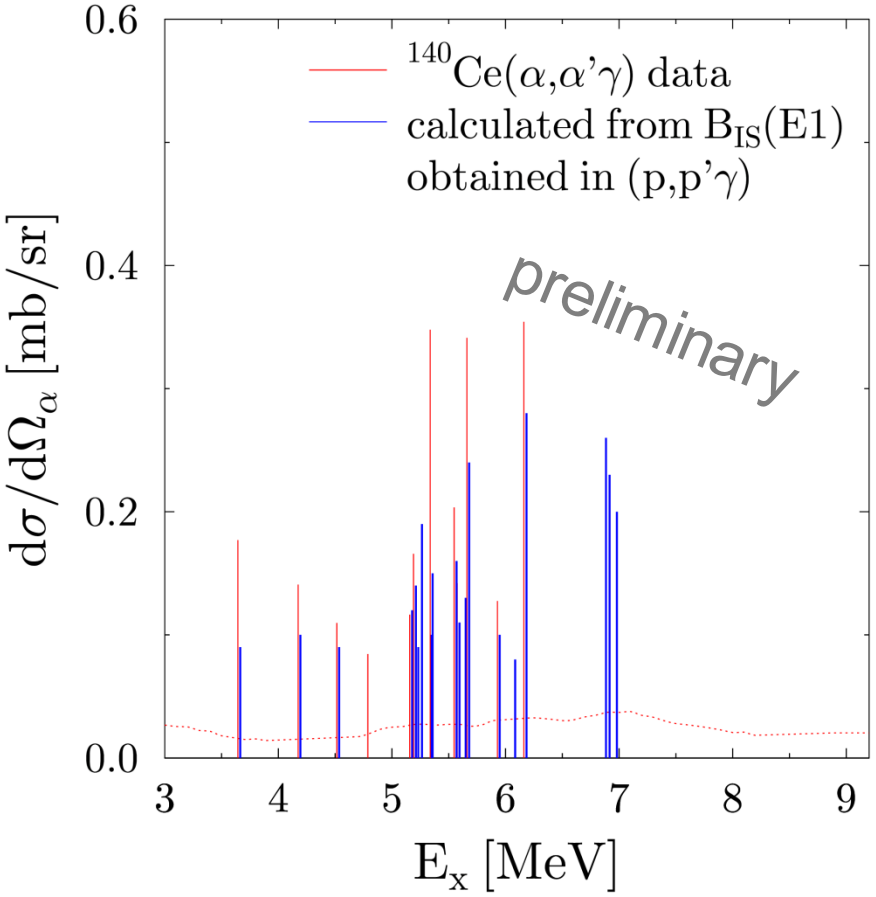




- Order of magnitude smaller cross sections
- General excitation behavior similar

Comparison of ^{140}Ce(α,α′γ) and ^{140}Ce(p,p′γ)





- Ratio of cross sections almost constant
- Fair reproduction with DWBA conversion

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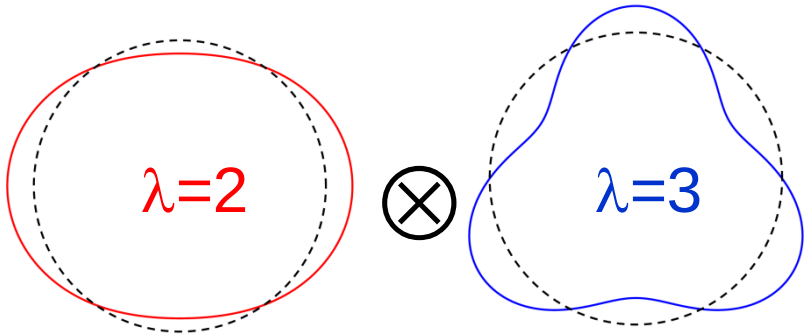
The $(2^+ \otimes 3^-)_{1^-}$ state

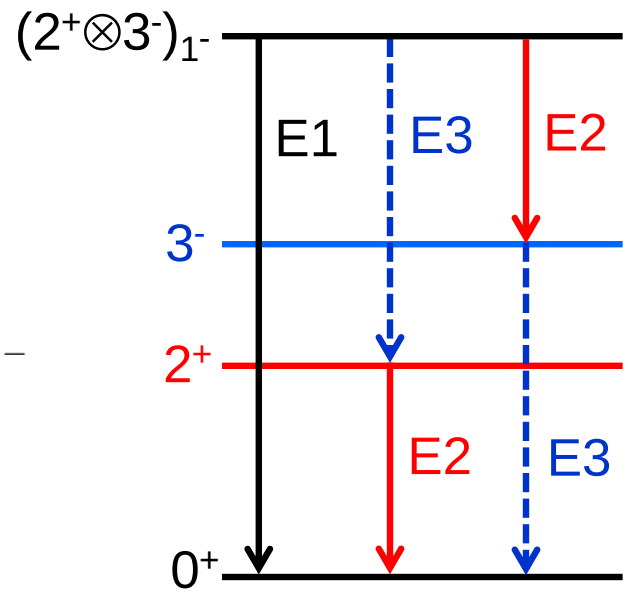
Surface vibrations

$$R(\theta,\phi) = R_0[1 + \sum_{\lambda\mu} a_{\lambda\mu} Y^*_{\lambda\mu}(\theta,\phi)]$$



Sum energy:

$$E_{(2^+ \otimes 3^-)_{J^\pi}} = E_{2^+} + E_{3^-}$$



Decay behavior:

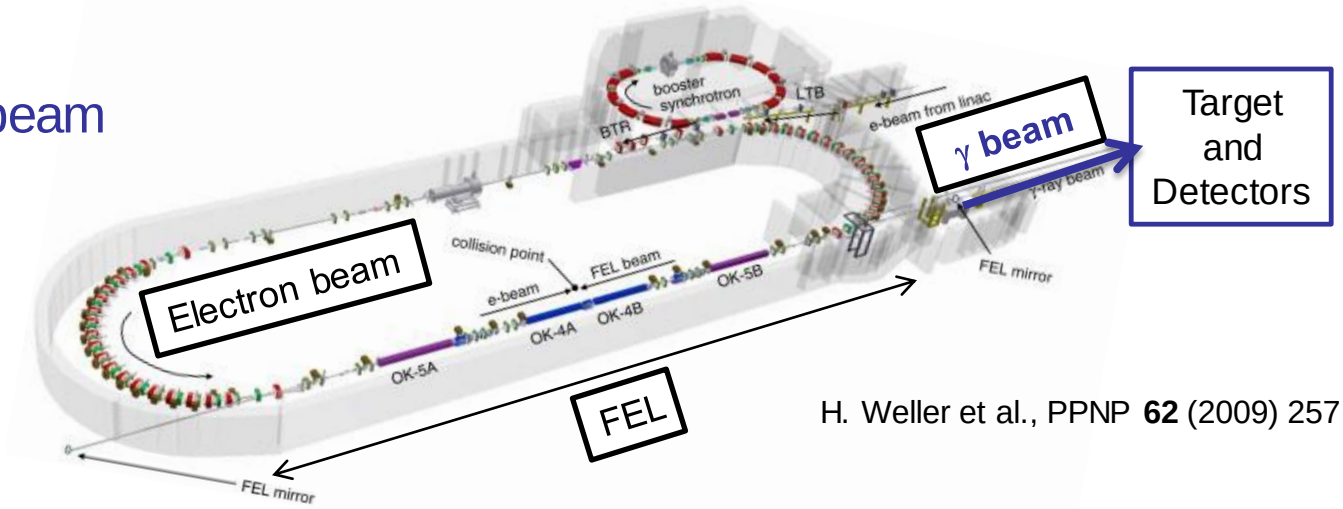
$$\frac{B(E2, 1^- \rightarrow 3^-)}{B(E2, 2^+ \rightarrow 0^+)} = 1$$

$$\frac{B(E3, 1^- \rightarrow 2^+)}{B(E3, 3^- \rightarrow 0^+)} = 1$$

NRF measurements at HIγS

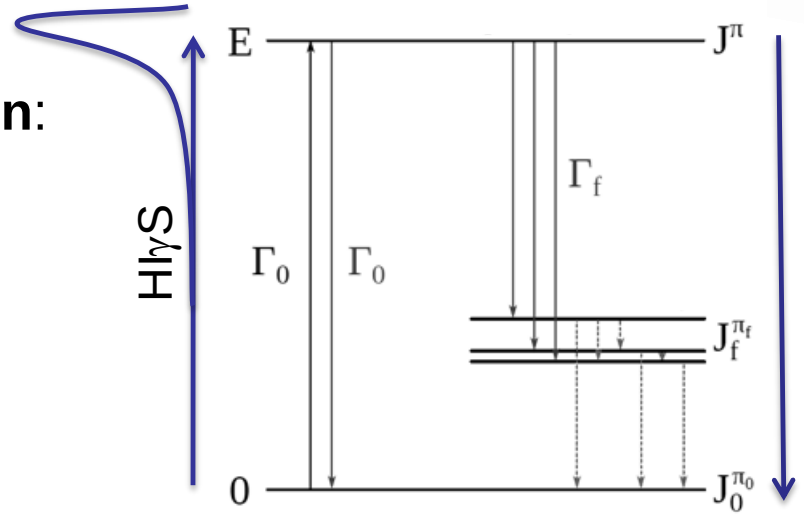
HIγS = High Intensity γ-Ray Source

linearly polarized,
mono-energetic γ beam



H. Weller et al., PPNP **62** (2009) 257

Selective **excitation**:
- Spin J=1
- Energy E_x



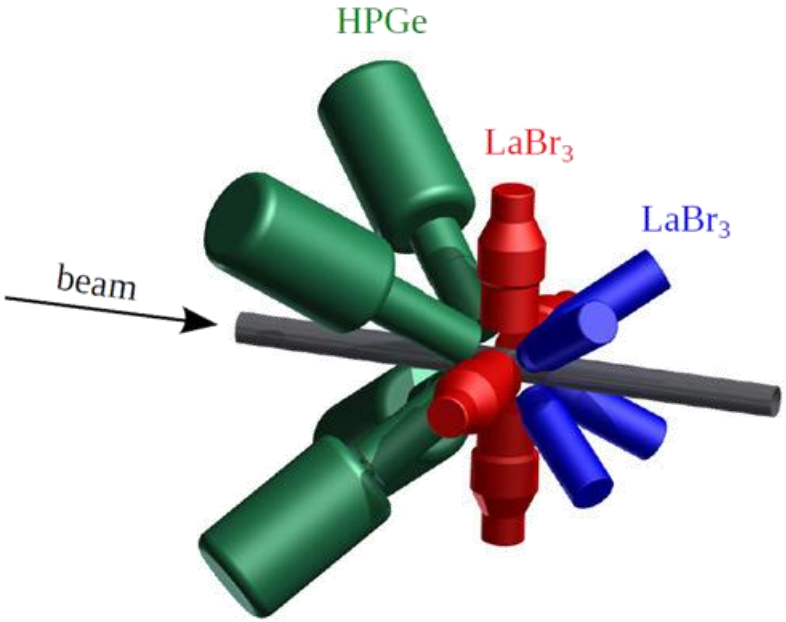
Decays to:
- Ground state
- Excited states

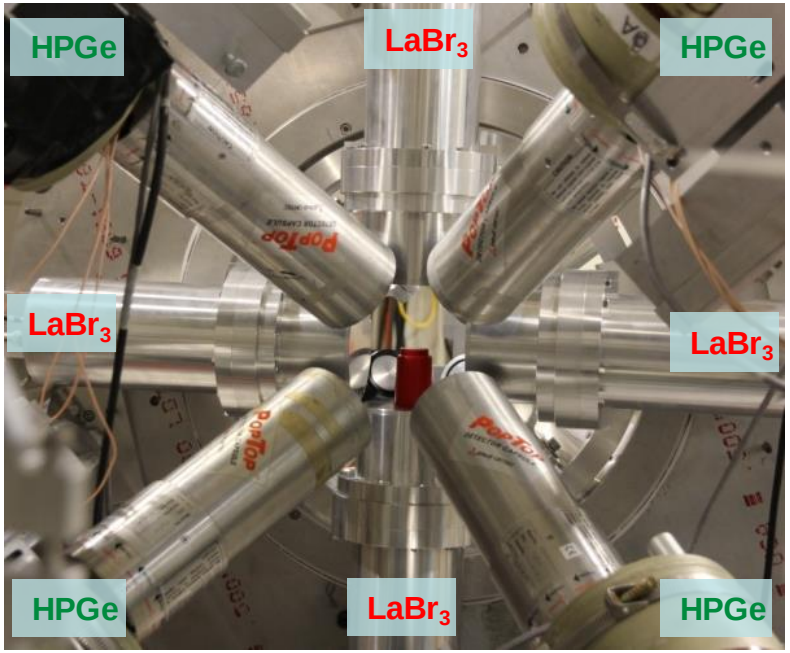
γ-ray detection with the **γ^3 setup**

The high-efficiency $\gamma\gamma$ coincidence setup γ^3

Detector array

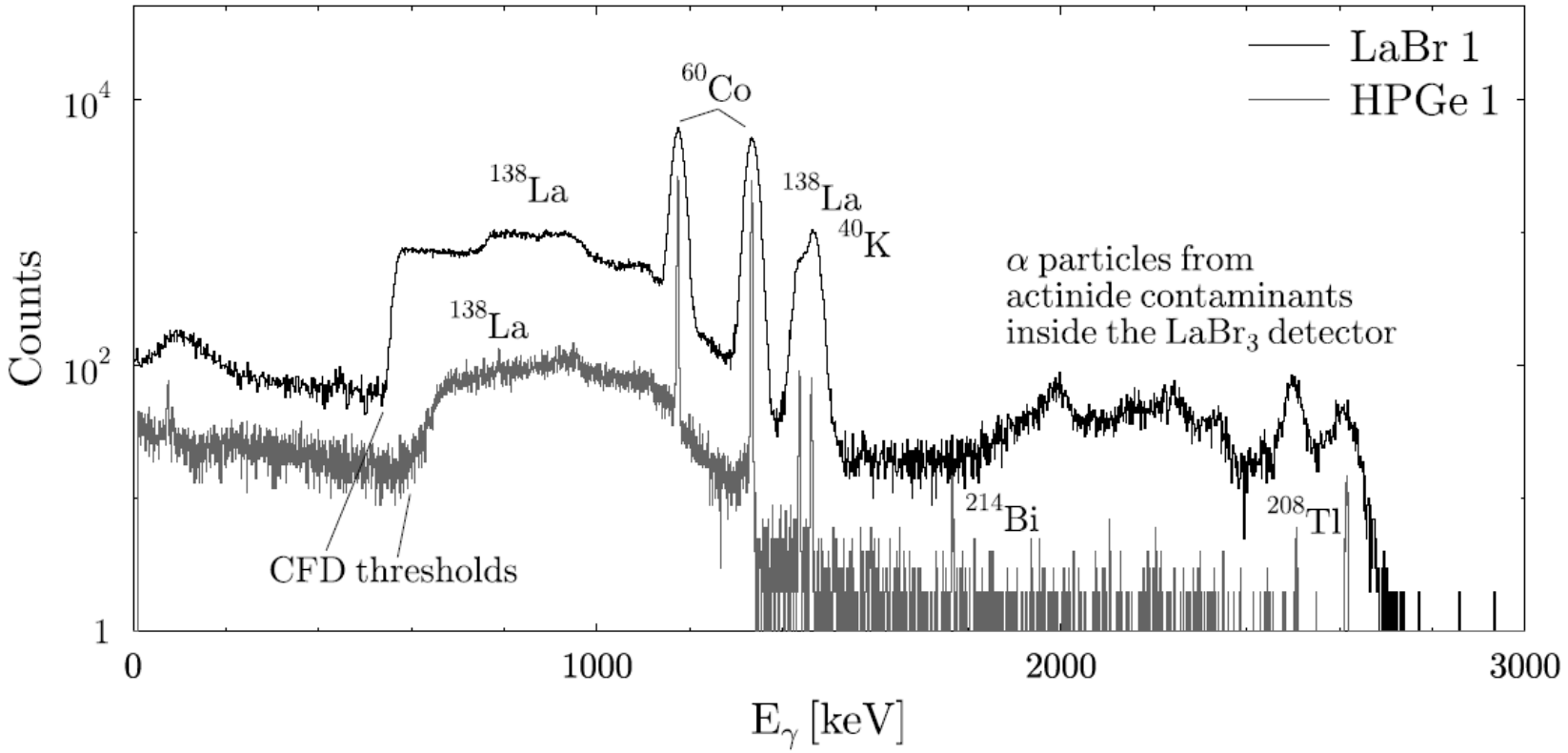
- Four 60% **HPGe** detectors at θ=135°
- Four 3"x3" **$LaBr_3$** detectors at θ=90°
- Efficiency: 1.2% (**HPGe**) + 5.1% (**$LaBr_3$**) at 1.3 MeV
- $\gamma\gamma$ coincidence measurements





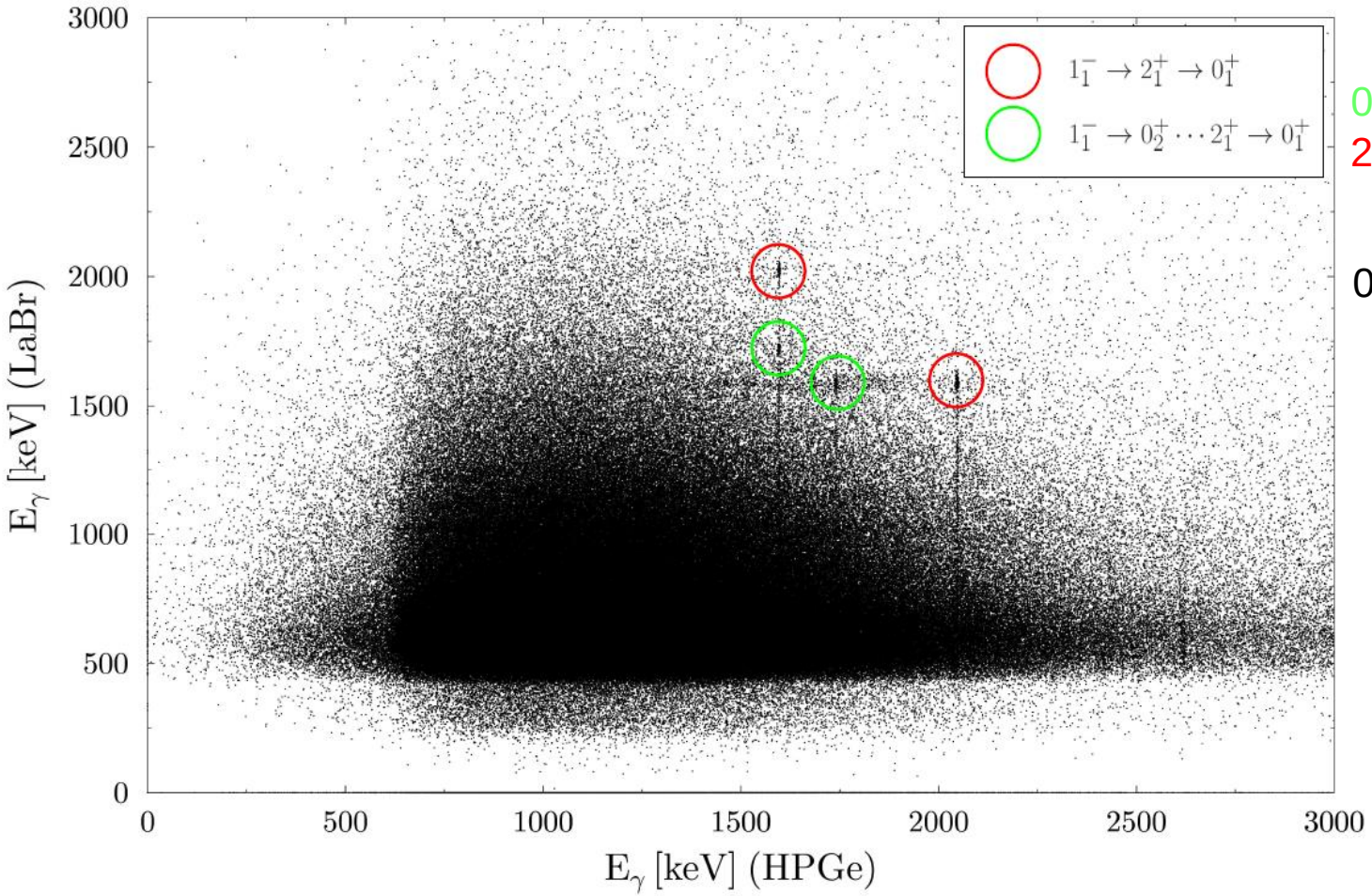
B. Löher, V. Derya et al., Nucl. Instr. Meth. A **723** (2013) 136

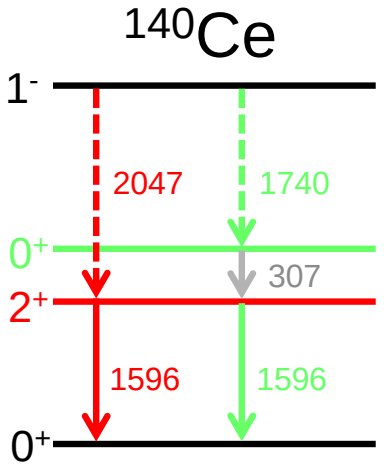
The γ^3 setup – Basic properties



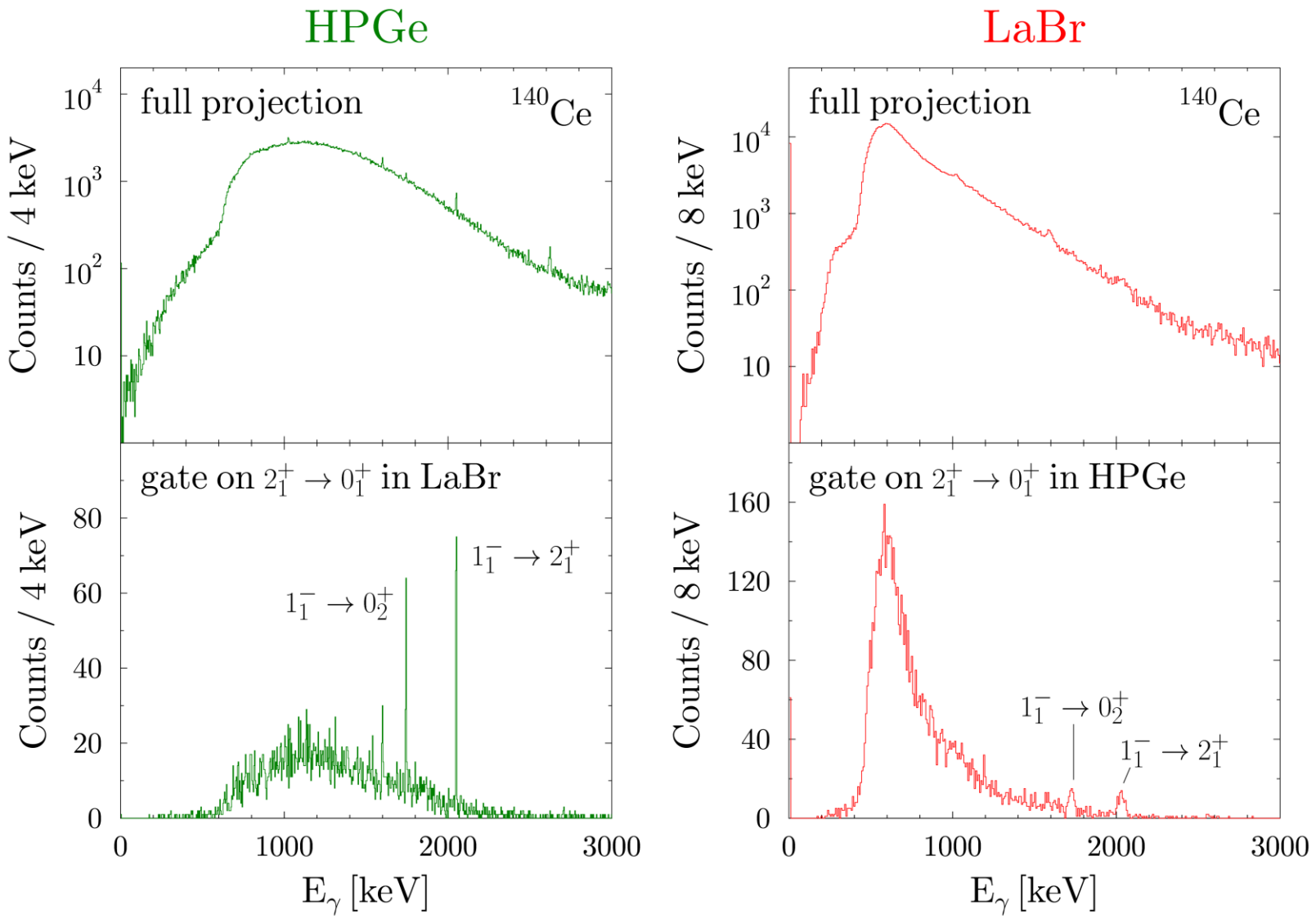
- **$LaBr_3$** → high efficiency
- **HPGe** → excellent energy resolution
- Intrinsic radiation of **$LaBr_3$** → random coincidences, suppressed with beam-pulse condition in analysis

HPGe-$LaBr_3$ coincidence matrix





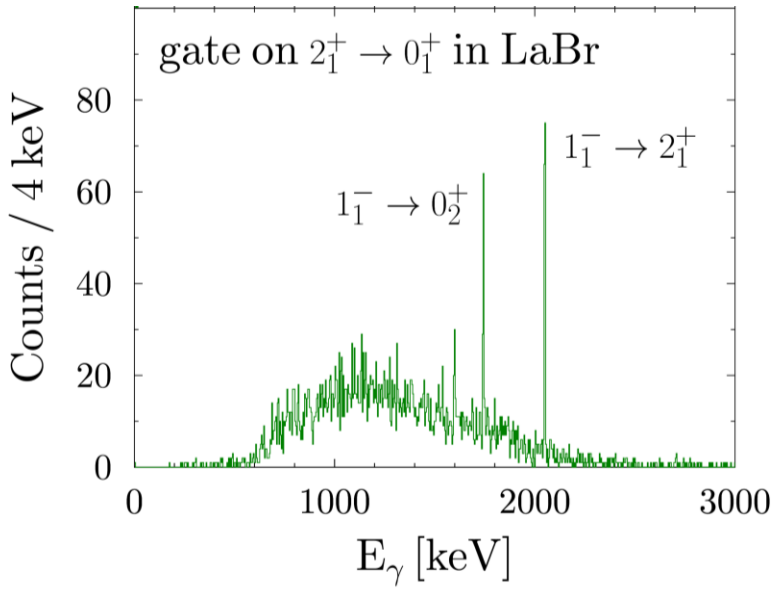
HPGe-$LaBr_3$ coincidence spectra

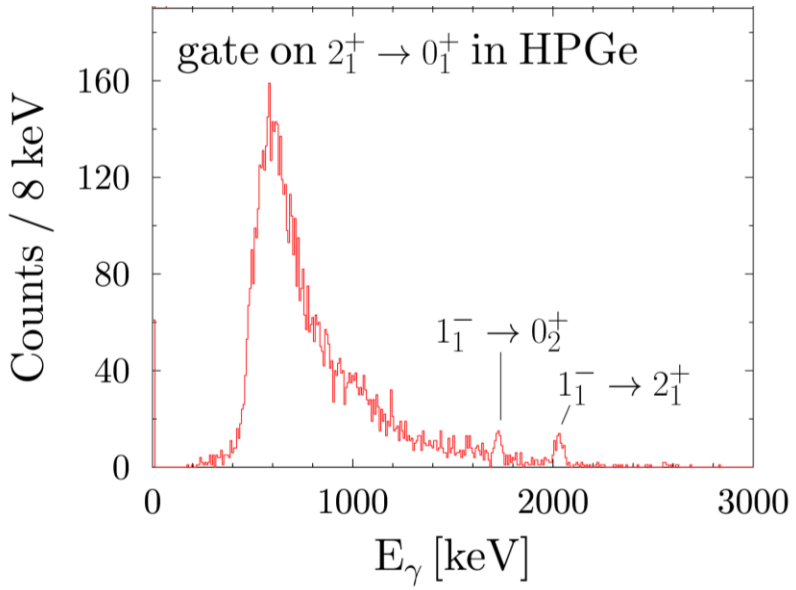


Results for ^{140}Ce

1^- state at 3.6 MeV

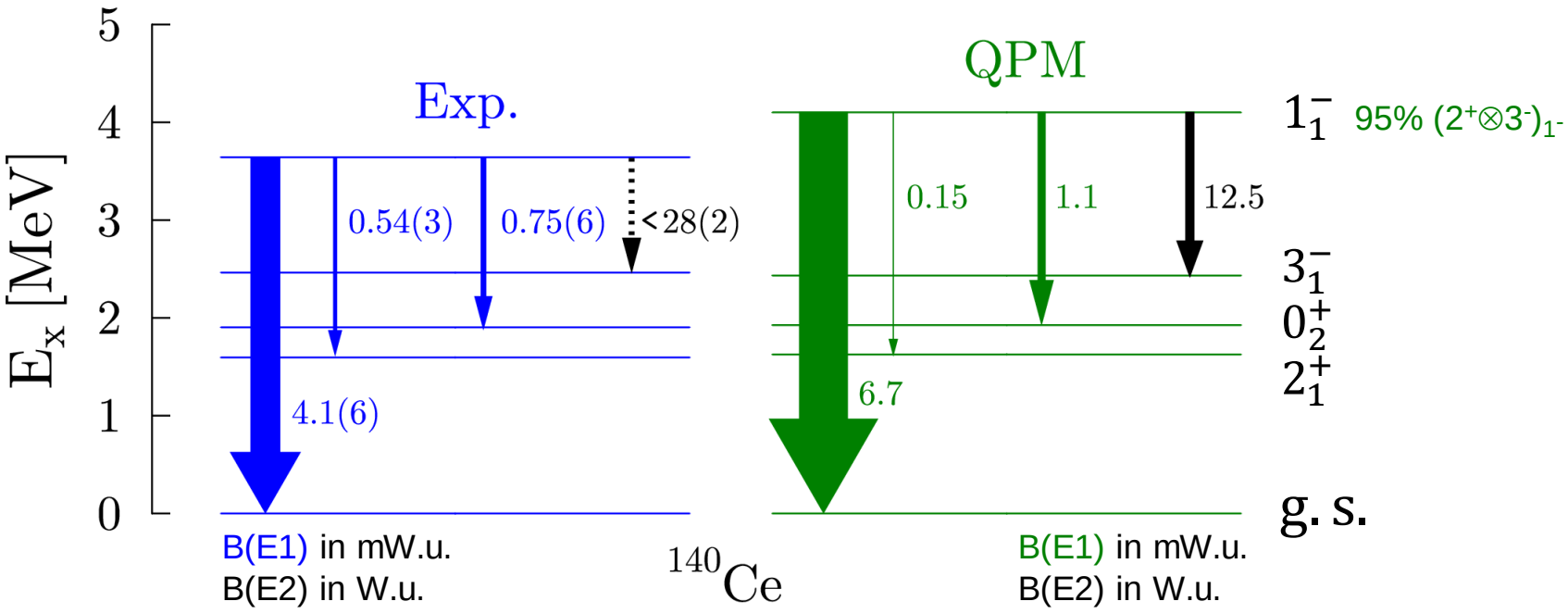
- Directly observed:
  decays into 2_1^+ (E_γ=2047 keV) and 0_2^+ (E_γ=1740 keV)
- Unobserved:
  decay into 3_1^- (E_γ=1179 keV) → upper limit





Results for ^{140}Ce – Comparison with theory

Excitation energies and transition strengths in comparison with QPM calculations[1]

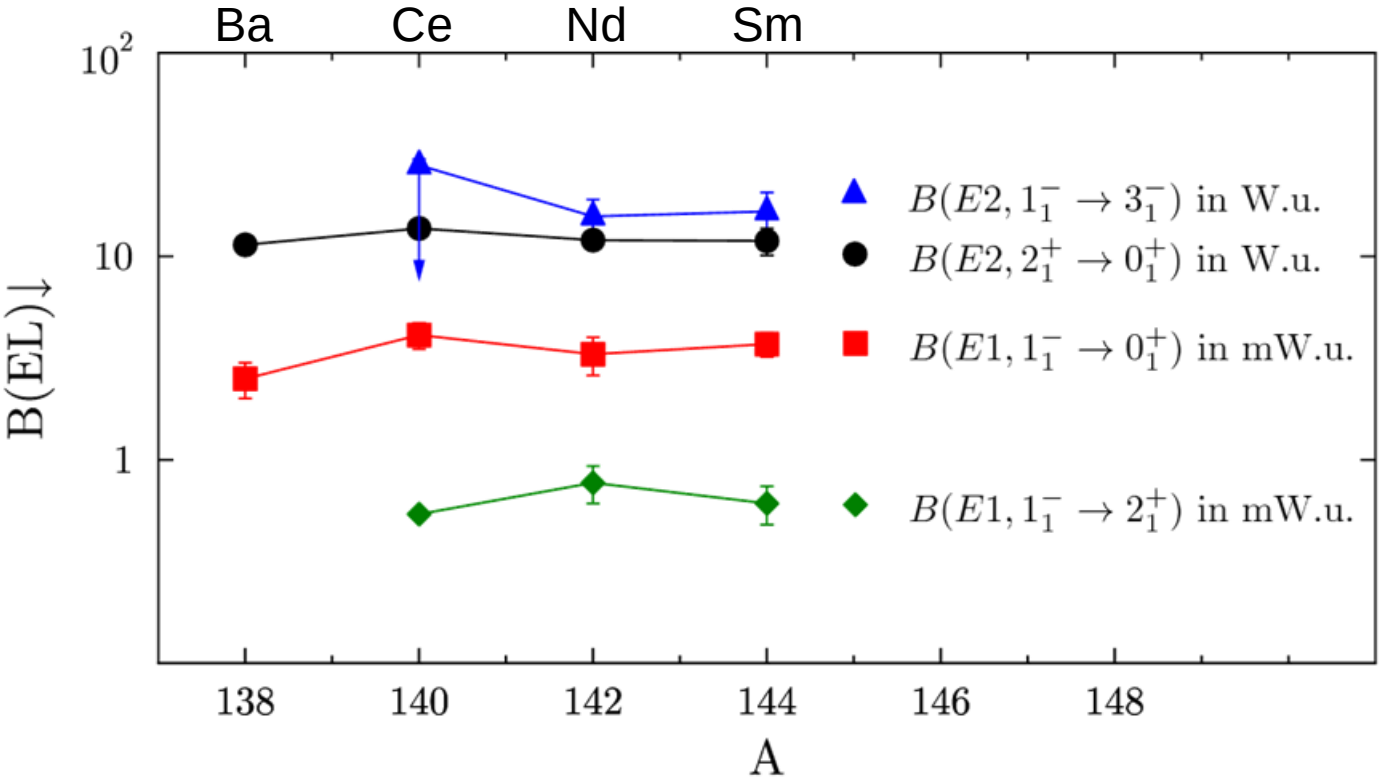


→ Hints to underlying $(2^+\otimes3^-)_{1^-}$ structure

[1] N. Tsoneva, private communication (2015)

Results for ^{140}Ce – Systematics

Transition strengths for possible two-phonon 1$^-$ states in the N=82 isotones



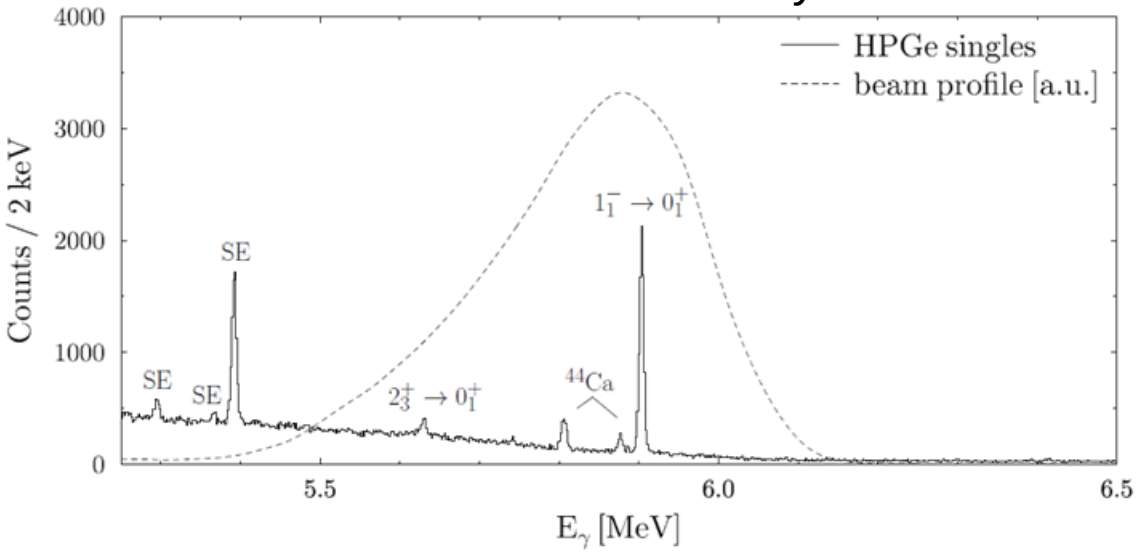
→ Indicates similar structure of the first 1$^-$ state

M. Wilhelm et al., PRC **54** (1996) R449
M. Wilhelm et al., PRC **57** (1998) 577
R.-D. Herzberg et al., NPA **592** (1995) 211
A. Barfield et al., ZPA **332** (1989) 29
T. Belgya et al., PRC **52** (1995) R2314

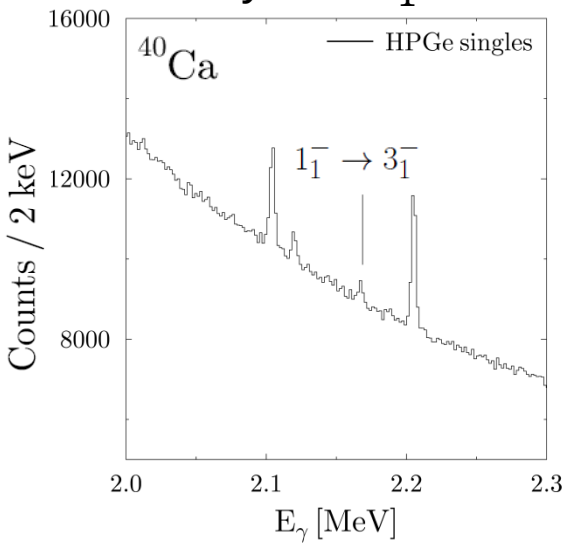
Results for ^{40}Ca

1$^-$ state at 5.9 MeV

Ground-state decay



Decay into 3_1^- state



- Transition strength: $B(E2, 1_1^- \to 3_1^-) = 34(10)\mathrm{e}^2\mathrm{fm}^4$ [a]
- Known: $B(E2, 2_1^+ \to 0_1^+) = 26.7(15)\mathrm{e}^2\mathrm{fm}^4$ [b]

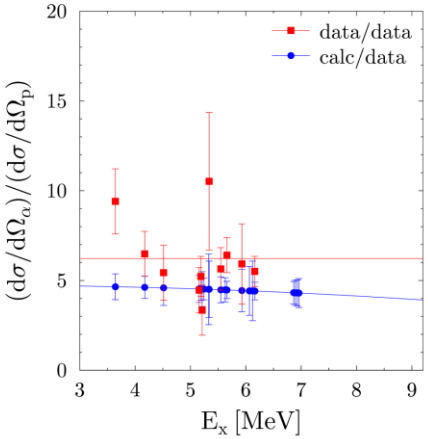
→ Supports $(2^+ \otimes 3^-)_{1^-}$ character within harmonic model

[a] V. Derya, PhD thesis (2014), Univ. of Cologne
[b] Adopted averaged value from
T. Hartmann et al., Phys. Rev. C 65 (2002) 034301

Summary

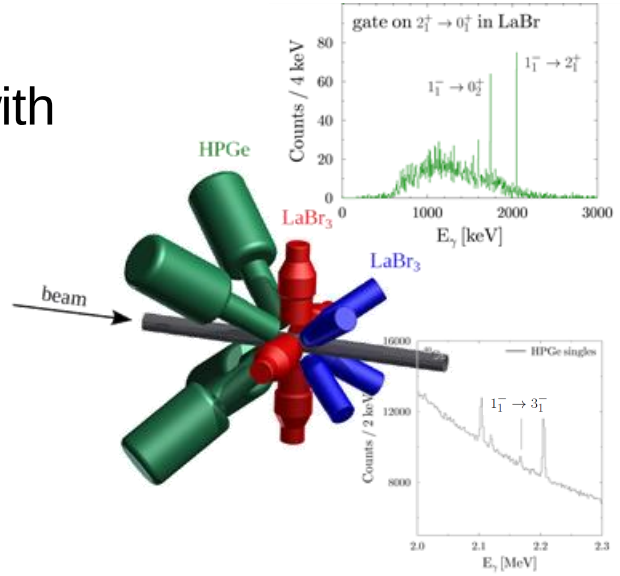
The PDR in ^{140}Ce

- **Comparison of different approaches** yield important observables to understand the underlying structure of the E1 strength
- First results of ^{140}Ce(p,p′γ) show smaller cross sections, but **similar excitation pattern** for the proton probe



The $(2^+ \otimes 3^-)_{1^-}$ state in ^{40}Ca and ^{140}Ce

- **^{140}Ce**: limit and observed decays consistent with two-phonon character (systematics and QPM calculations)
- **^{40}Ca**: observed decay supports two-phonon character



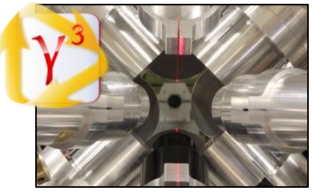
Outlook

Character of PDR in light, deformed, exotic nuclei?

- RIKEN: $(\alpha,\alpha'\gamma)$ experiments in inverse kinematics on radioactive and stable nuclei
- iThemba LABS and CAGRA@RCNP: $(\alpha,\alpha'\gamma)$ and $(p,p'\gamma)$ experiments on stable nuclei

Decay behavior of low-lying E1 excitations?

- γ^3@HIγS: $\gamma\gamma$ coincidence experiments
- In the future: ELIADE@ELI-NP



- SONIC@HORUS in Cologne: particle-γ coincidence experiments