

Decay of the PDR in ^{140}Ce . First results from the γ^3 coincidence setup at HIyS



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 H.Scheit⁵, J.Silva^{1,2}, A.Tonchev⁷, W.Tornow⁴,
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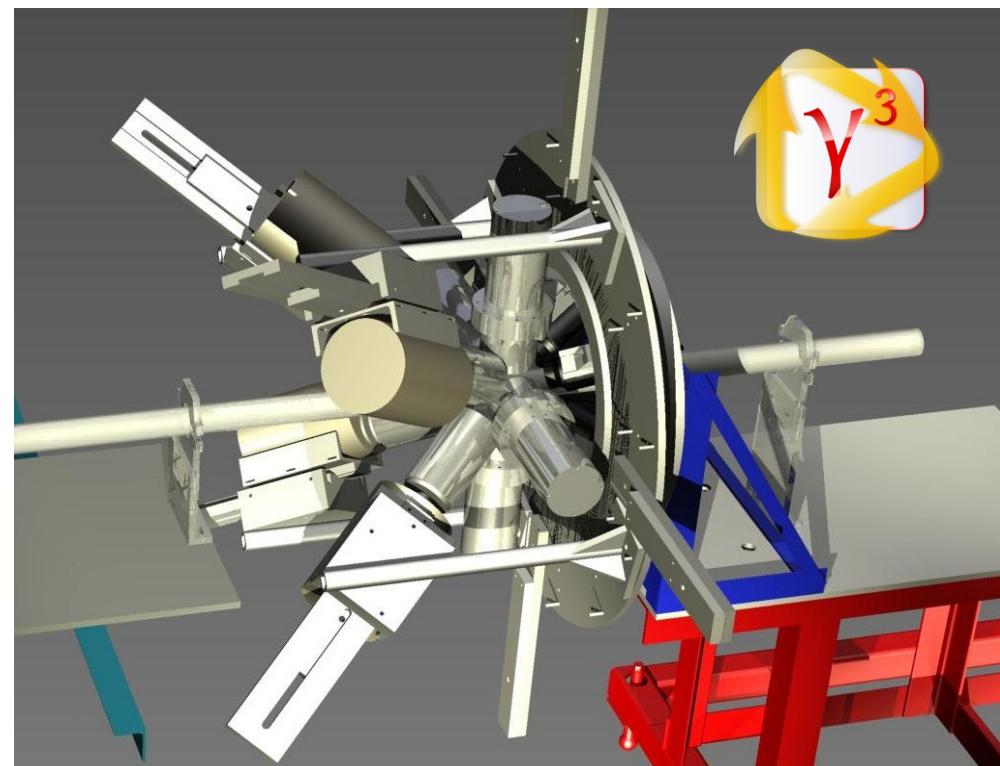
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⁶WNSL, Yale University, USA

⁷Lawrence Livermore National Lab, Livermore, CA, USA

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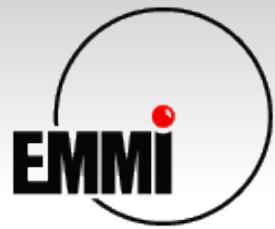


Motivation

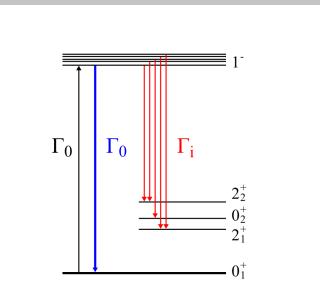
New experimental possibilities at γ^3 to study decay patterns of photo-excited states

- Study of the Pygmy Dipole Resonance
- Deeper Investigation of the Scissors Mode
- Two phonon excitations in light and heavy nuclei

Motivation



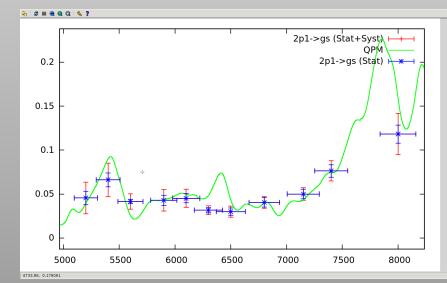
Introduction



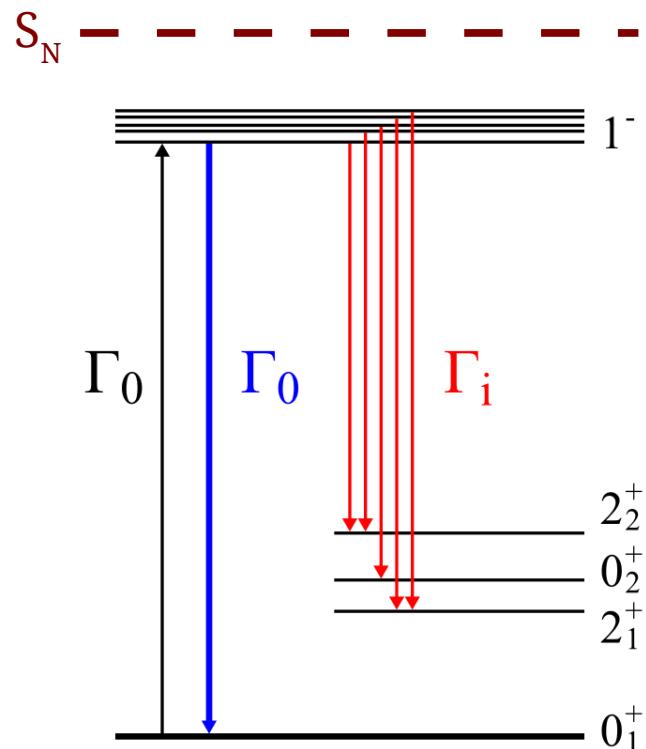
Experiment



Results



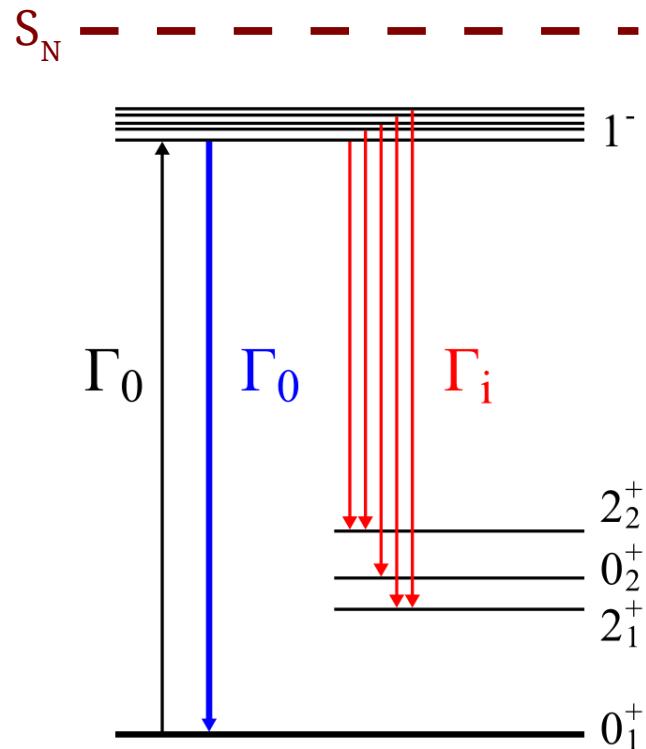
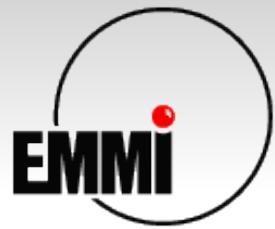
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- Decay „elastic“ (Γ_0) or „inelastic“ (Γ_i)
- Elastic channel dominant: ($\Gamma_0 \gg \Gamma_i$)

Nuclear Resonance Fluorescence (NRF)

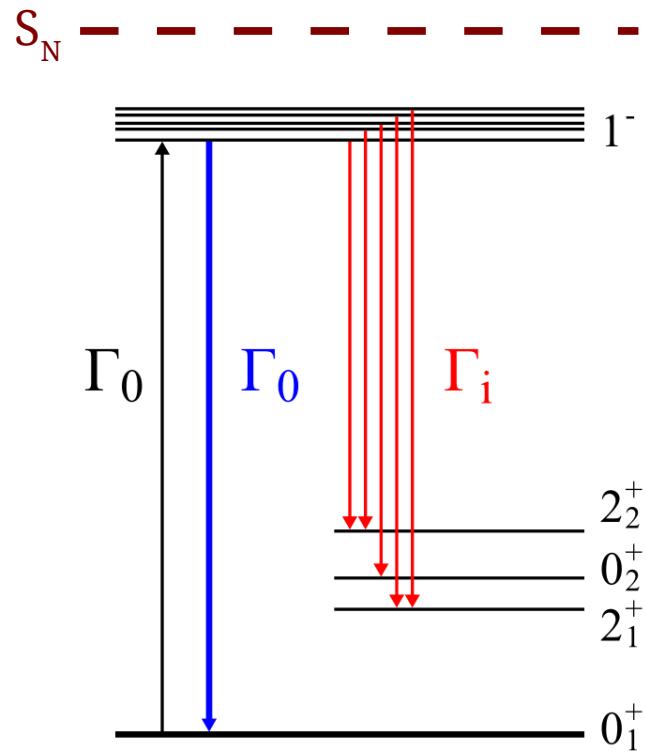
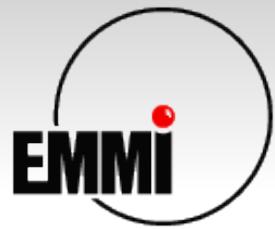
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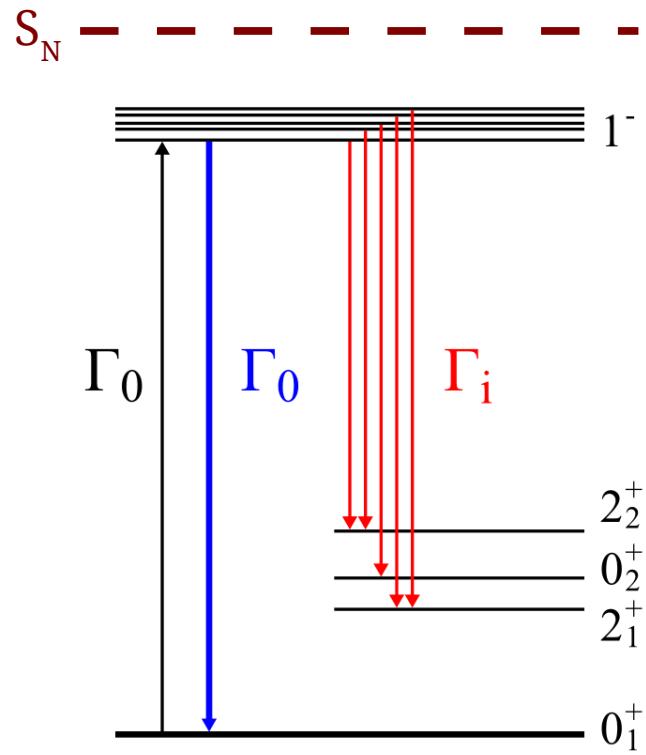
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- BUT: $\Gamma_0 \gg \sum_i \Gamma_i$?

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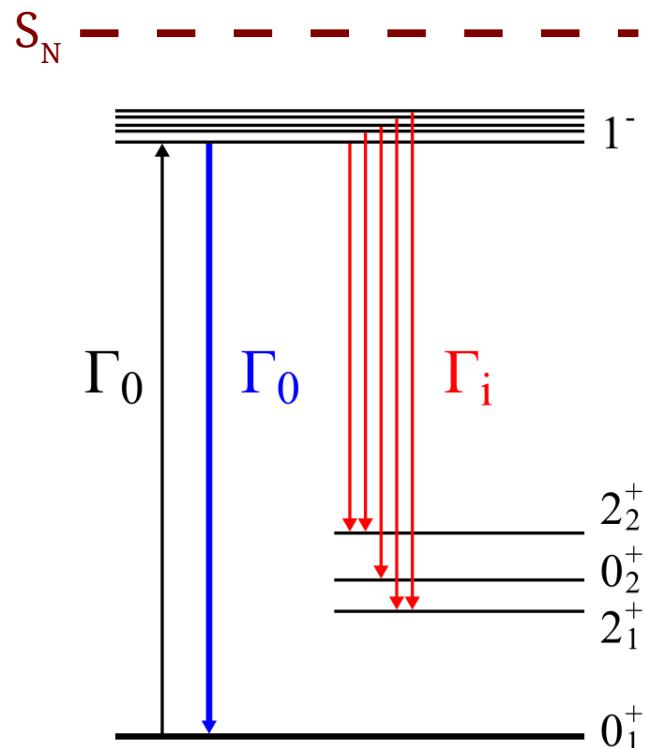
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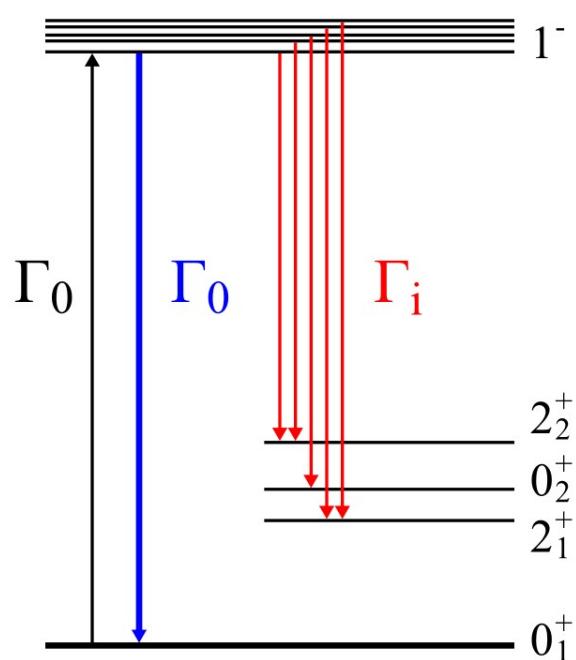
Experimental Method



Determine Decay Pattern,
and directly measure Γ_i

Challenge:
Measure small branching ratios

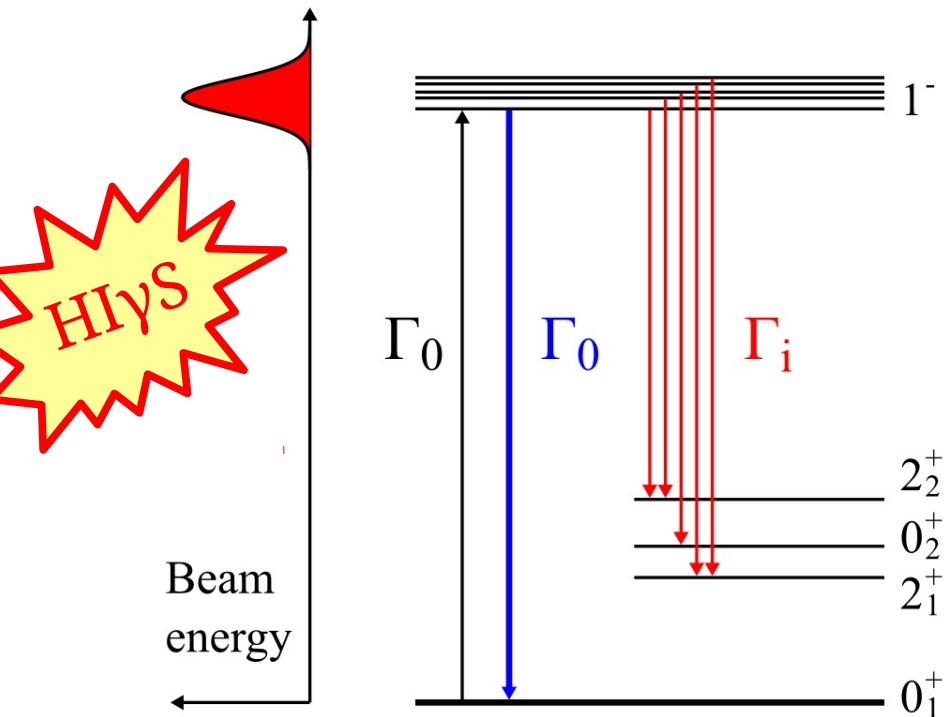
Experimental Method



Use:

- Selectivity of NRF reaction
→ Populate mostly $J=1$ states

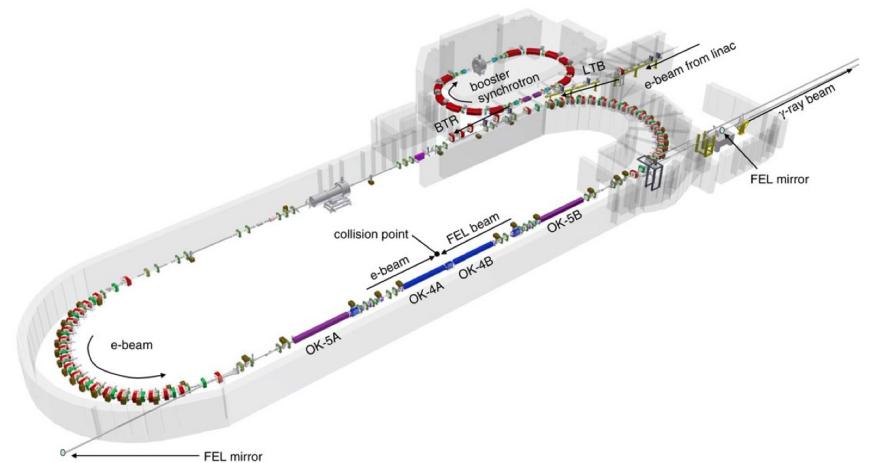
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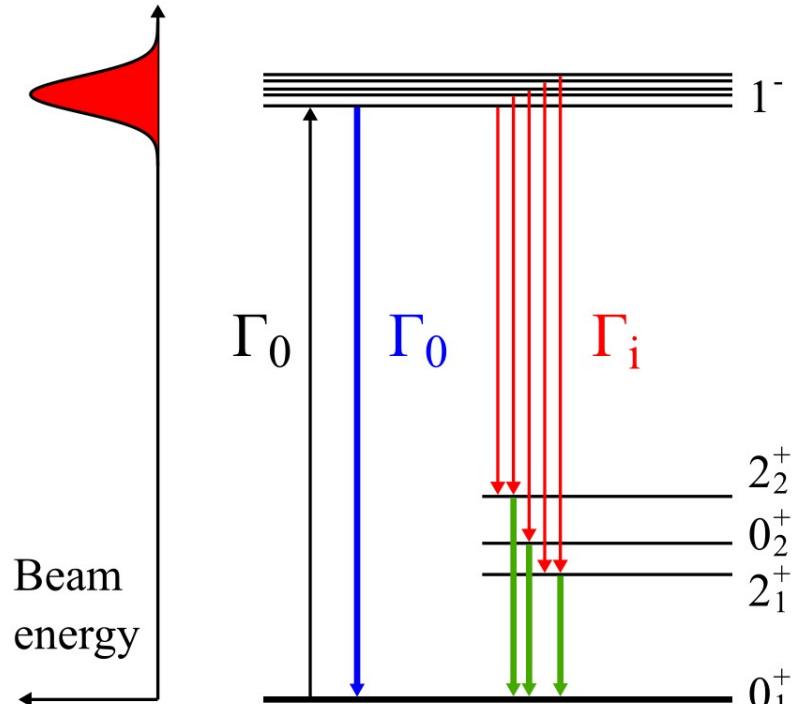
Weller et al., Prog. Part. Nucl. Phys. 62 (2009) 257

Use:

- Selectivity of NRF reaction
→ **Populate mostly $J=1$ states**
- and **mono-energetic beam**
→ **Narrow energy range**



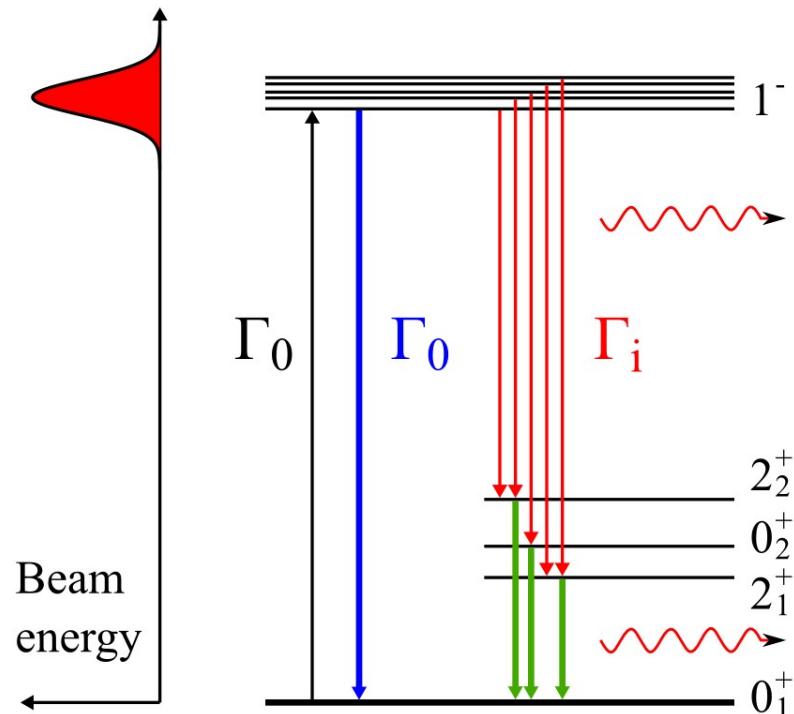
Experimental Method



Use:

- Selectivity of NRF reaction
→ **Populate mostly $J=1$ states**
- and mono-energetic beam
→ **Narrow energy range**
- **Sensitivity of γ - γ coincidence method**
- **Select low energy decay**
- **Identify primary transitions**

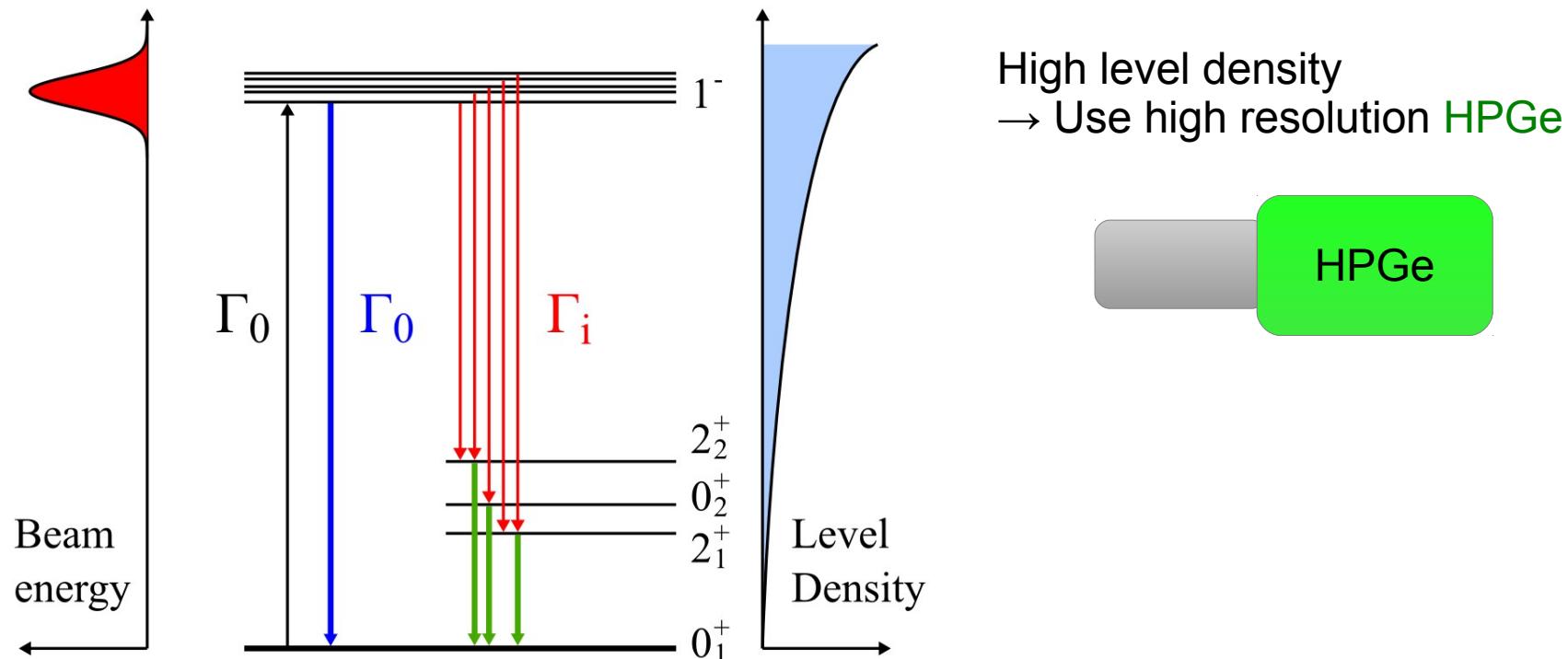
The γ^3 setup



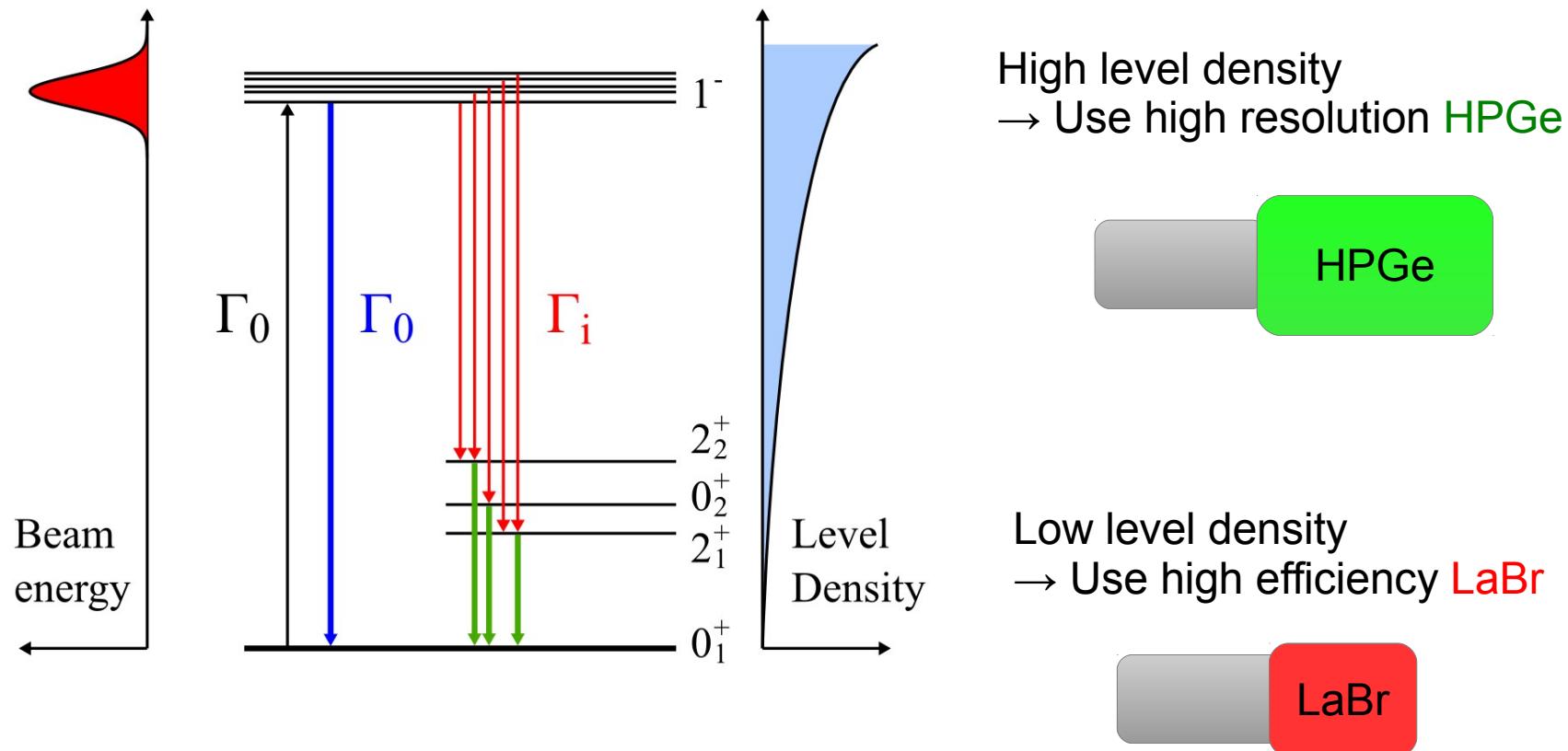
Detect **two photons** in coincidence
→ **High photo peak efficiency**



The γ^3 setup

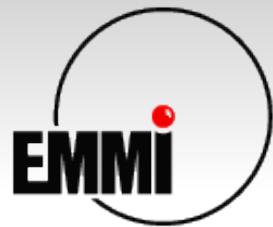


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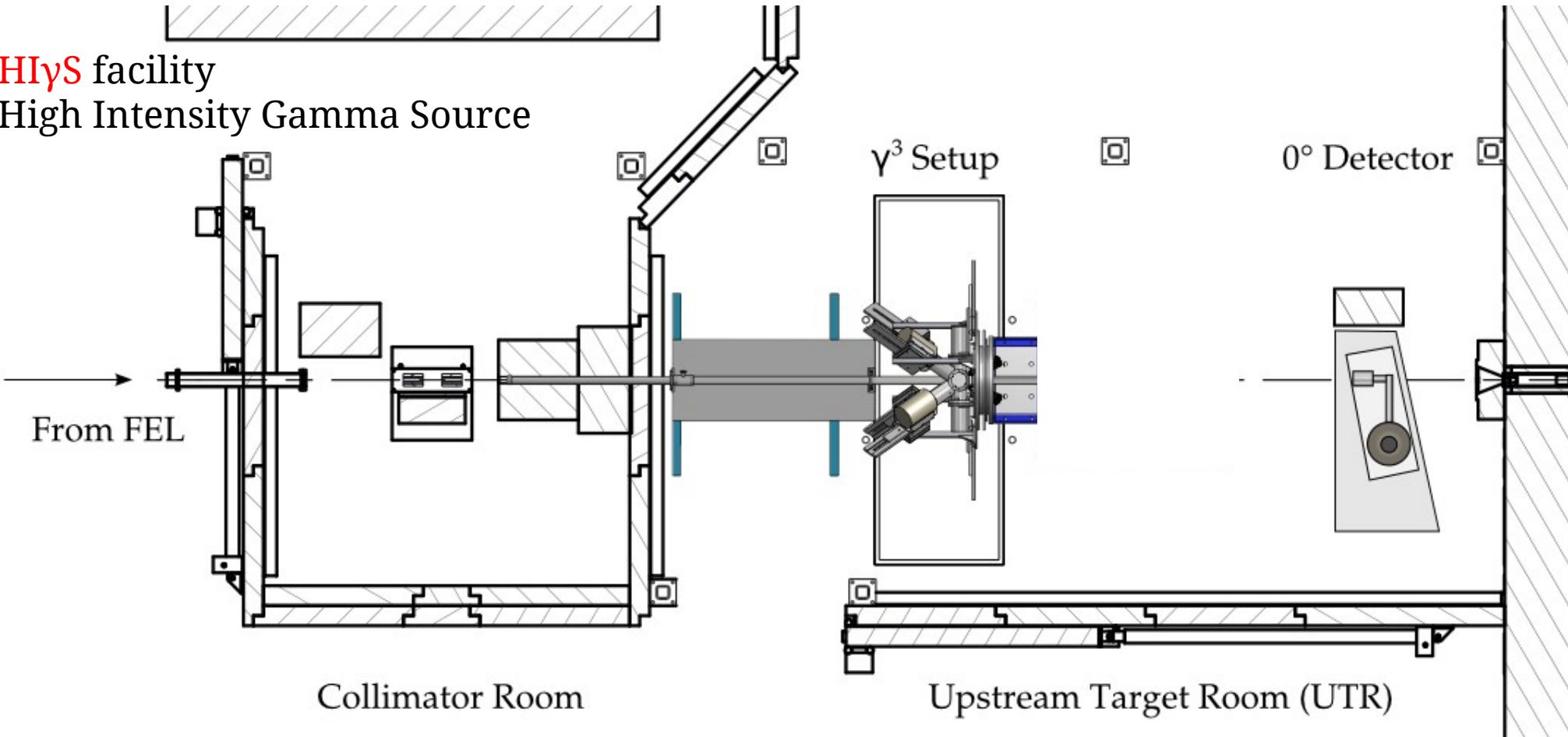


- Combine **HPGe** with **LaBr** detectors

The γ^3 setup

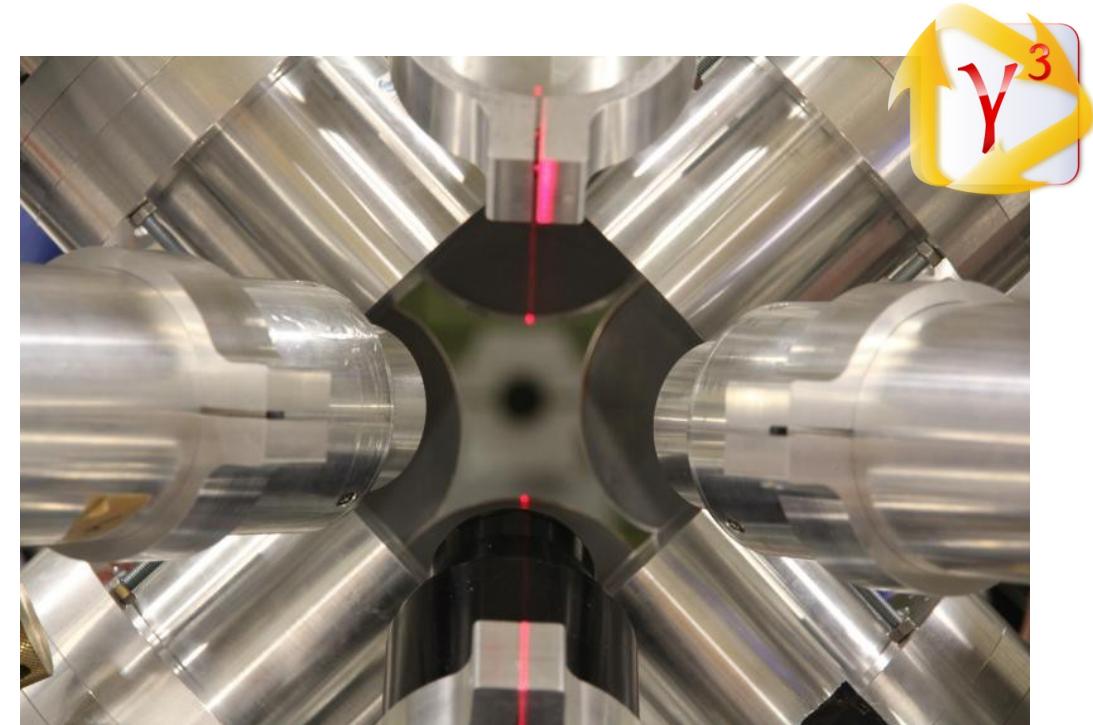
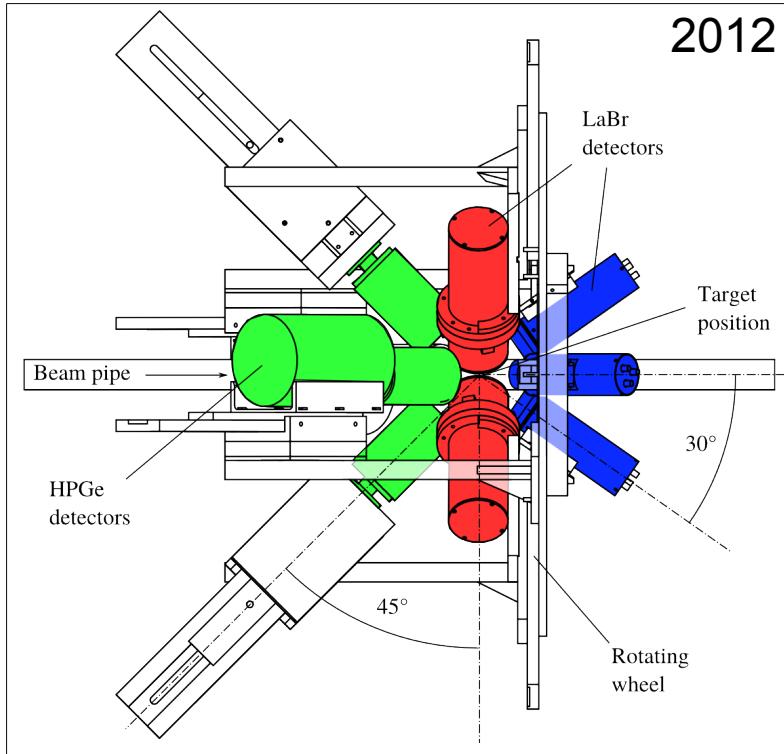


HI γ S facility
High Intensity Gamma Source





The γ^3 setup



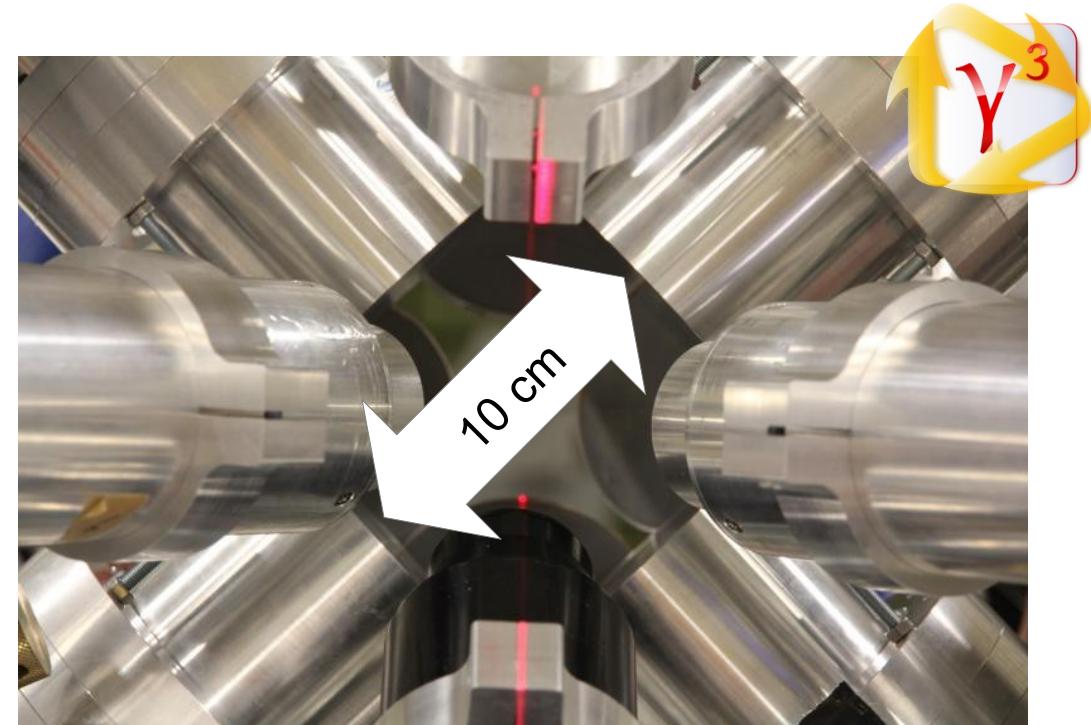
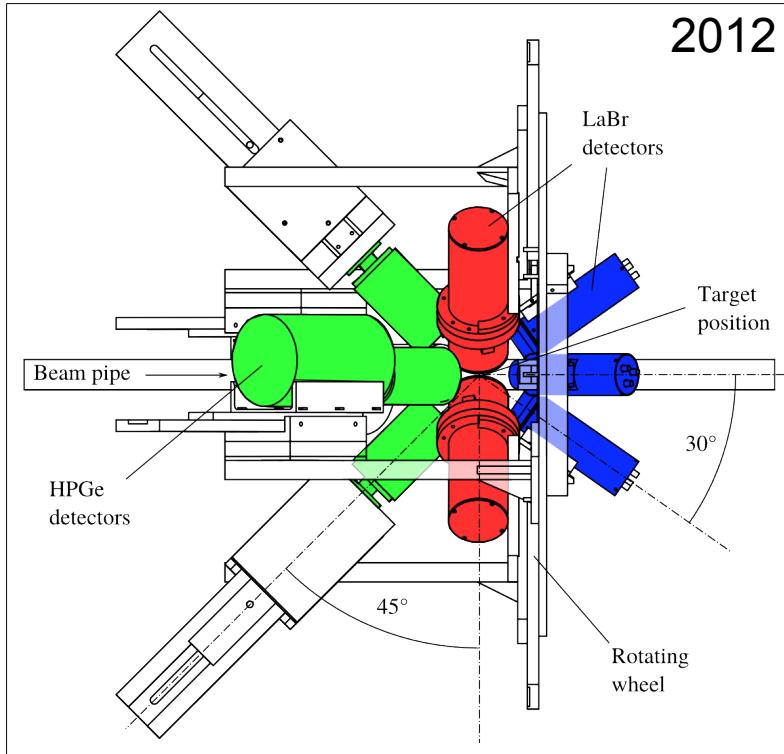
B. Löher et al., Nucl. Instruments Methods Phys. Res. Sect. A **723**, 136–142 (2013).

New detector array at HI γ S

- 4 high resolution **HPGe** detectors
- 7 high efficiency **LaBr** detectors



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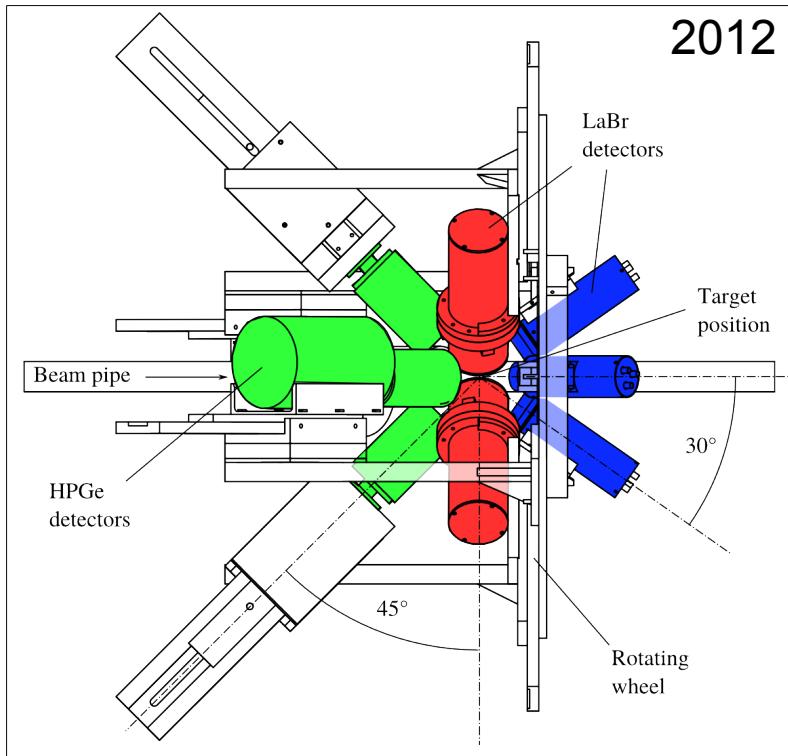


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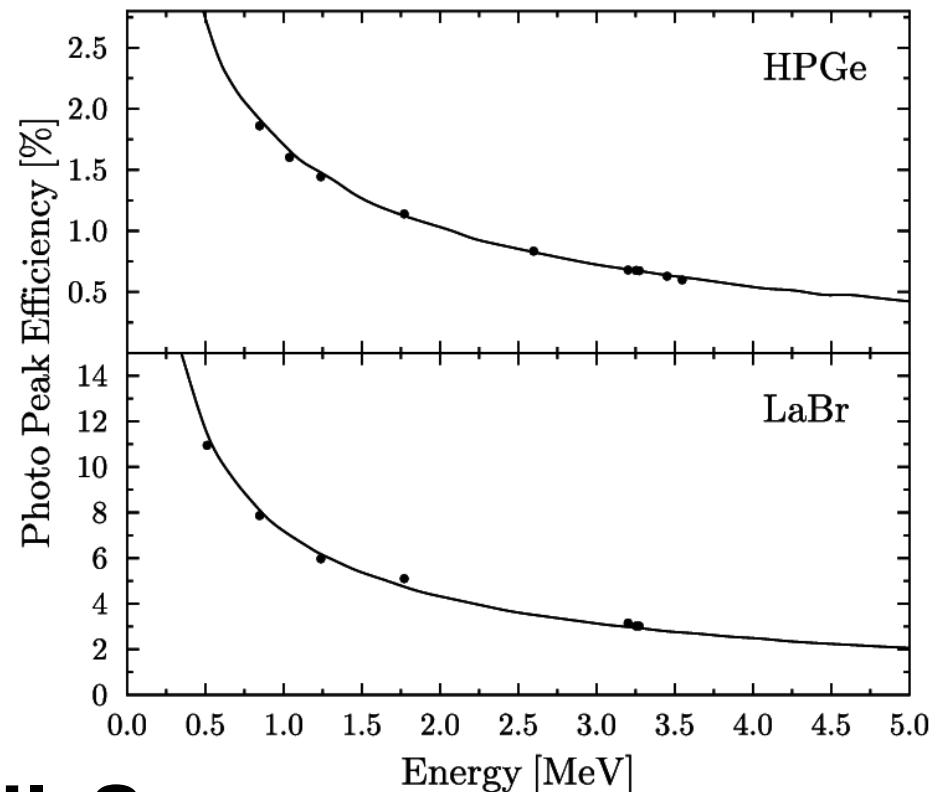
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The γ^3 setup



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New detector array at H1 γ S

- Total efficiency: >7% @ 1.3 MeV (LaBr+HPGe)



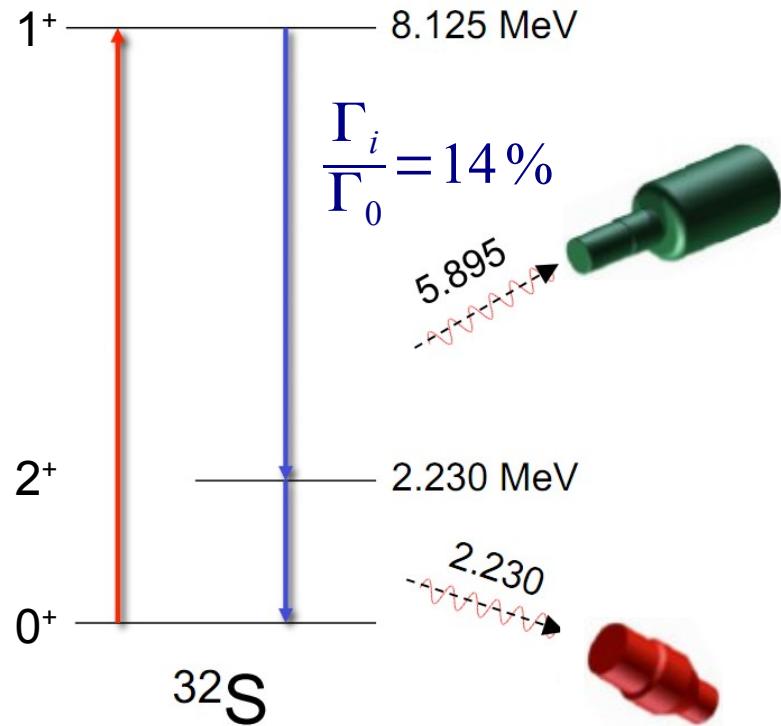
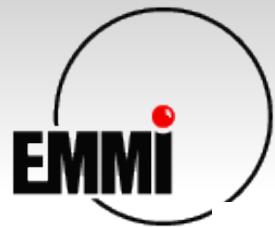
Experiments

Experiment



- Commissioning phase 2012 (^{32}S)
- Experimental Campaign 2012
- Experimental Campaign 2013

Setup Commissioning

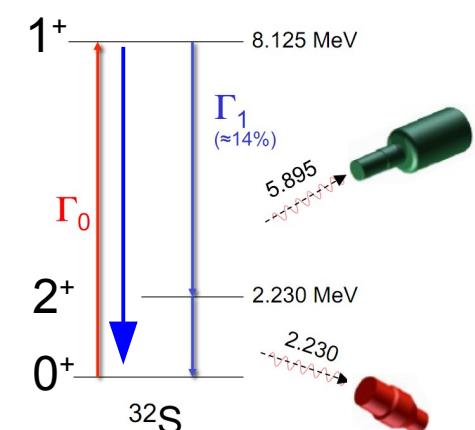
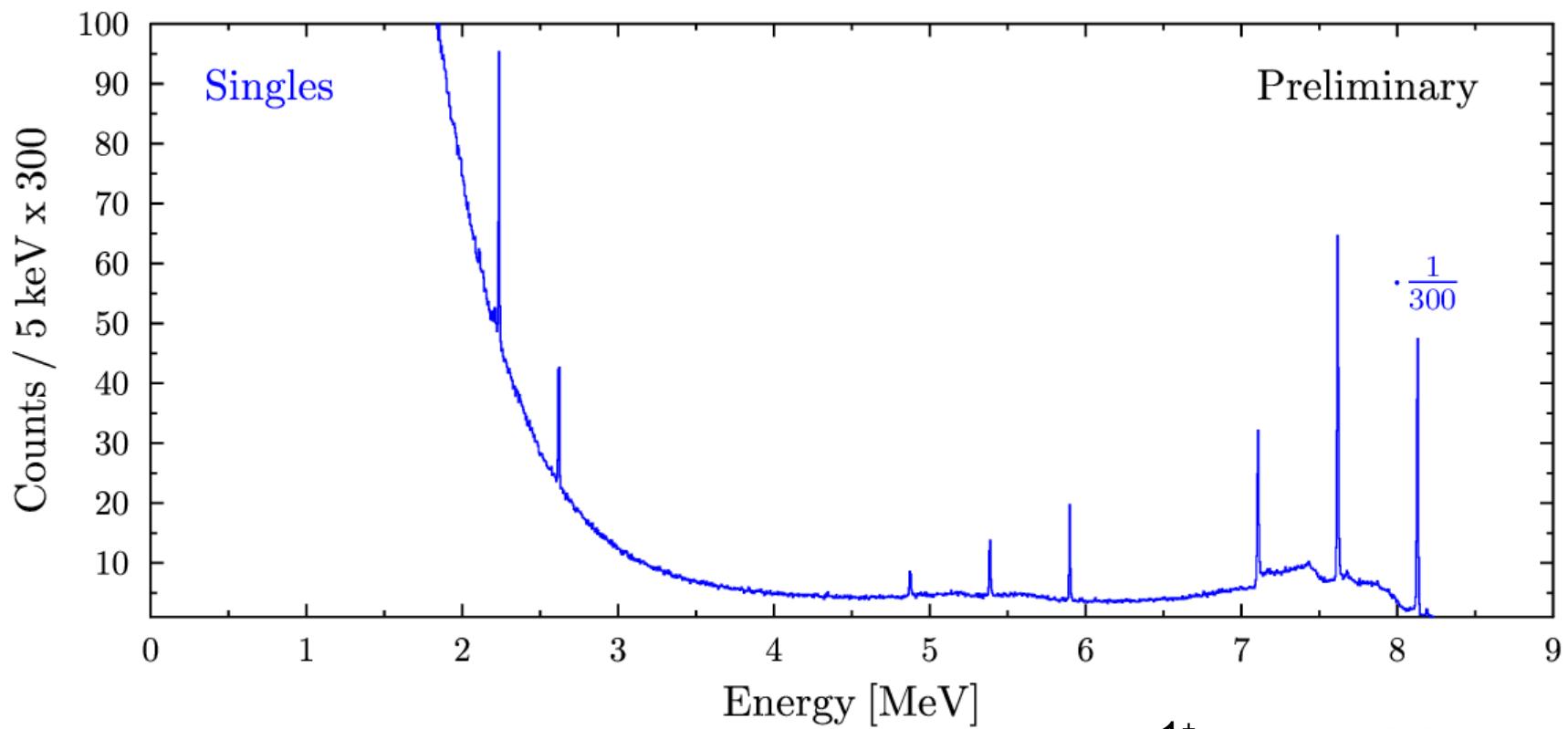
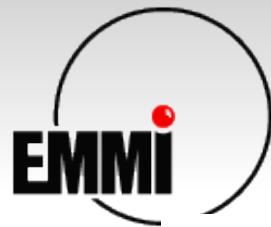


Detectors:

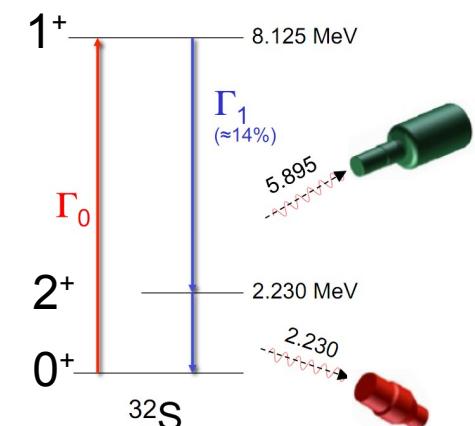
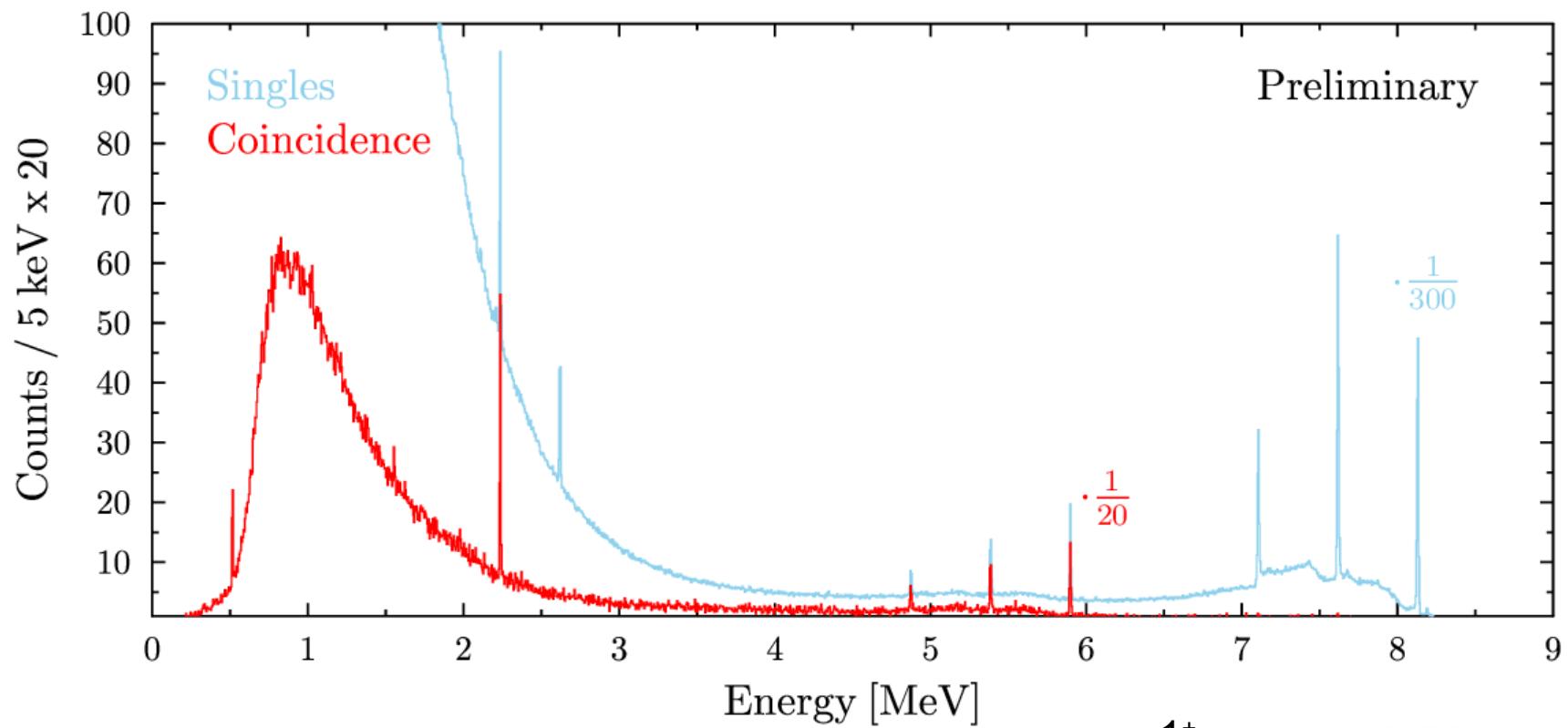
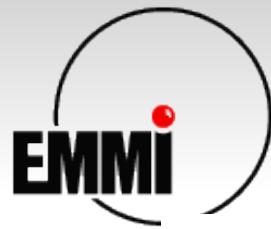
4x HPGe (60%)
+ 4x 3"x3" LaBr

- Target: ^{32}S @ 8.125 MeV beam energy
- Beam on Target: 4 h

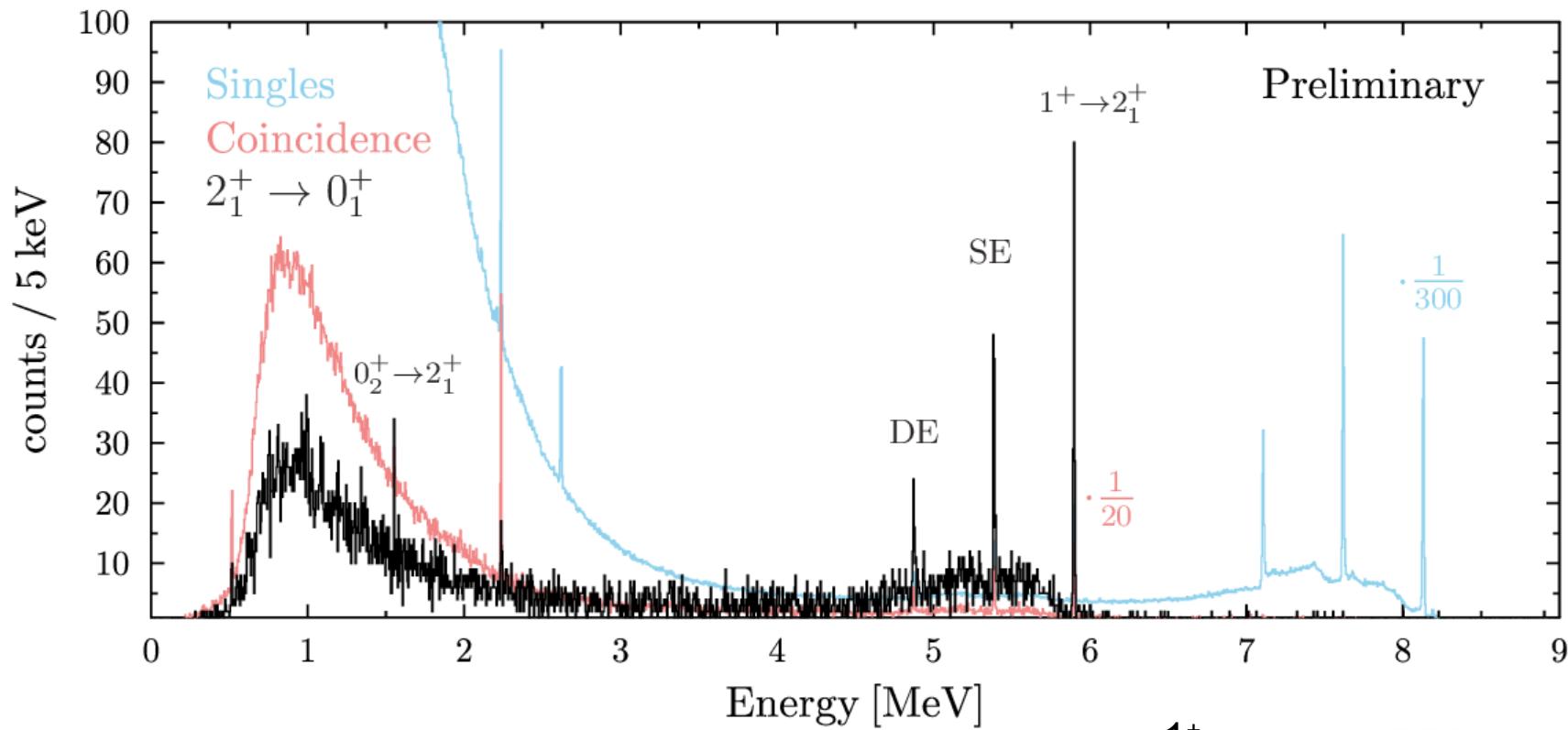
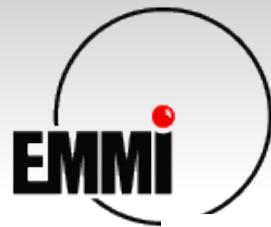
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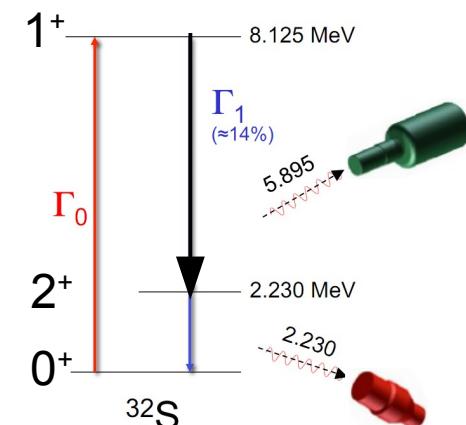


Peak to Background:

2230 keV

- Singles: 0.197(3)
- Energy Cut: 9.6(15)
- Singles: 1.03(2)
- Energy Cut: 11.7(13)

5894 keV





Experiments

Experiment



- Commissioning phase 2012 (^{32}S)
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Experiments

Beam time 2012:

- Investigated 7+3 nuclei:
- ^{124}Sn , ^{140}Ce , ^{76}Ge , ^{40}Ca , ^{156}Gd + ^{240}Pu , ^{233}U , ^{32}S

Beam time 2013:

- Investigated 9+2 nuclei:
 - ^{128}Te , $^{152,156}\text{Gd}$, ^{140}Ce , $^{92,94}\text{Zr}$, ^{206}Pb , $^{162,164}\text{Dy}$ + ^{11}B , ^{32}S

Goals:

- Parities, Decay of Scissors Mode and PDR,
Measurement of the PSF, 2 phonon state



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→ D.Symochko,
HK 10.7



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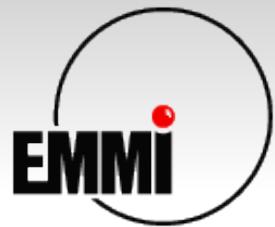
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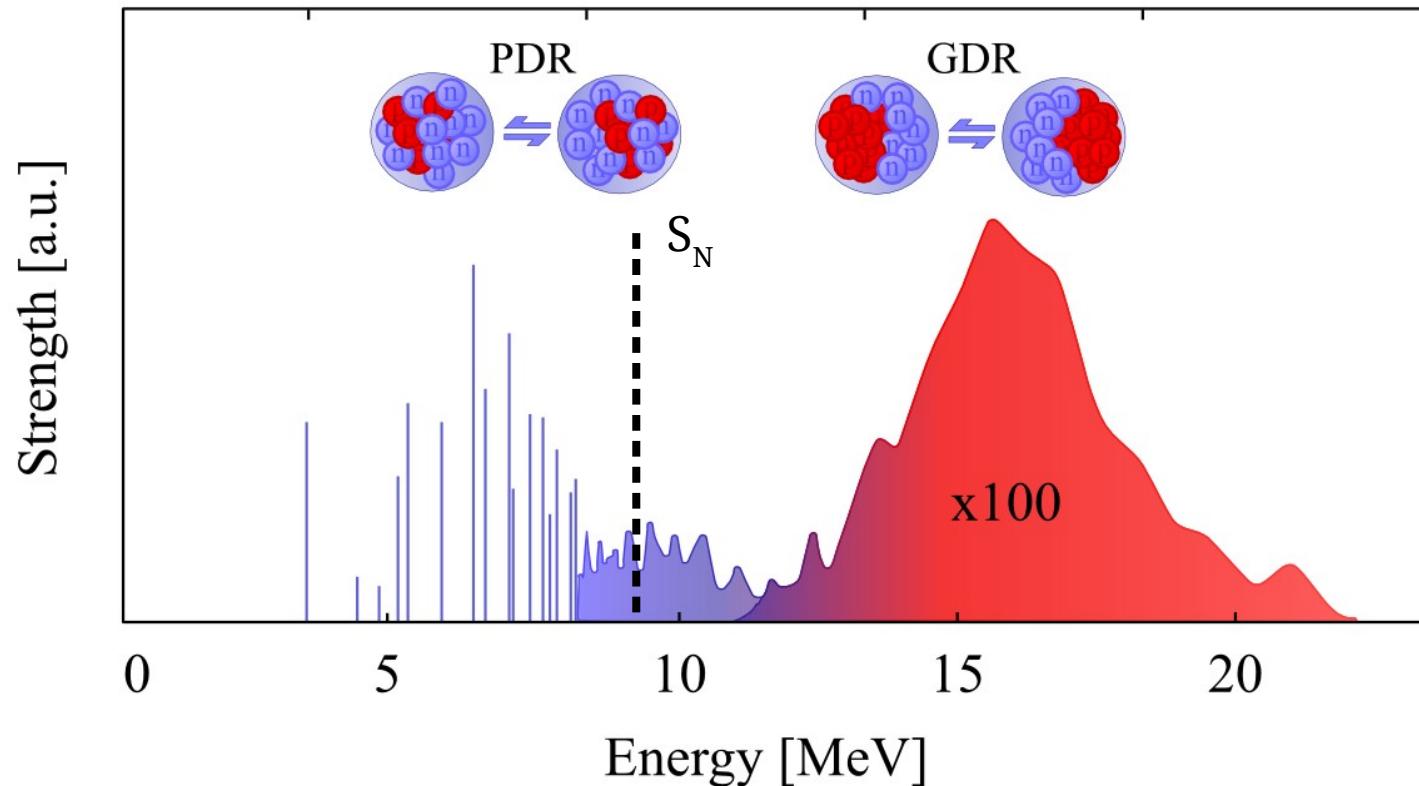
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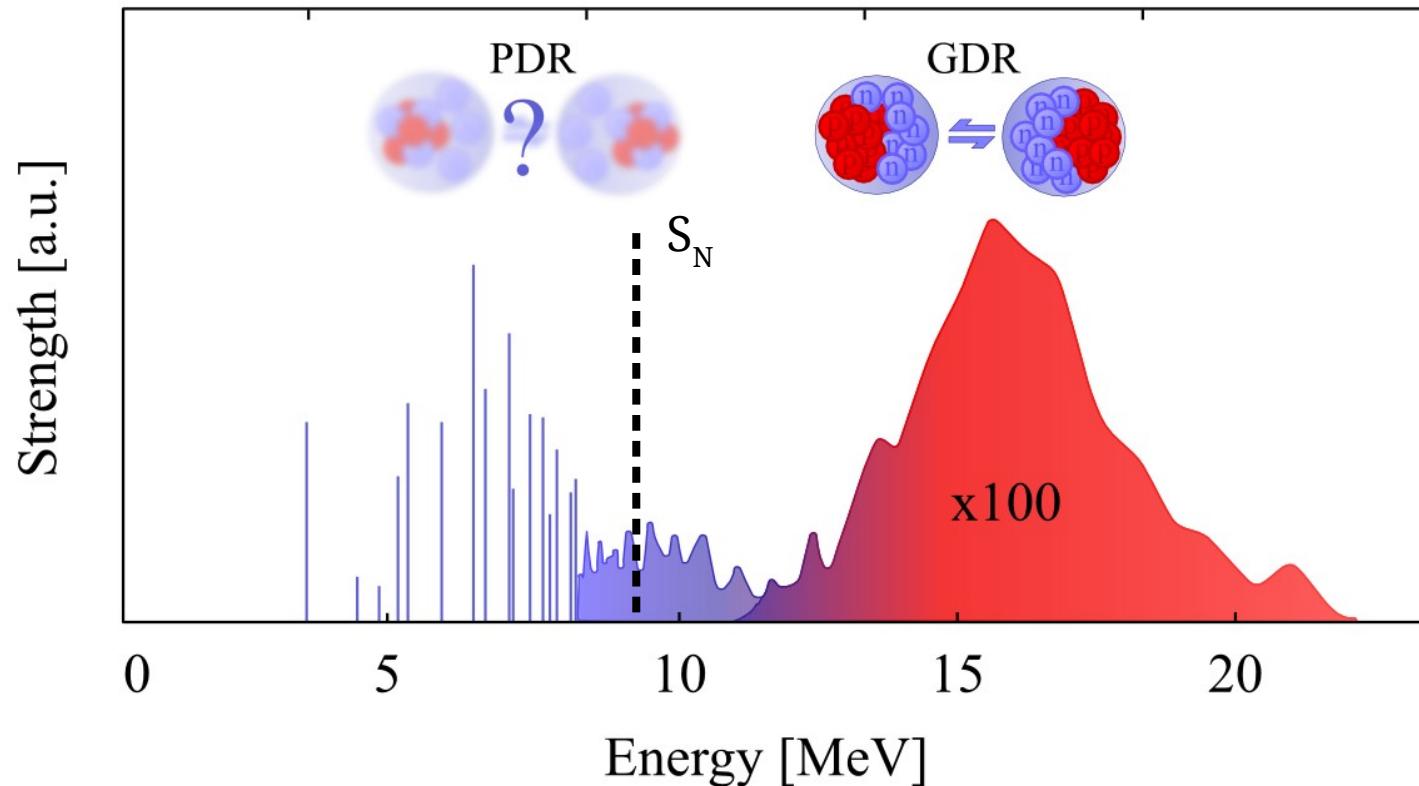


Dipole Photoresponse of (spherical) nuclei

- **GDR**: Oscillation of Neutrons vs. Protons
- **PDR**: Oscillation of Neutron skin vs. Core



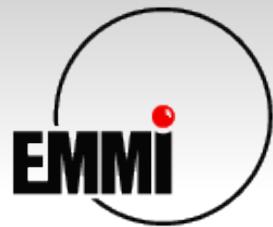
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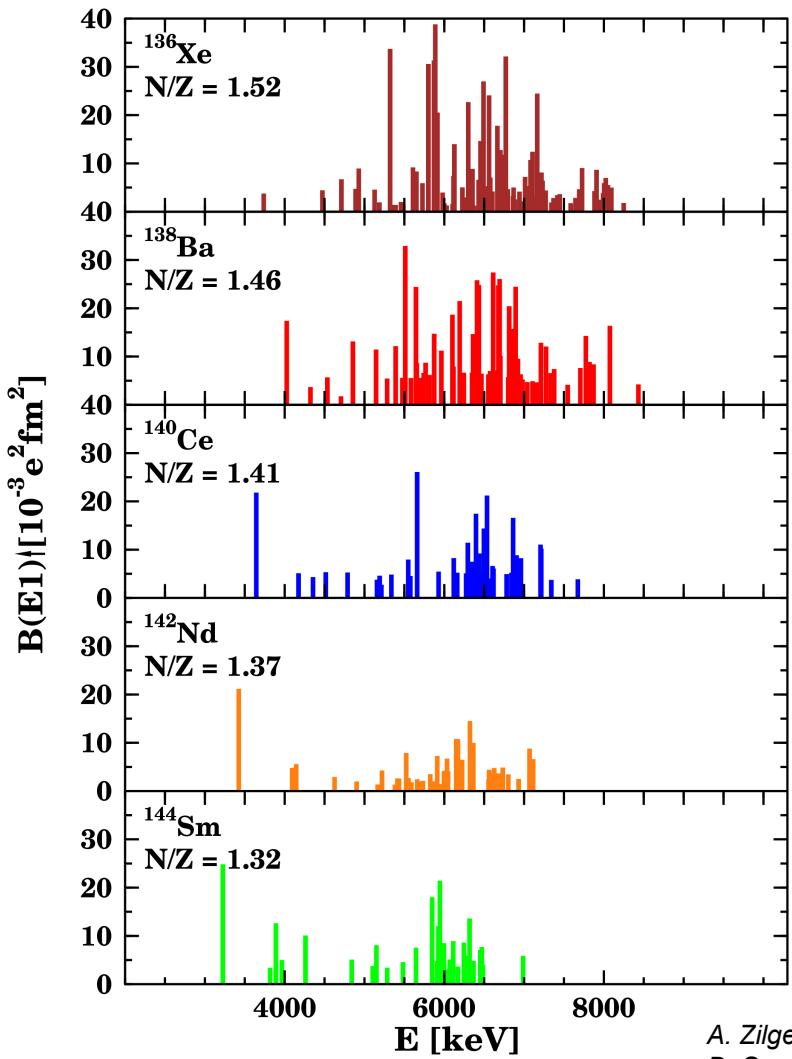
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The PDR in N=82



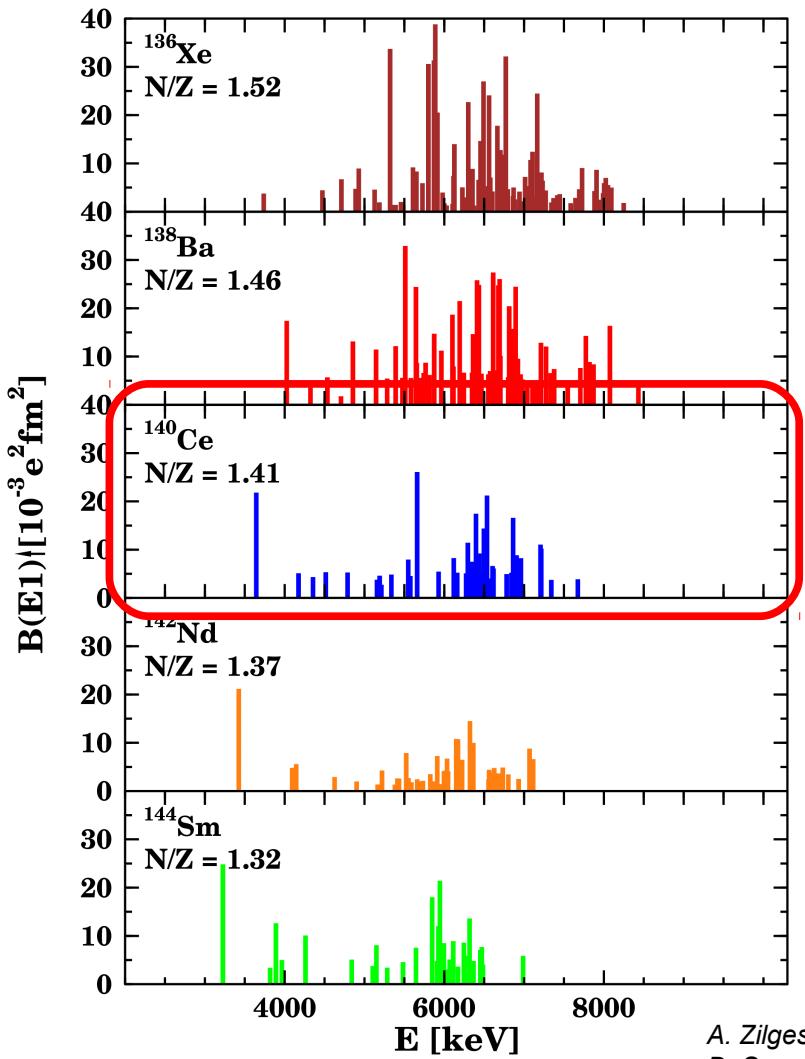
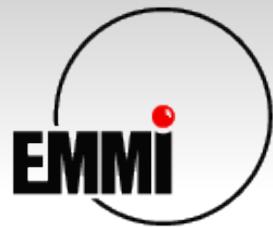
Systematics of the PDR:

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- Strong fragmentation
- Summed strength may scale with N/Z

A. Zilges et al., PLB 542, 43 (2002).

D. Savran et al., Prog. Part. Nucl. Phys. 70, (2013) 210-245

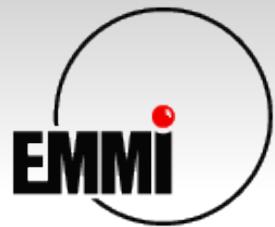
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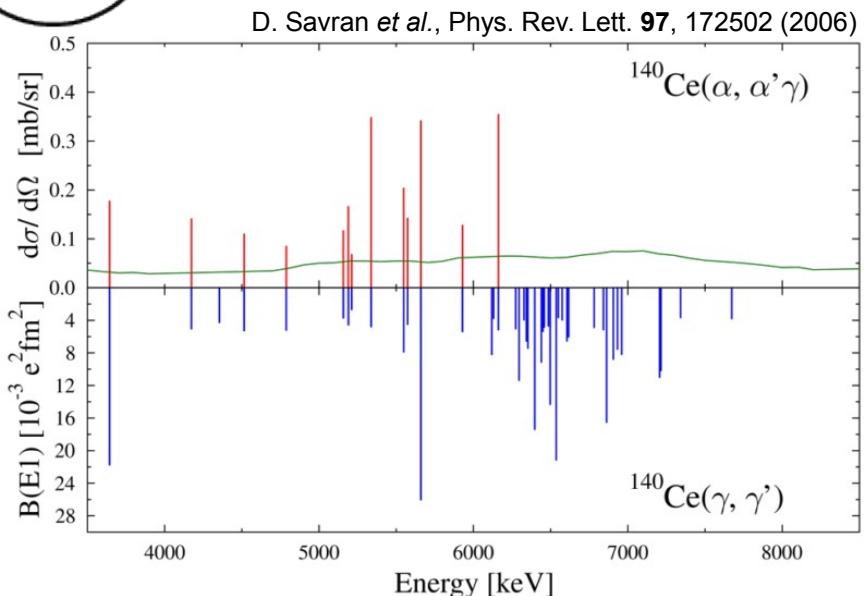
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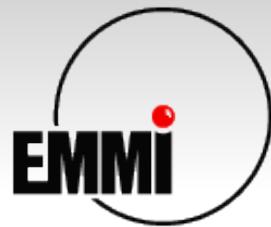
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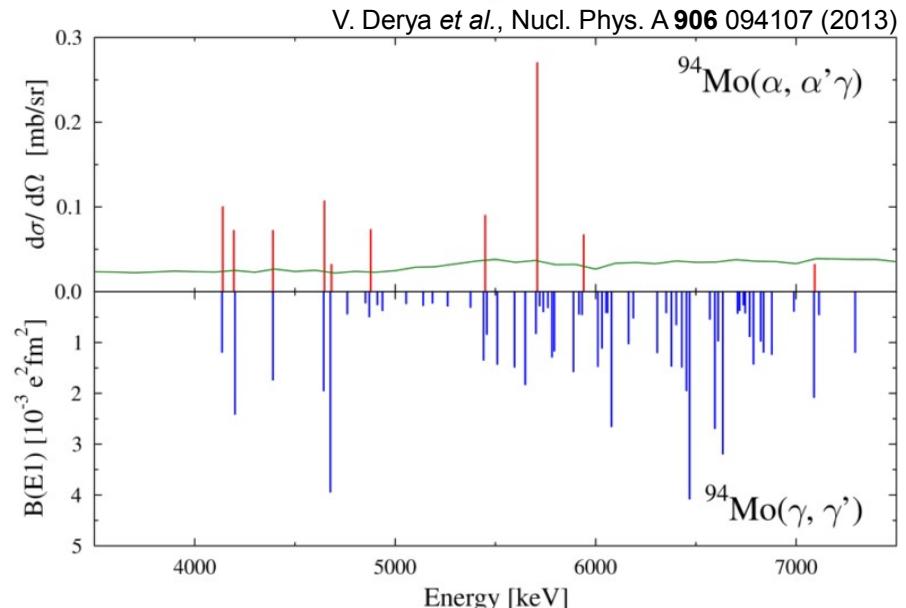
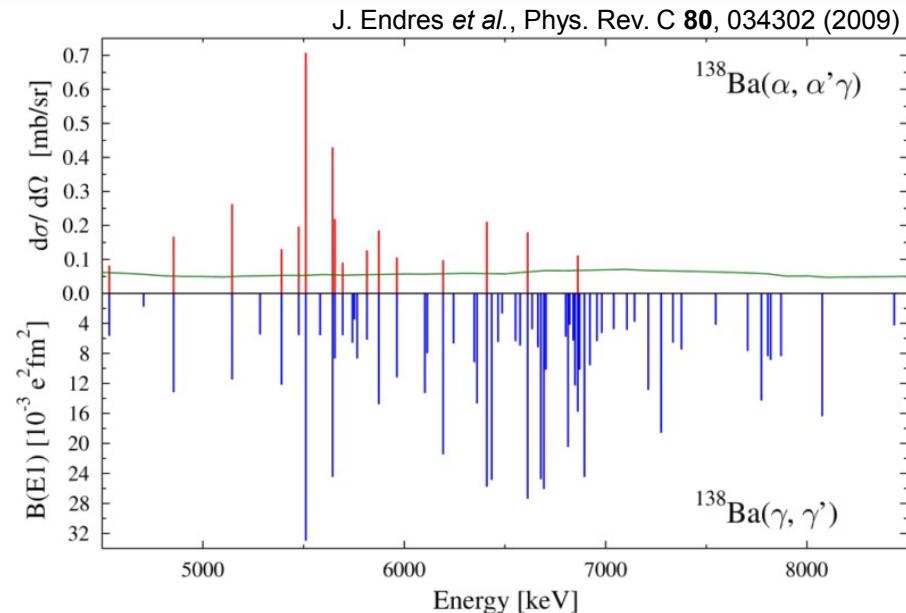
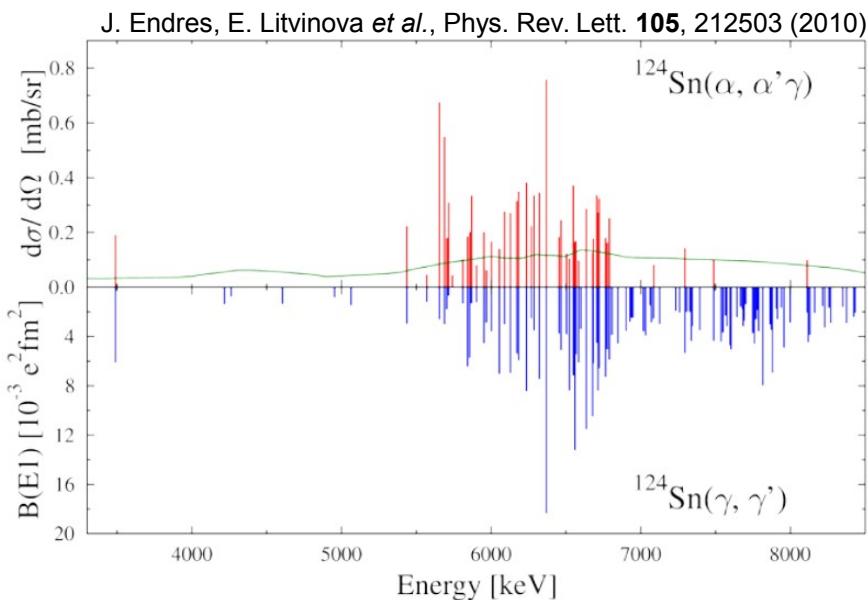
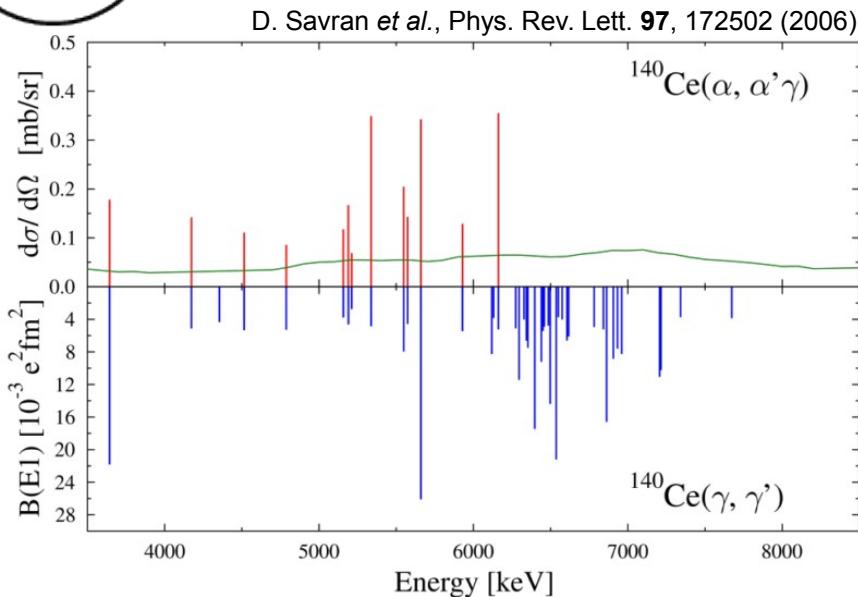


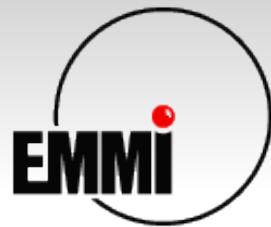
Splitting of the PDR



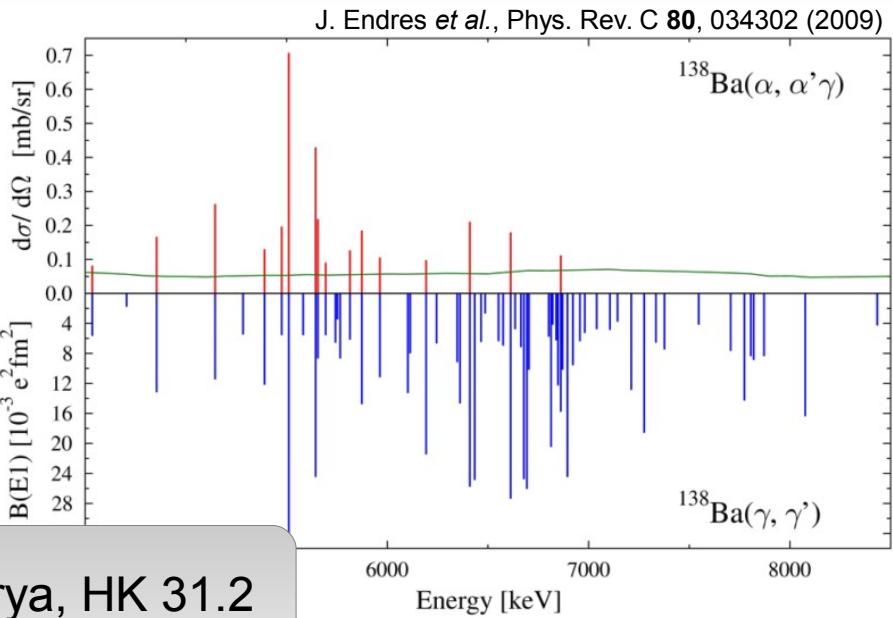
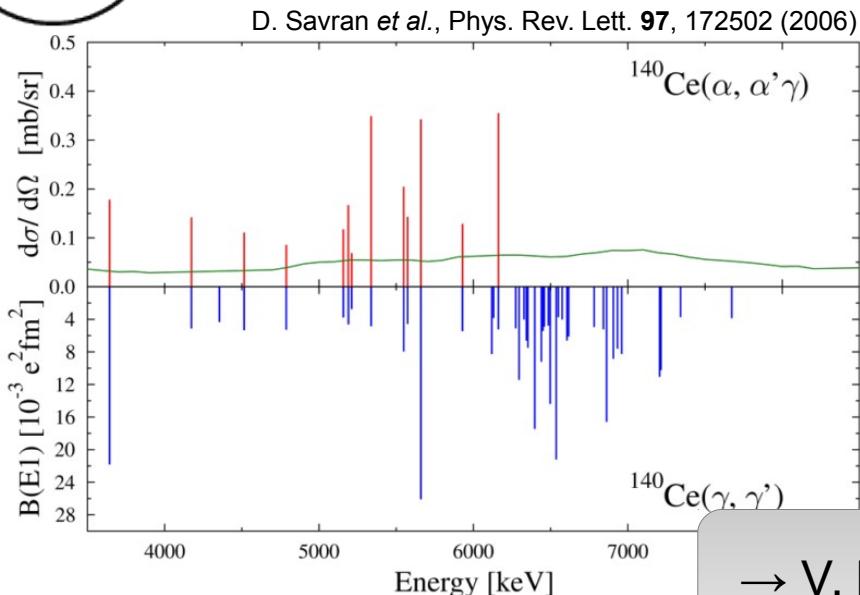


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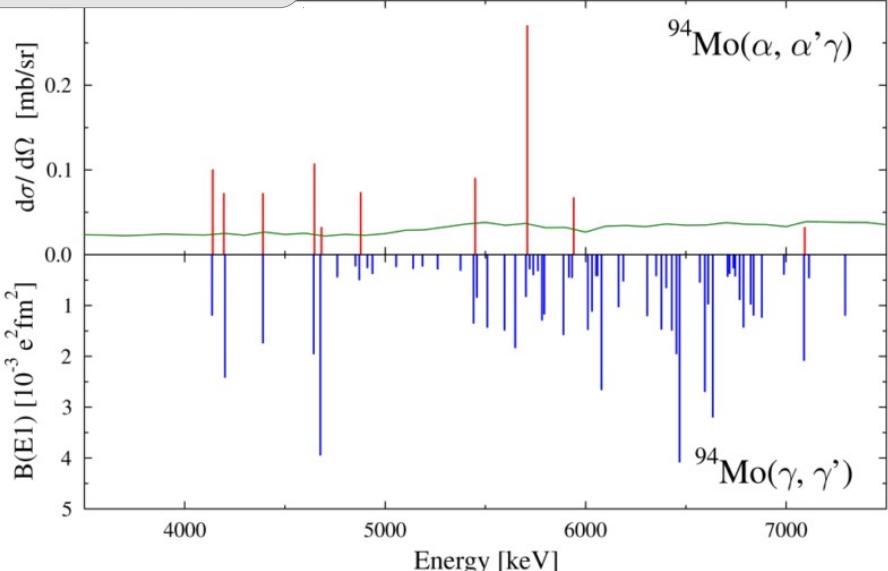
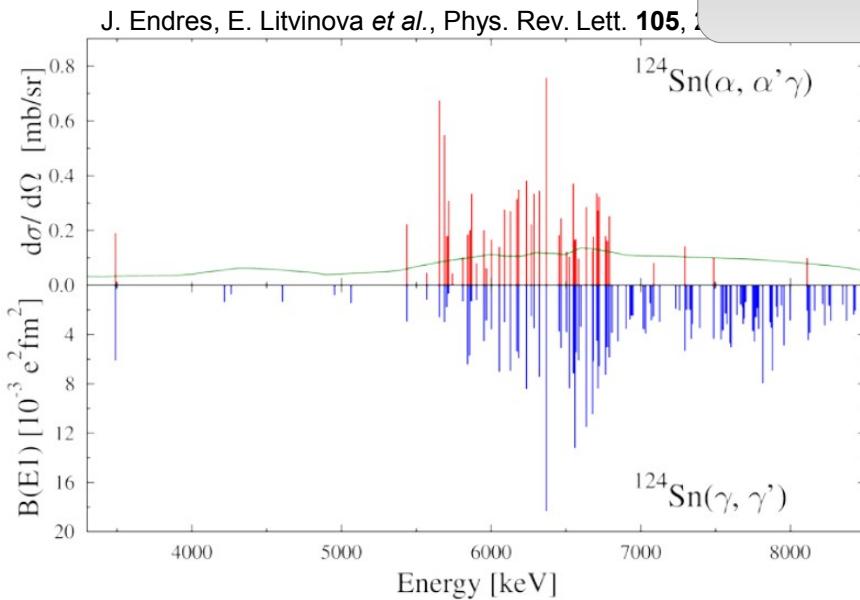




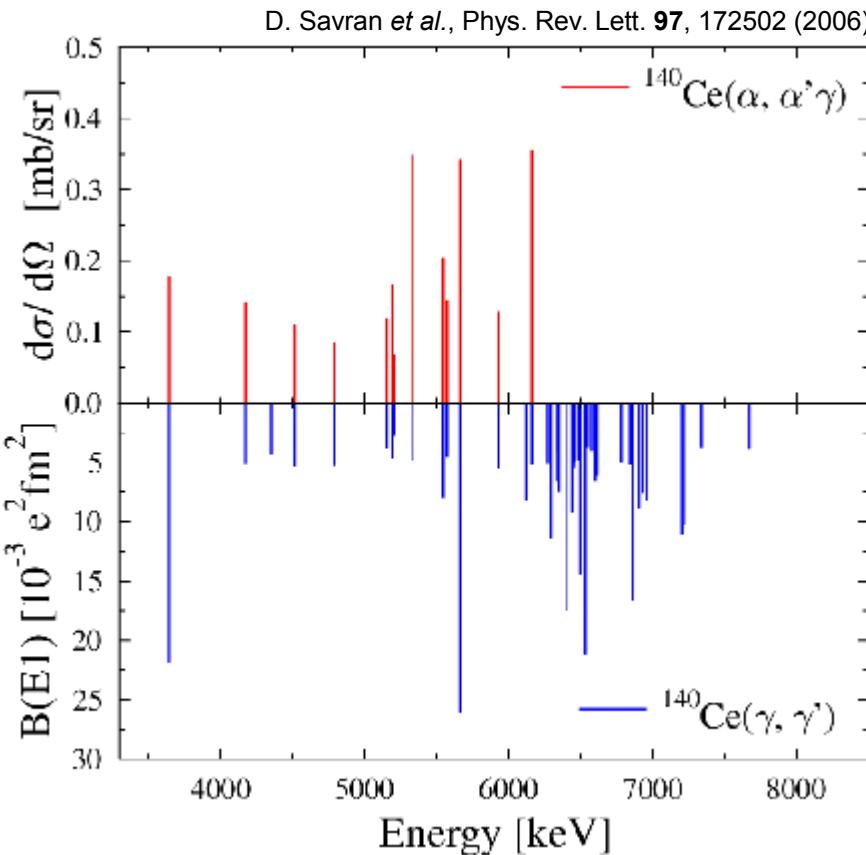
Splitting of the PDR



→ V. Derya, HK 31.2



^{140}Ce (γ, γ')

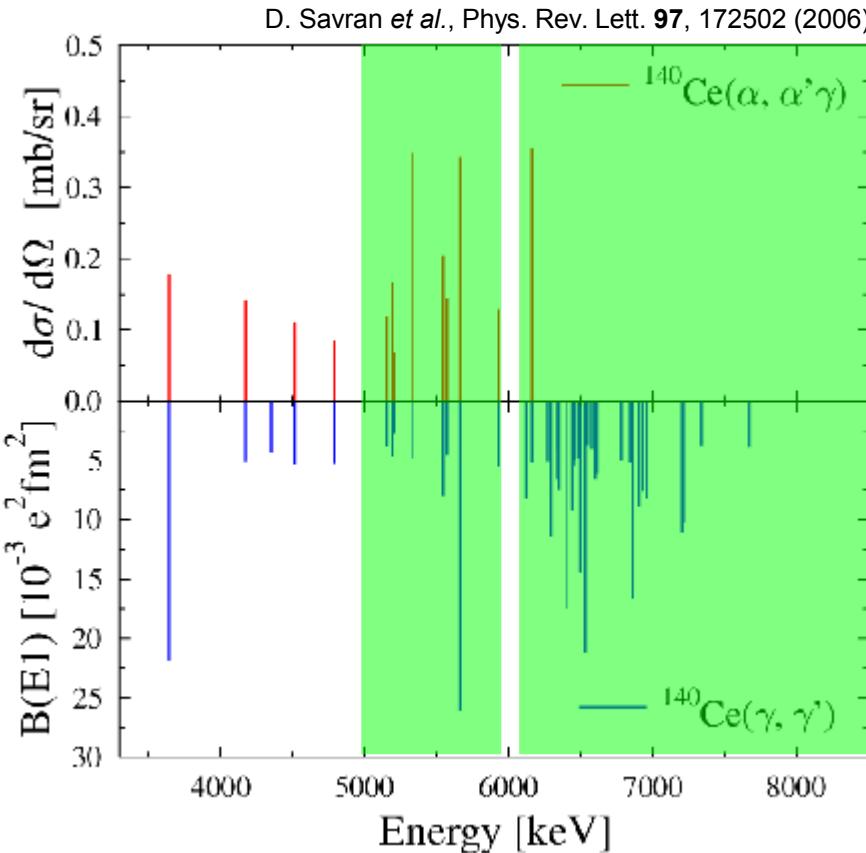


Experiment at HIγS:

- 5 days of beamtime
- 11 Beam energies (+2 in 2013)
- ~100 h beam on target
- Target: 2.35 g enriched $^{140}\text{CeO}_2$

Splitting of PDR observed with different probes
 → Decay pattern may yield additional information

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

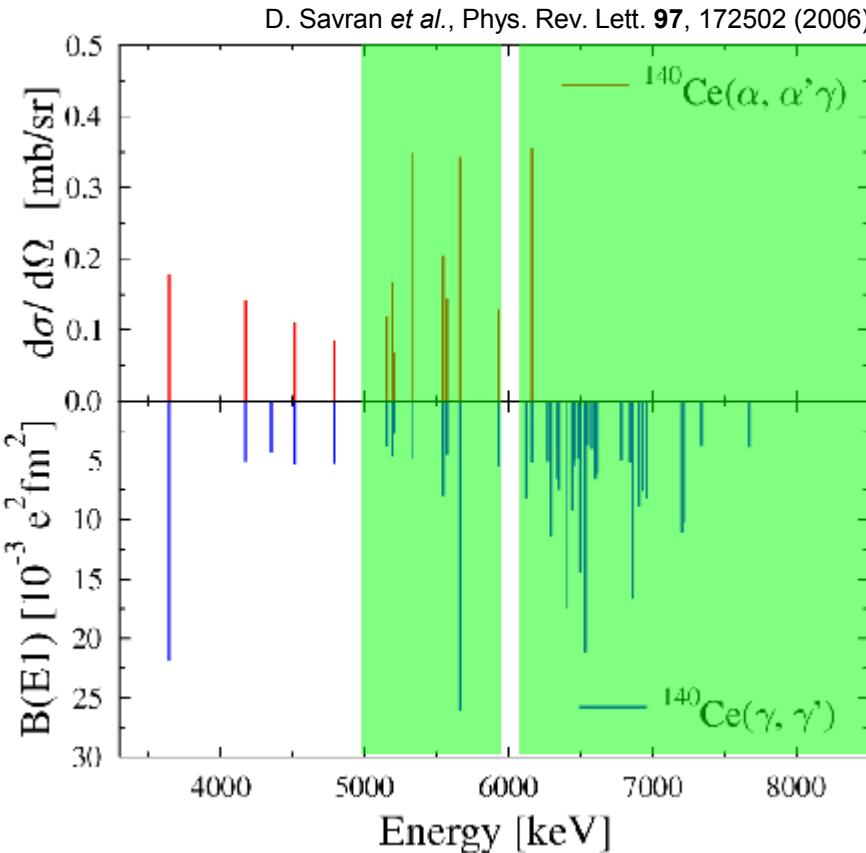


Experiment at HI γ S:

- 5 days of beamtime
- 11 Beam energies (+2 in 2013)
- ~100 h beam on target
- Target: 2.35 g enriched $^{140}\text{CeO}_2$

Splitting of PDR observed with different probes
→ Decay pattern may yield additional information

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



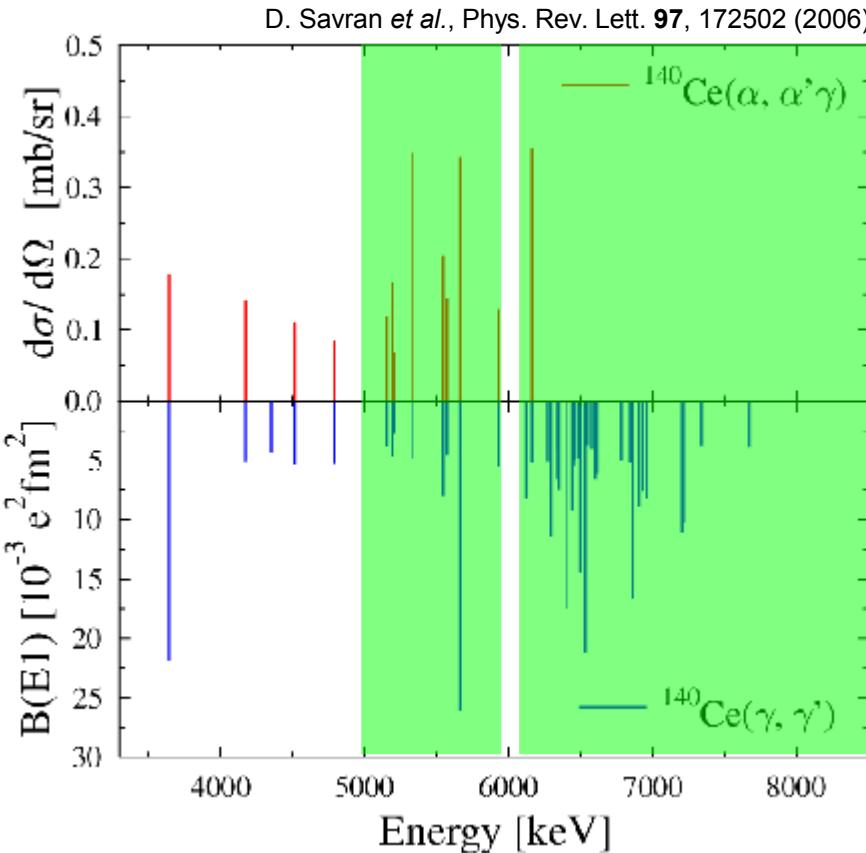
Experiment at HI γ S:

- 5 days of beamtime
- 11 Beam energies (+2 in 2013)
- ~100 h beam on target
- Target: 2.35 g enriched $^{140}\text{CeO}_2$

Analysis:

- Singles → Cross-Sections, Parities
- Coincidences → Branching Ratios

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



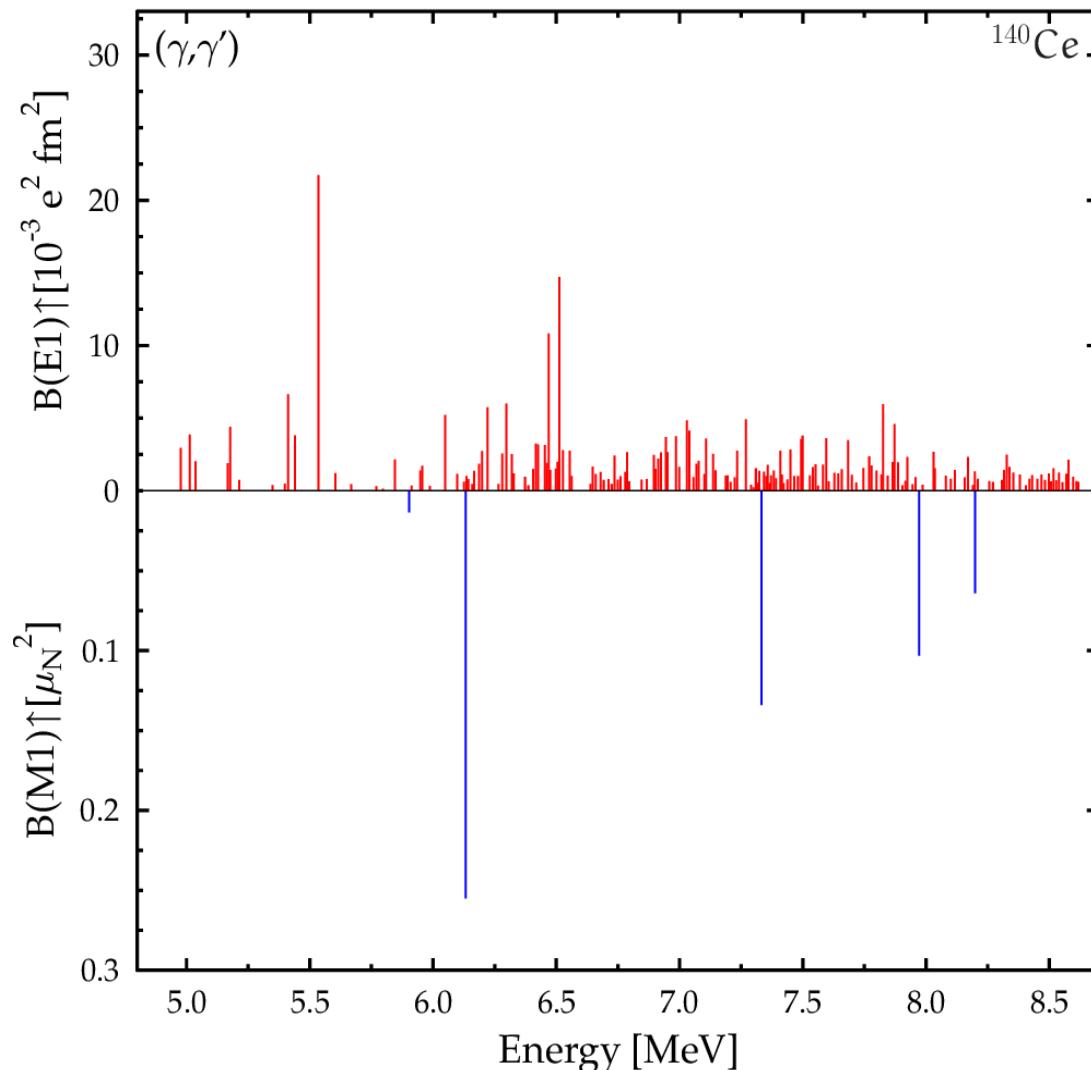
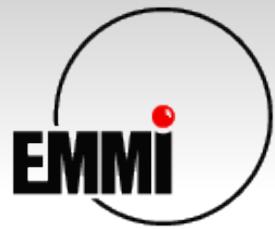
Experiment at HI γ S:

- 5 days of beamtime
- 11 Beam energies (+2 in 2013)
- ~100 h beam on target
- Target: 2.35 g enriched $^{140}\text{CeO}_2$

Analysis:

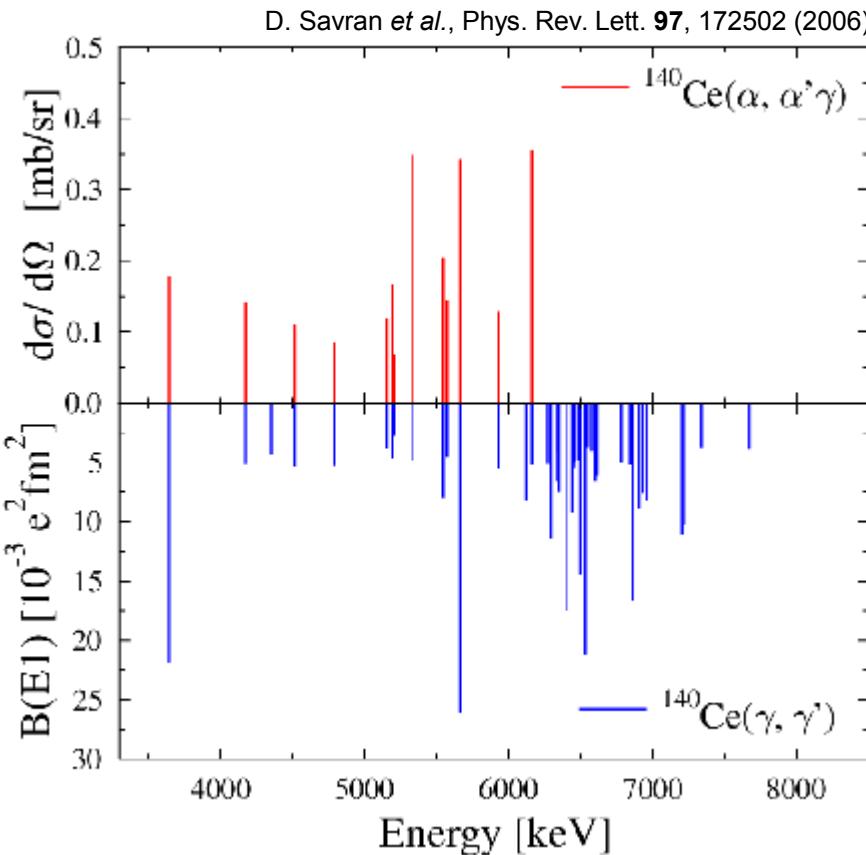
- Singles → Cross-Sections, Parities
- Coincidences → Branching Ratios

^{140}Ce B(E1)



- 210 J=1 levels
- 5 M1 transitions
- Summed strength: $0.42(5) \text{ e}^2 \text{ fm}^2$ ($\Gamma = \Gamma_0$)
- 0.57% of EWSR
- QPM $\sim 0.7 \text{ e}^2 \text{ fm}^2$

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



Experiment at HIγS:

- 5 days of beamtime
- 11 Beam energies (+2 in 2013)
- ~100 h beam on target
- Target: 2.35 g enriched $^{140}\text{CeO}_2$

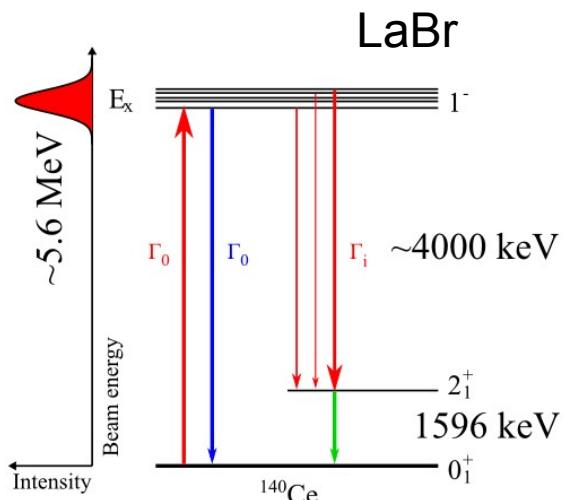
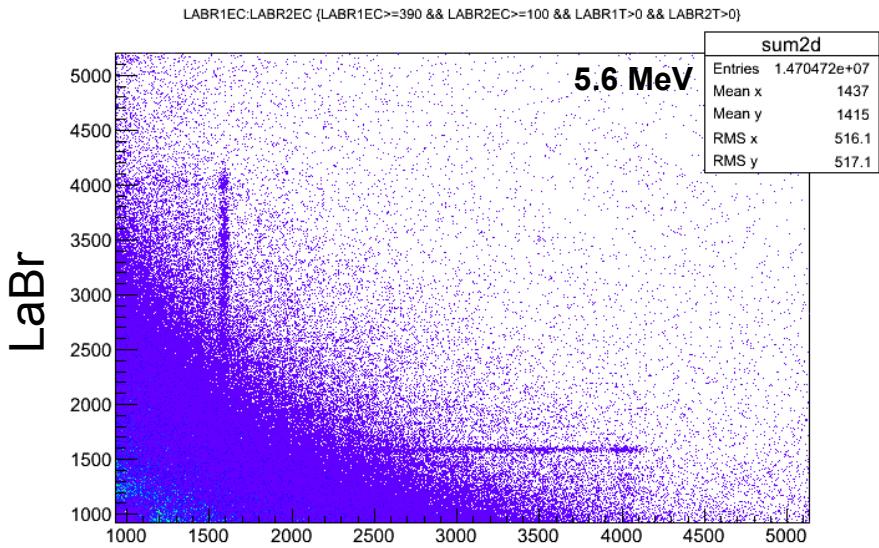
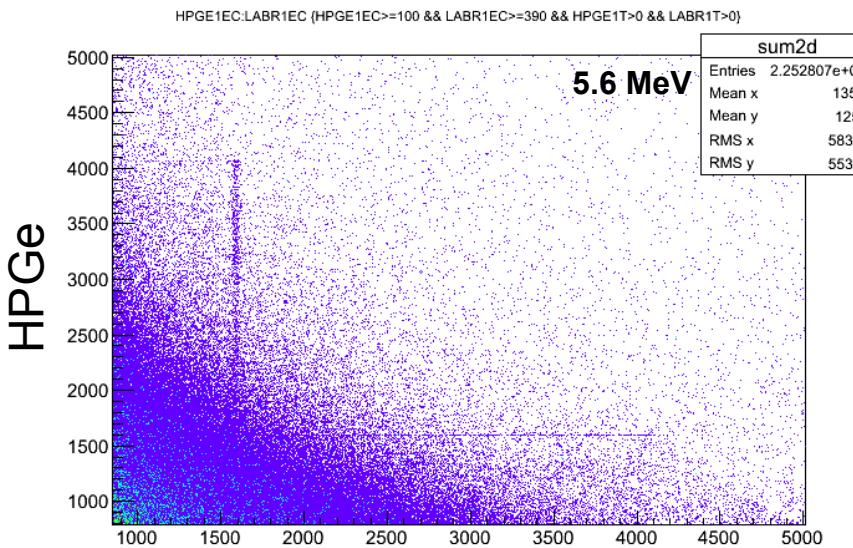
Analysis:

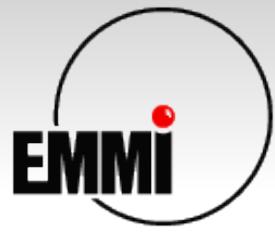
- Singles → Cross-Sections, Parities
- **Coincidences** → Branching Ratios

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



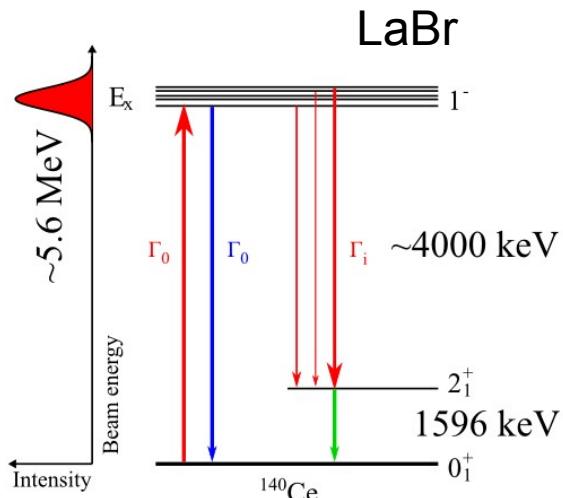
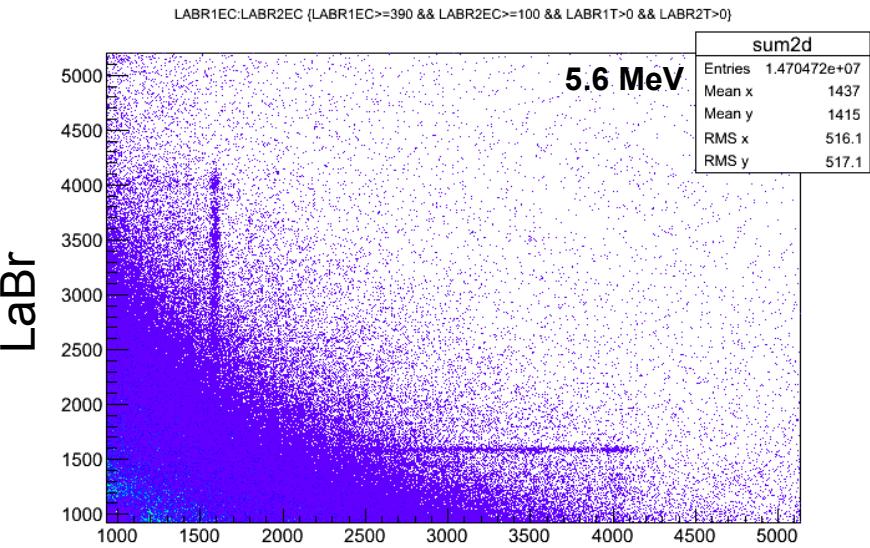
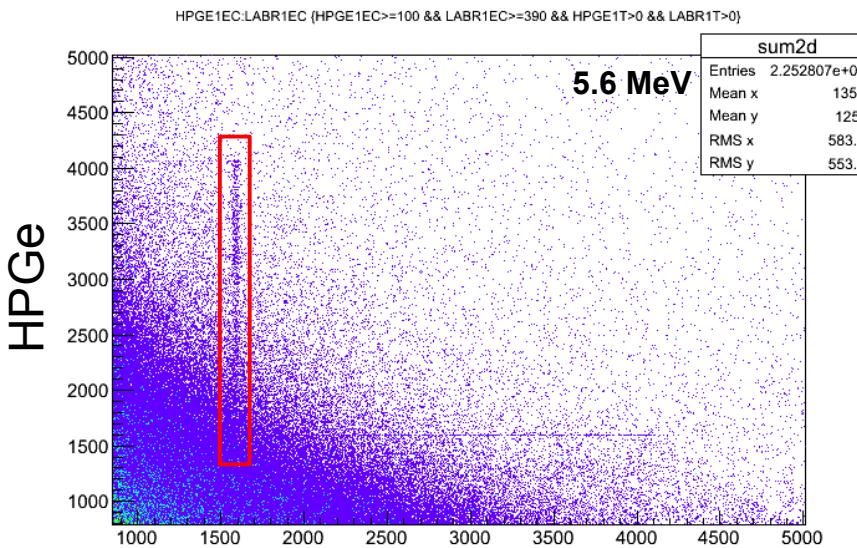
Experimental data yields two matrices:





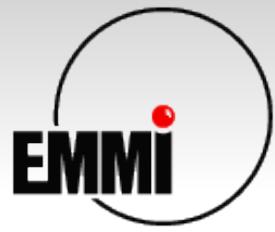
$^{140}\text{Ce} (\gamma, \gamma')$

Experimental data yields two matrices:



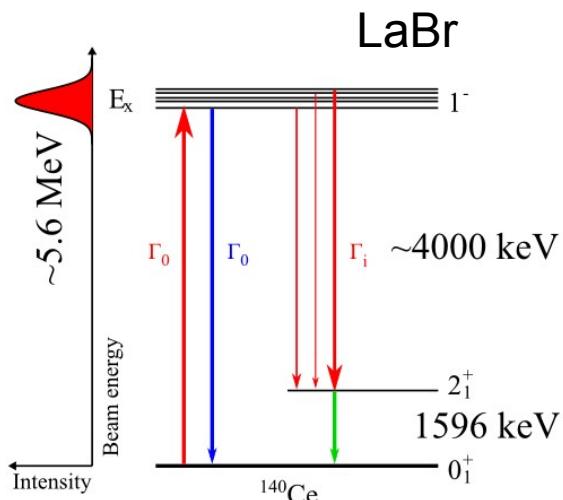
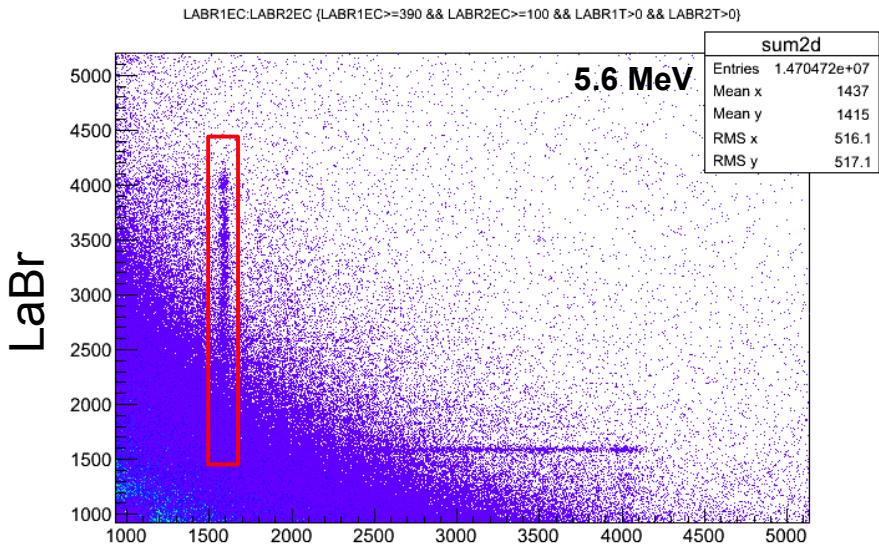
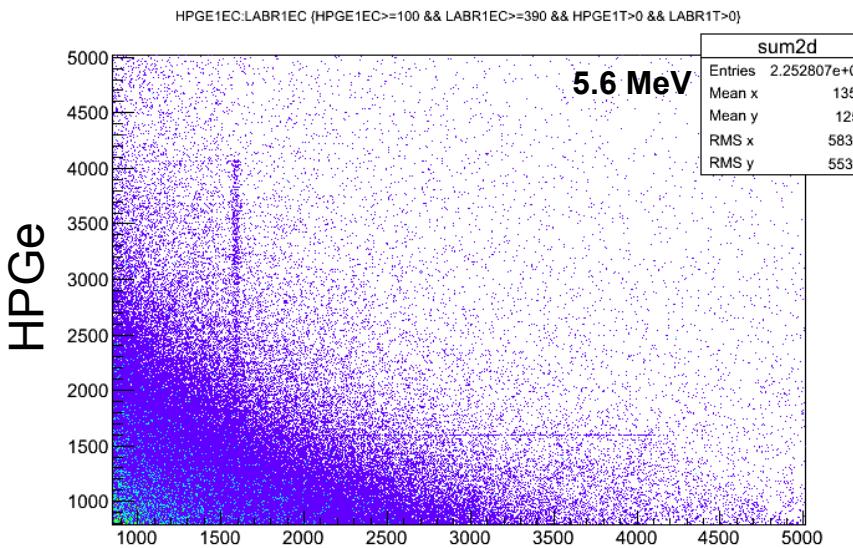
Possible analyses:

- Gate on $2^+_1 \rightarrow 0^+$ in LaBr:
 - 1) HPGe spectra (high resolution \rightarrow single states)



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

Experimental data yields two matrices:



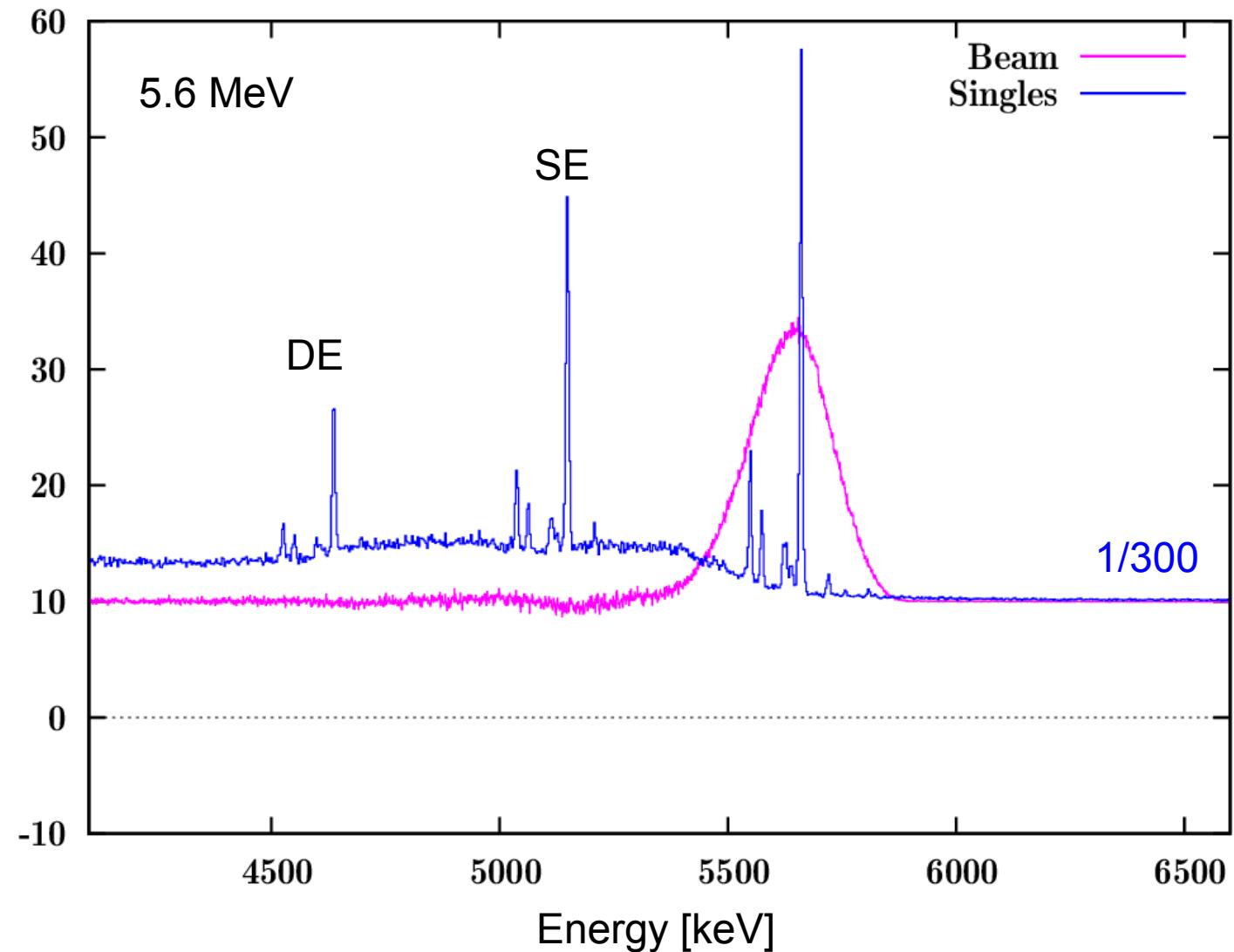
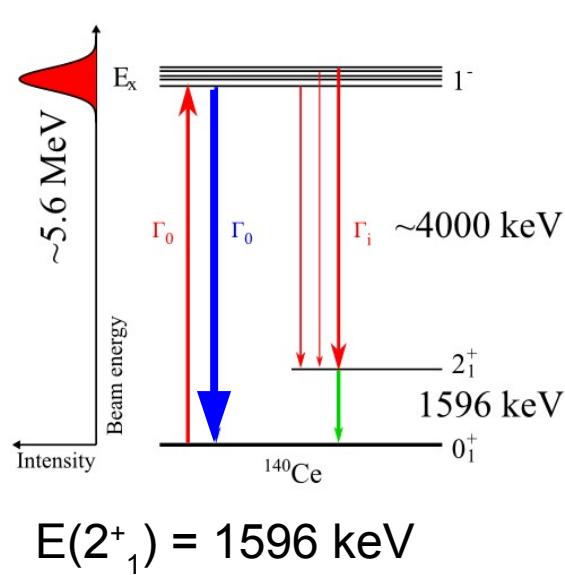
Possible analyses:

- Gate on $2^+_1 \rightarrow 0^+$ in LaBr:
 - 1) HPGe spectra (high resolution \rightarrow single states)
 - 2) LaBr spectra (better efficiency \rightarrow averaged)

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



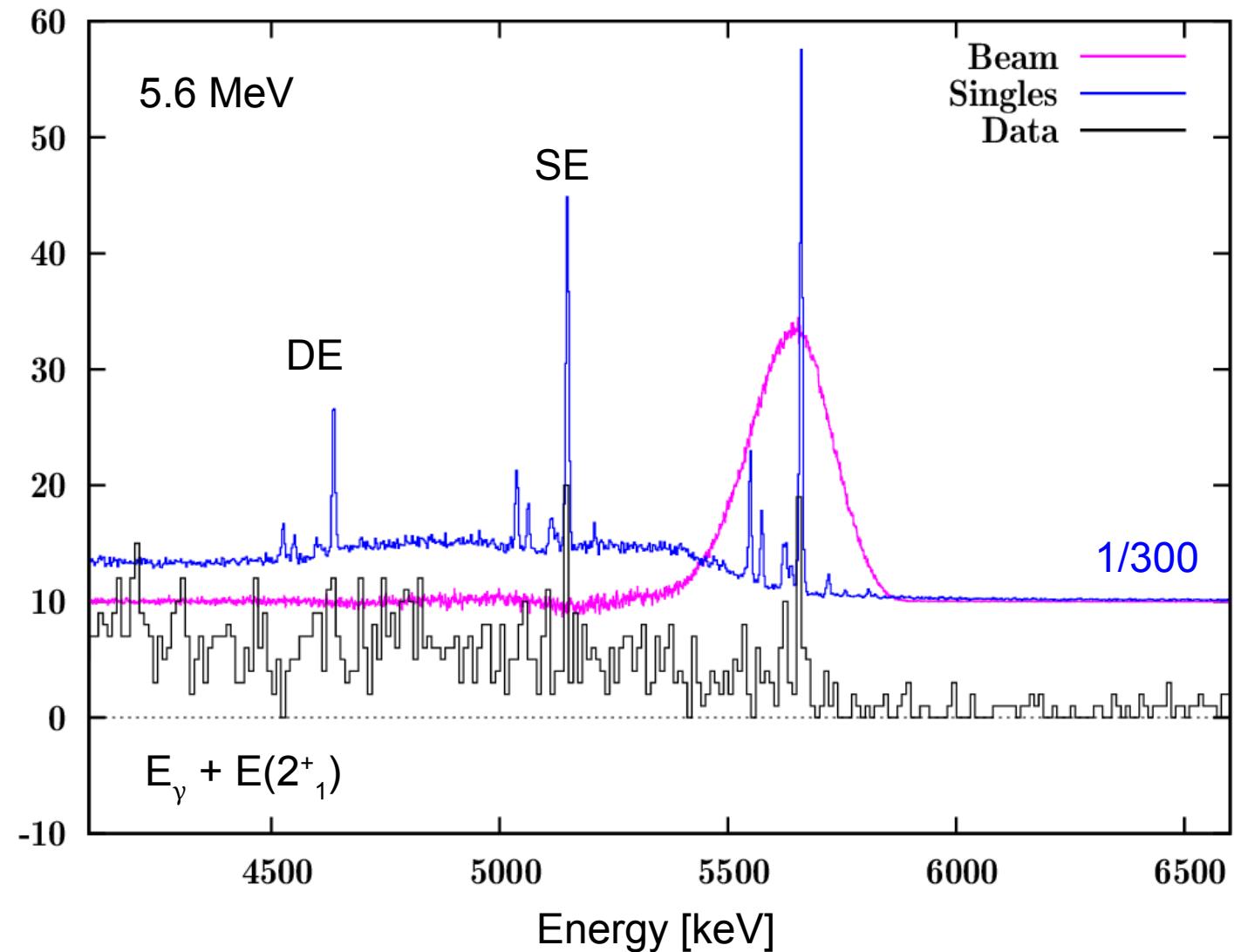
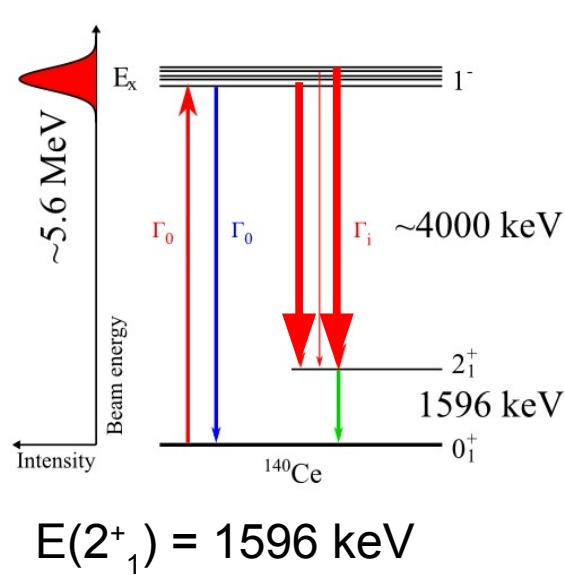
Gate on $\text{LaBr} \rightarrow \text{HPGe}$ spectra



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



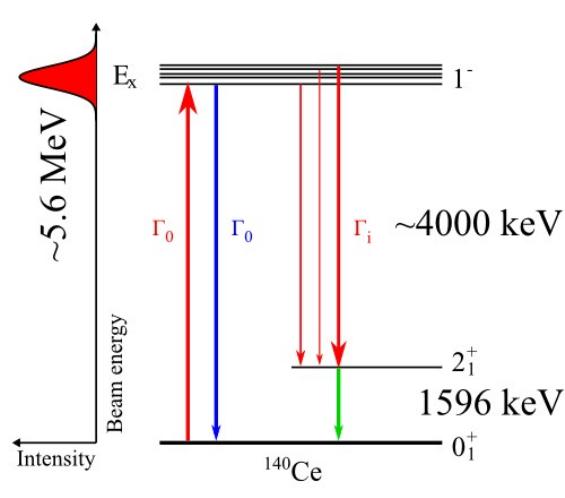
Gate on $\text{LaBr} \rightarrow \text{HPGe}$ spectra



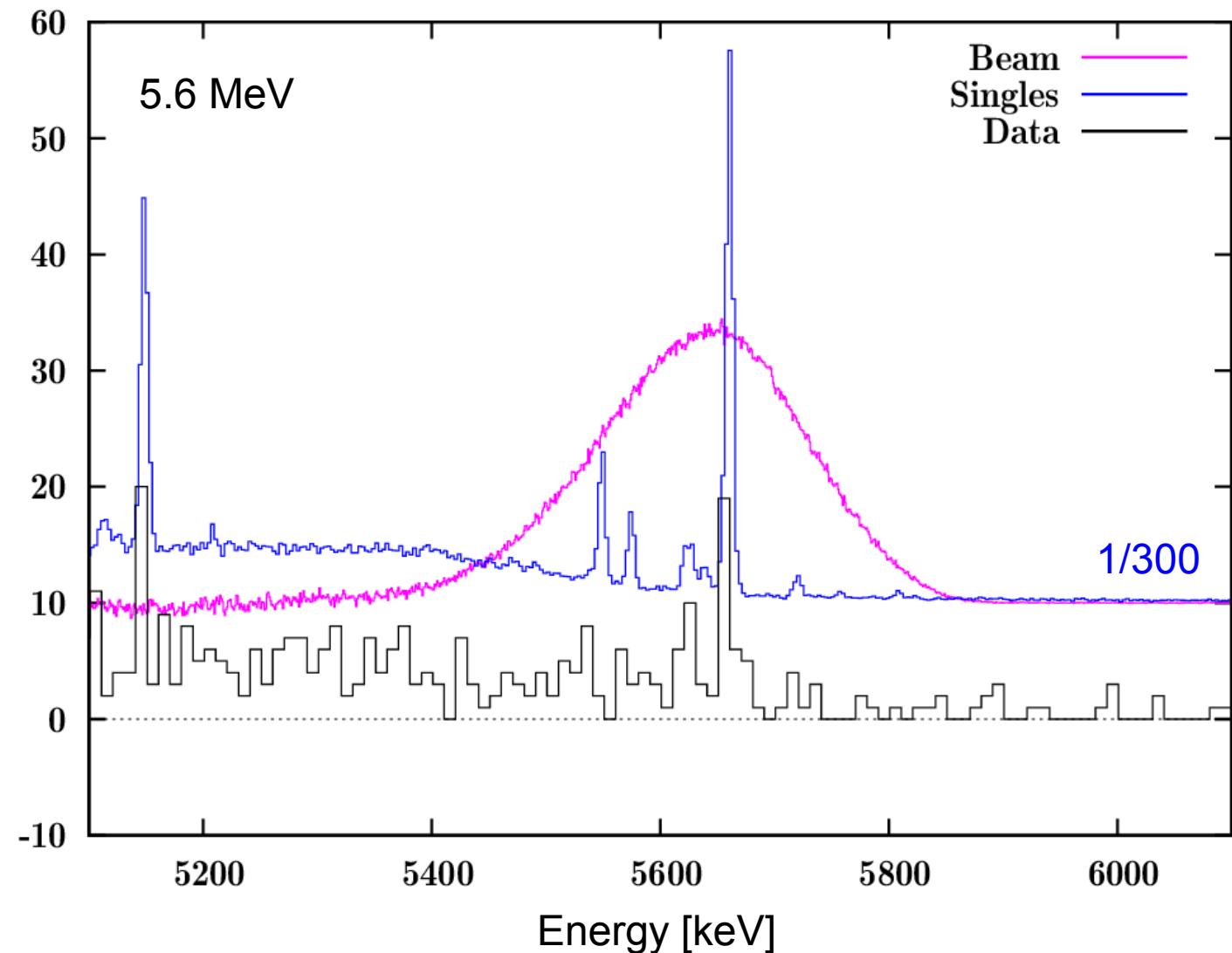
$^{140}\text{Ce} (\gamma, \gamma')$



Gate on $\text{LaBr} \rightarrow \text{HPGe}$ spectra



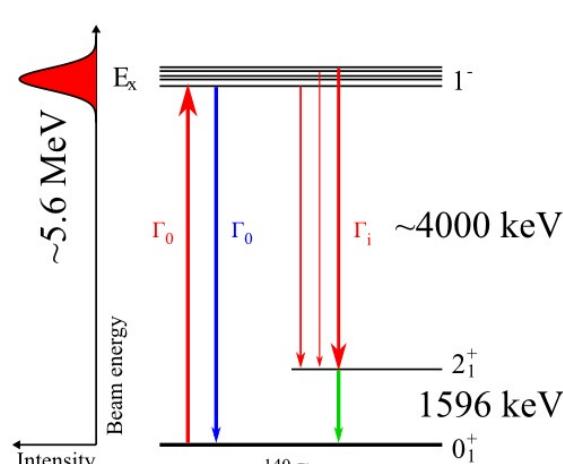
$$E(2^+_1) = 1596 \text{ keV}$$



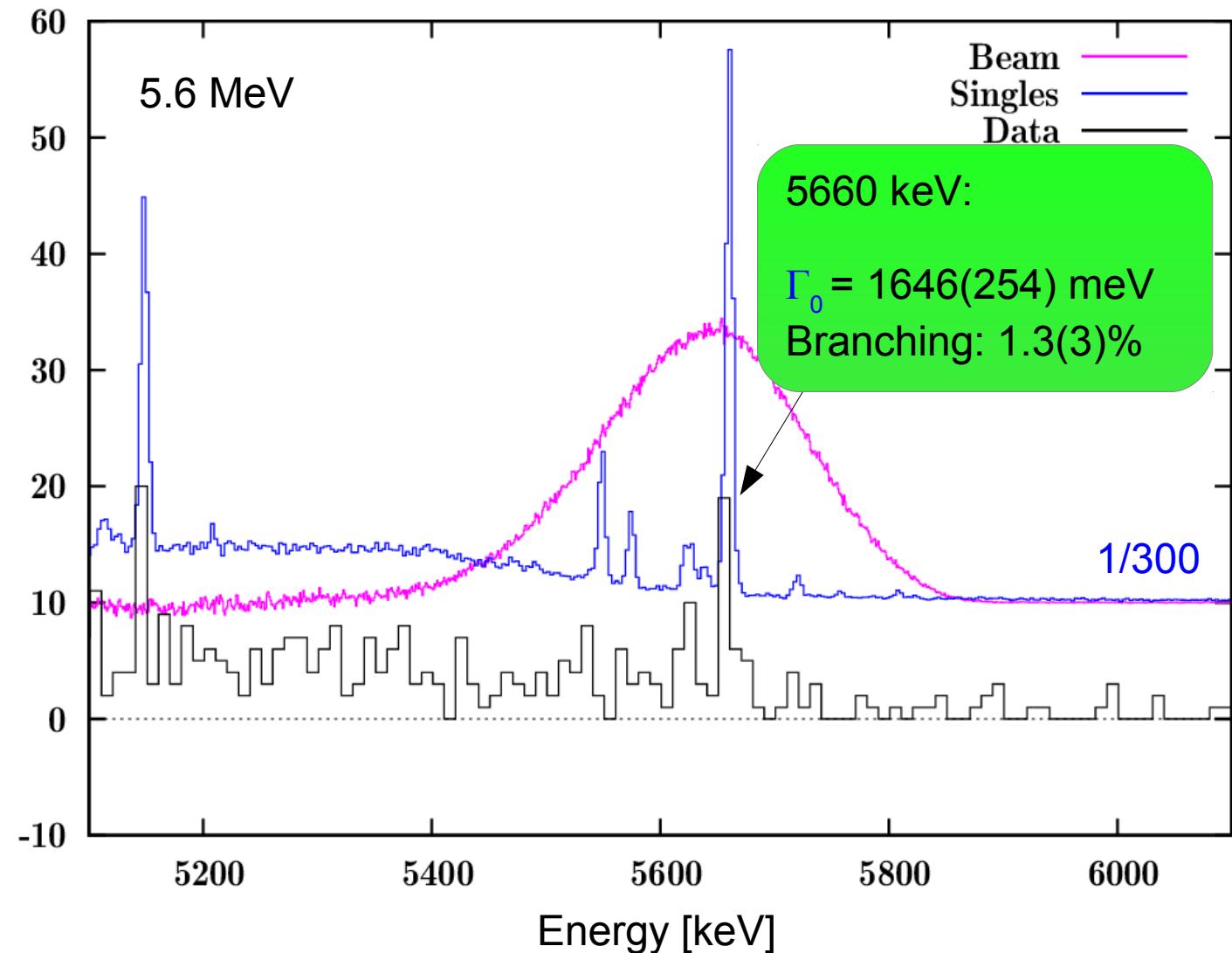
$^{140}\text{Ce} (\gamma, \gamma')$



Gate on $\text{LaBr} \rightarrow \text{HPGe}$ spectra



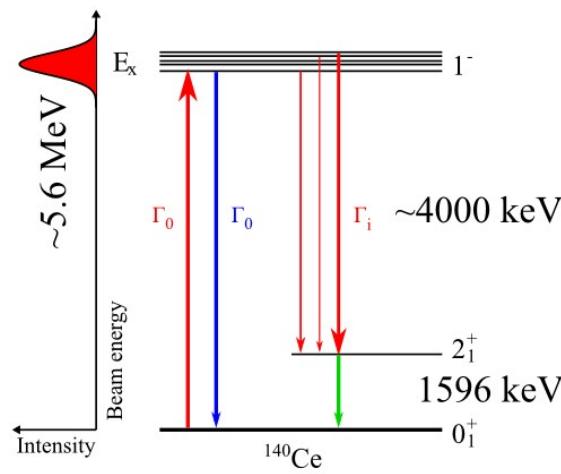
$$E(2^+_1) = 1596 \text{ keV}$$



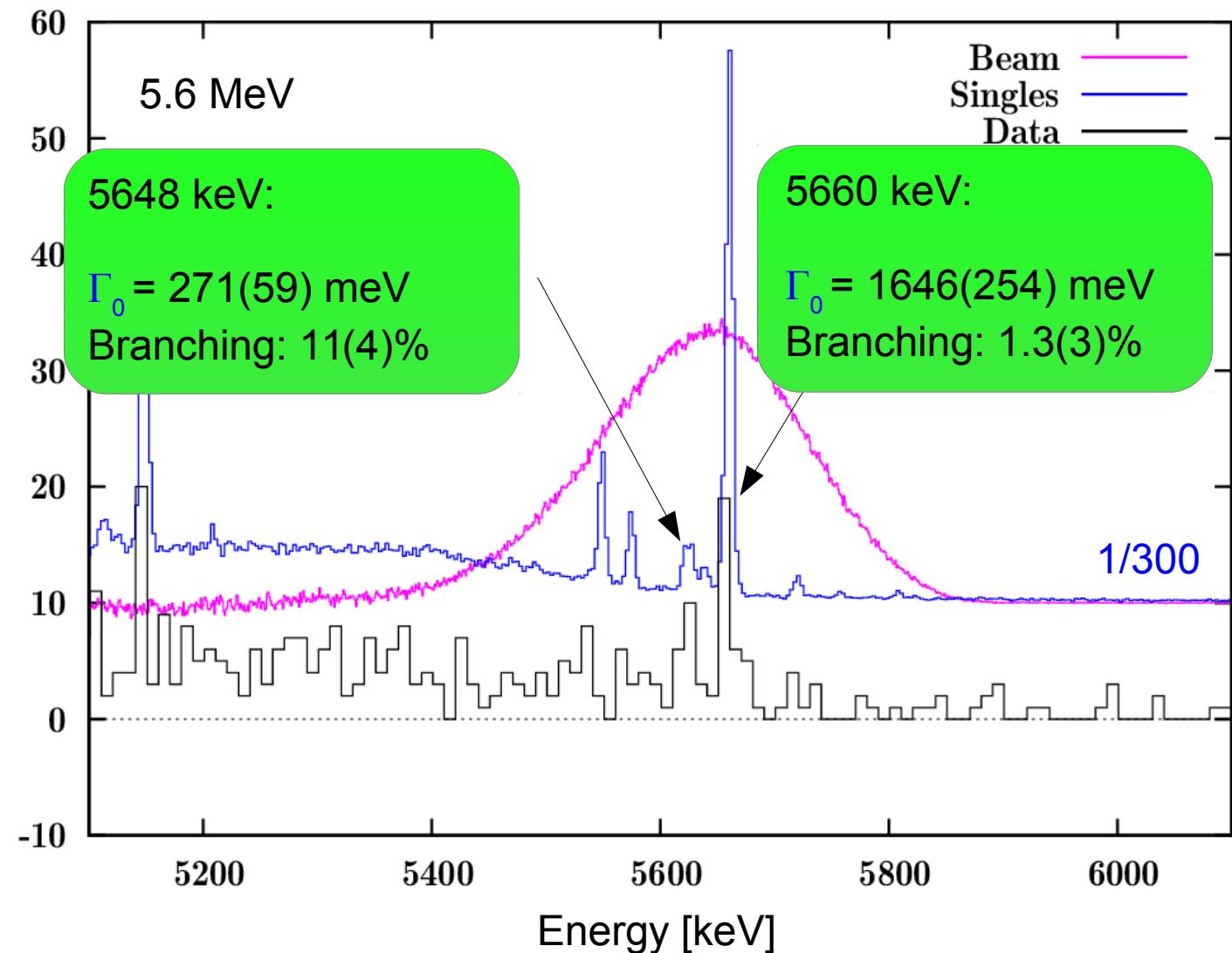
$^{140}\text{Ce} (\gamma, \gamma')$



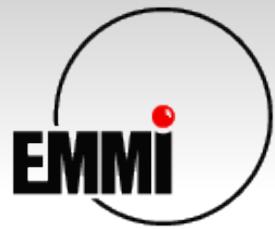
Gate on $\text{LaBr} \rightarrow \text{HPGe}$ spectra



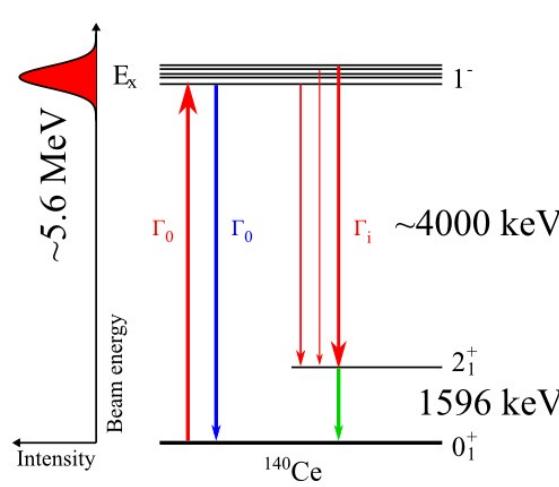
$$E(2^+_1) = 1596 \text{ keV}$$



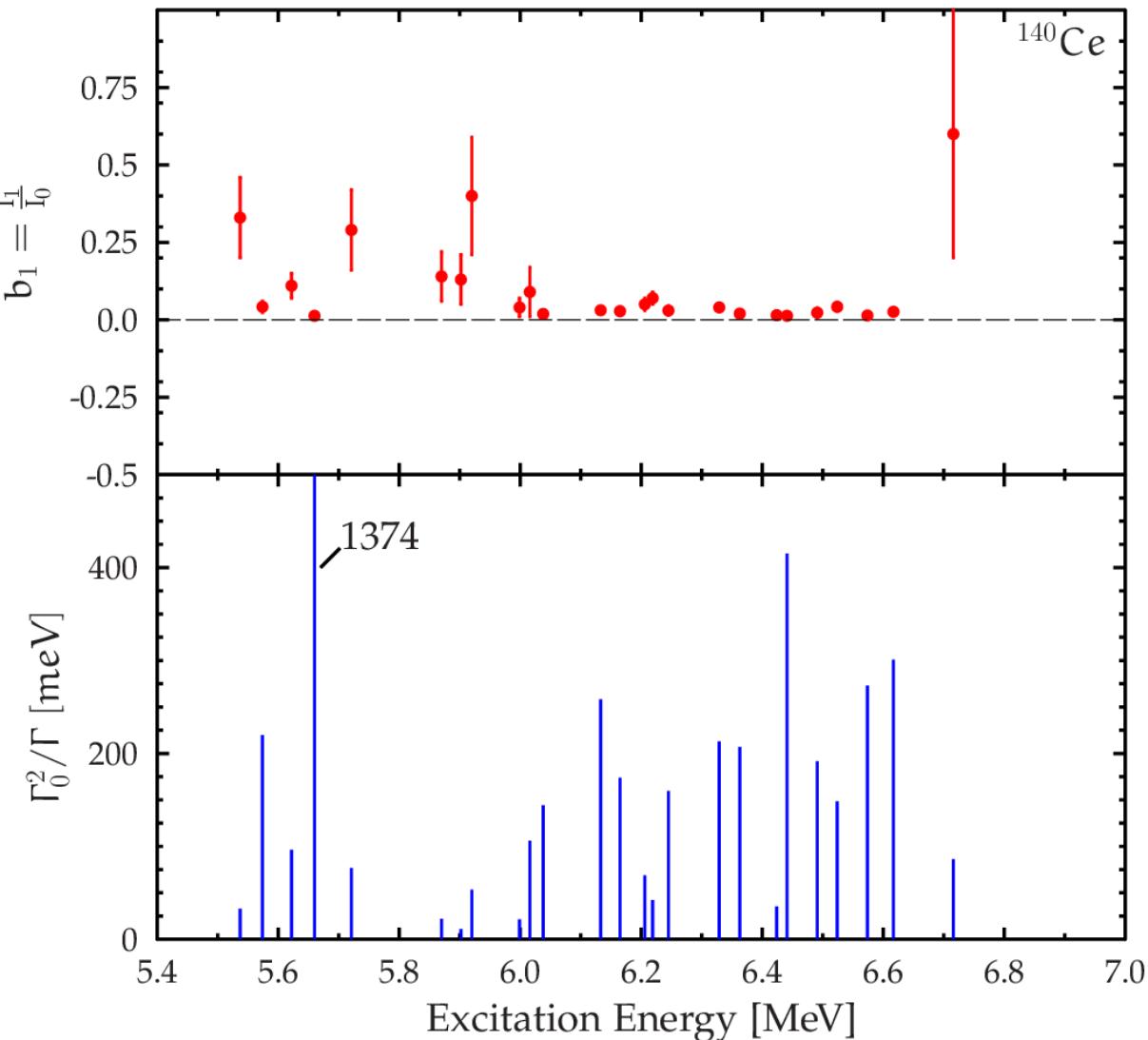
$^{140}\text{Ce} (\gamma, \gamma')$



Branching ratio to first 2^+ for single states



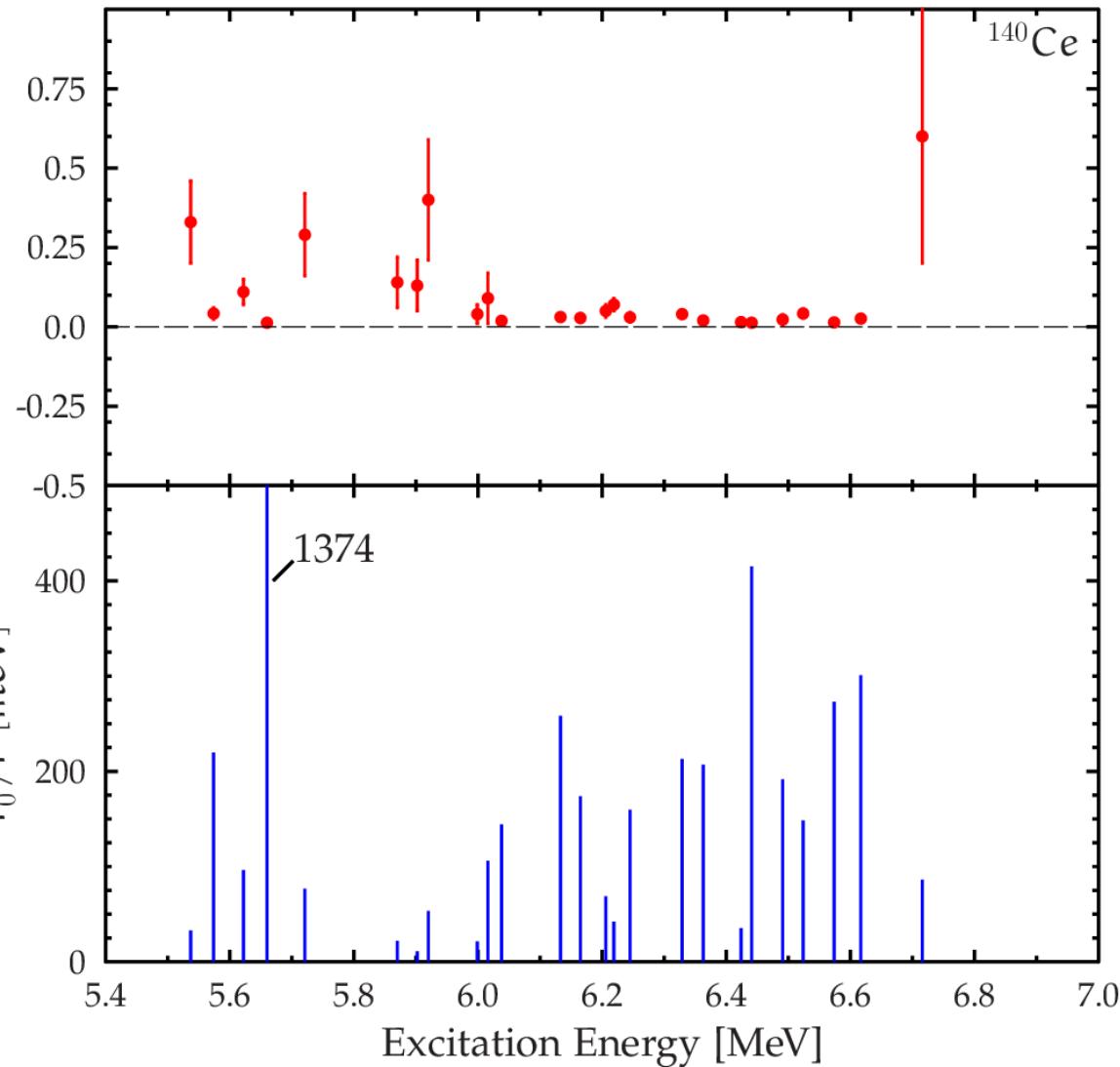
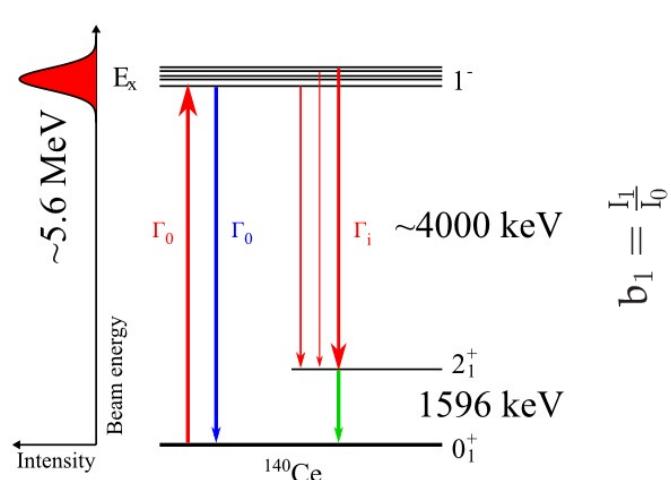
$$E(2^+_1) = 1596 \text{ keV}$$



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



Branching ratio to first 2^+ for single states

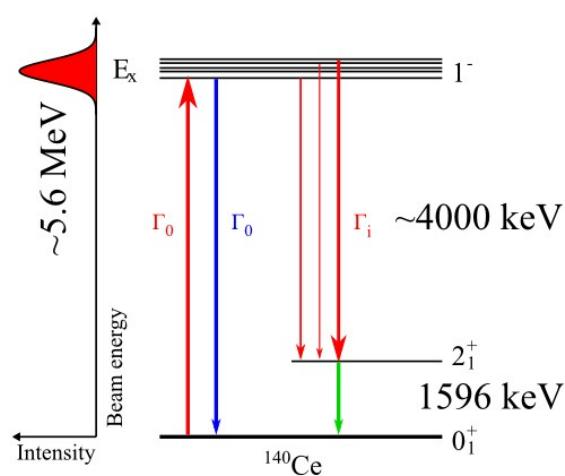


D. Savran *et al.*, Phys. Rev. Lett. **97**, 172502 (2006)

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

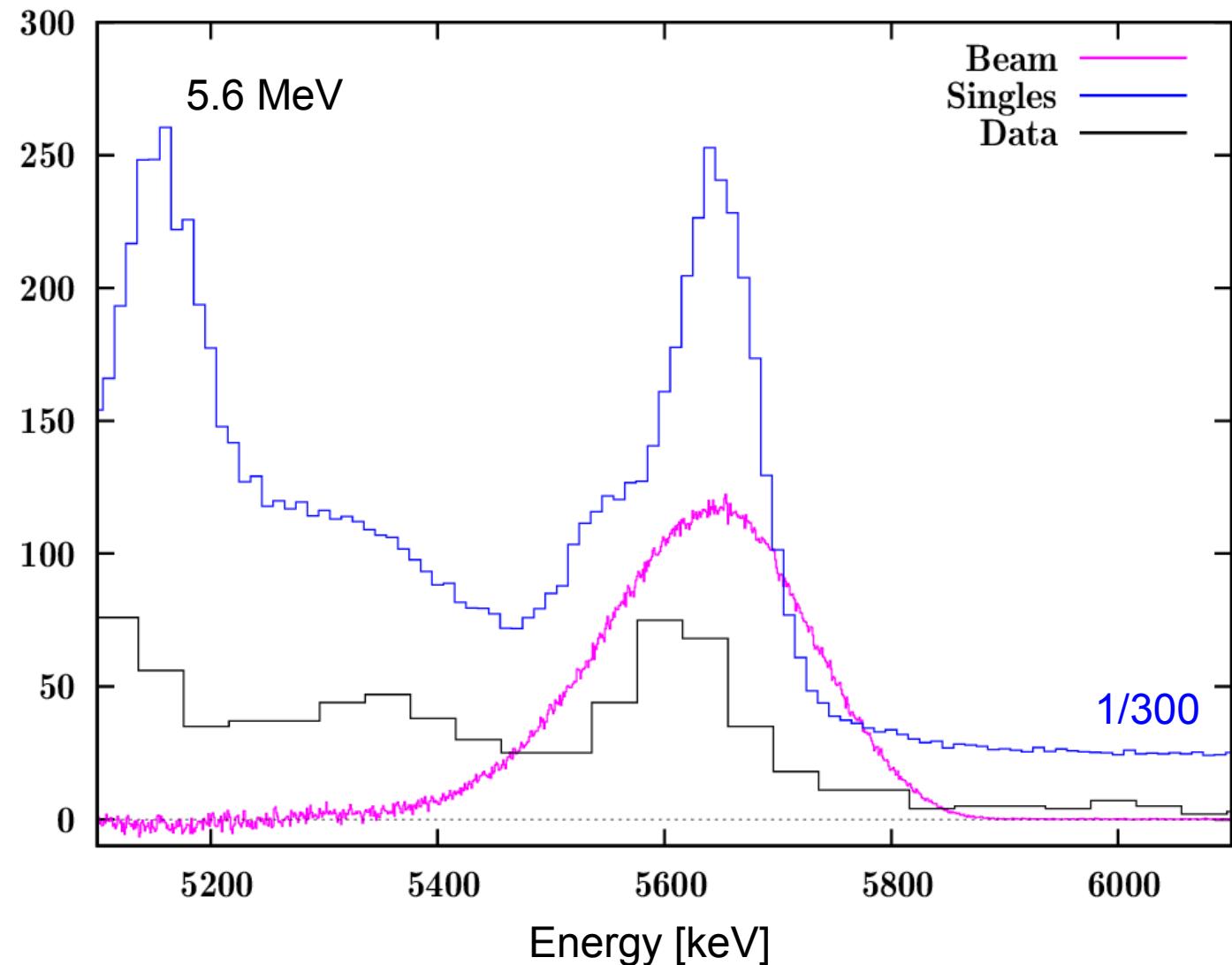


Gate on $\text{LaBr} \rightarrow \text{LaBr}$ spectra



Average branching ratio

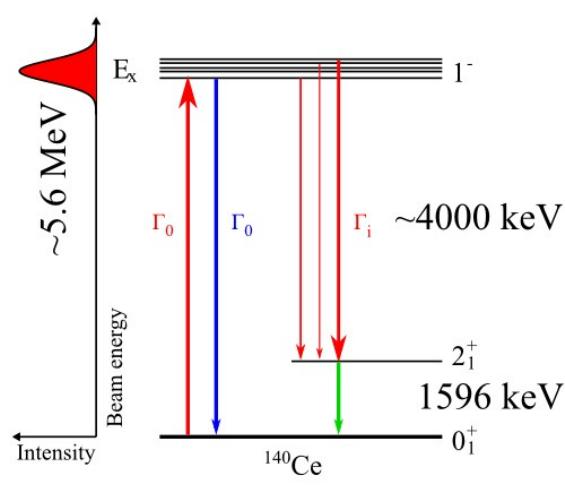
$$\langle b_1 \rangle = \frac{I_1}{I_0} = \frac{\sum_i \Gamma_0 \Gamma_1 / \Gamma}{\sum_i \Gamma_0^2 / \Gamma}$$



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



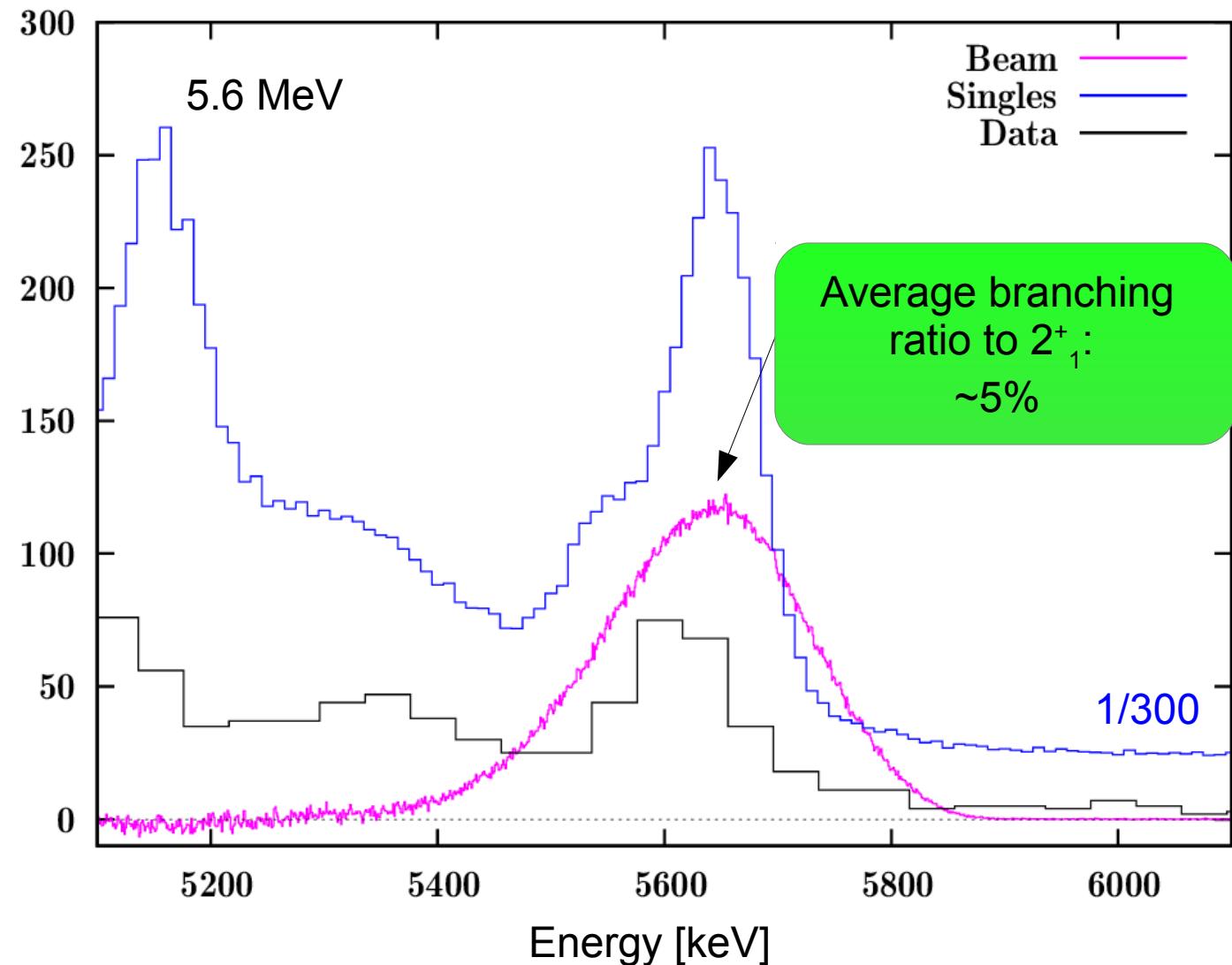
Gate on $\text{LaBr} \rightarrow \text{LaBr}$ spectra



$$E(2^+_1) = 1596 \text{ keV}$$

Average branching ratio

$$\langle b_1 \rangle = \frac{I_1}{I_0} = \frac{\sum_i \Gamma_0 \Gamma_1 / \Gamma}{\sum_i \Gamma_0^2 / \Gamma}$$

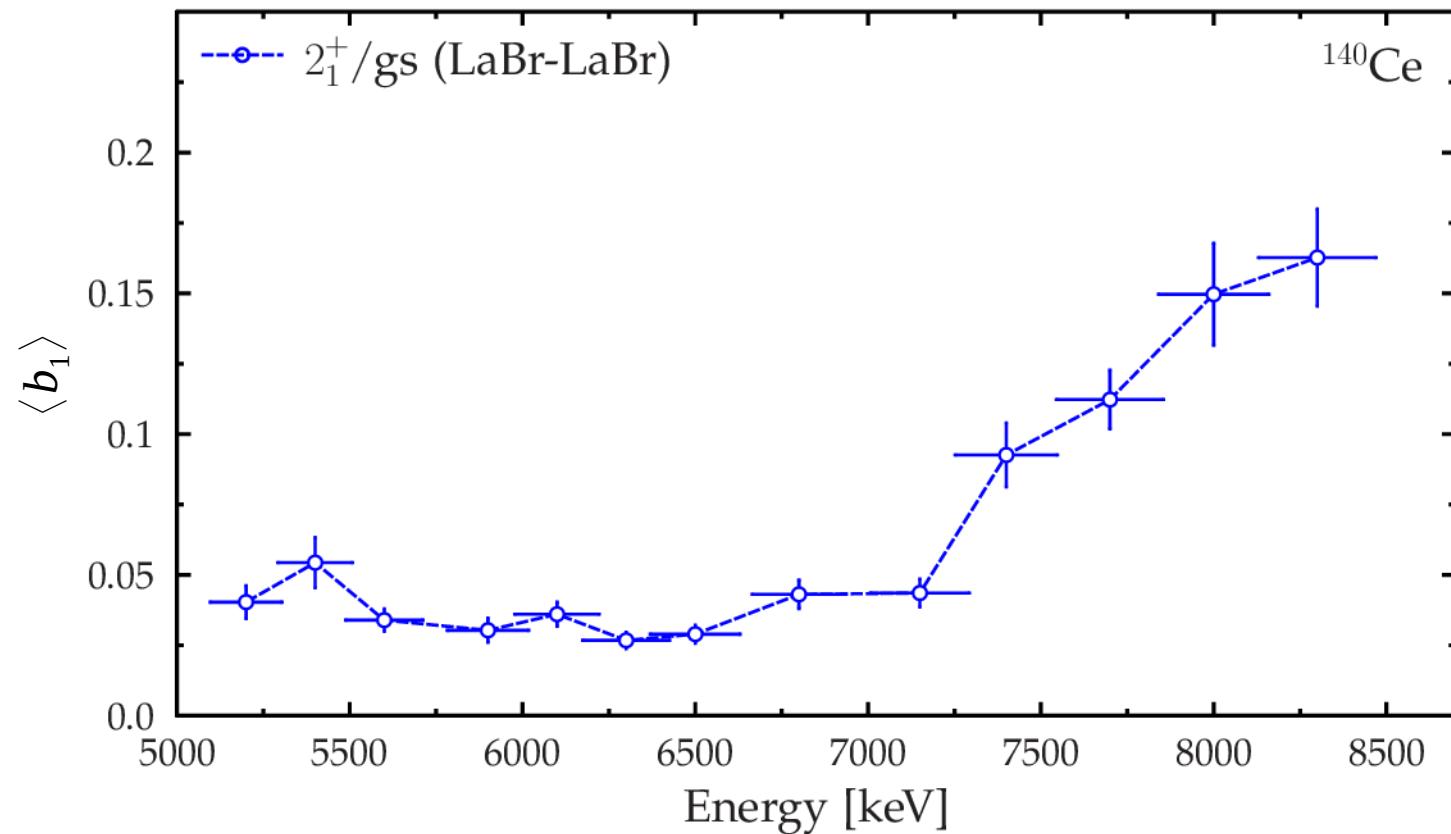


$^{140}\text{Ce} (\gamma, \gamma')$



Average branching ratio to first excited states

$$\langle b_1 \rangle = \frac{I_1}{I_0} = \frac{\sum_i \Gamma_0 \Gamma_1 / \Gamma}{\sum_i \Gamma_0^2 / \Gamma}$$

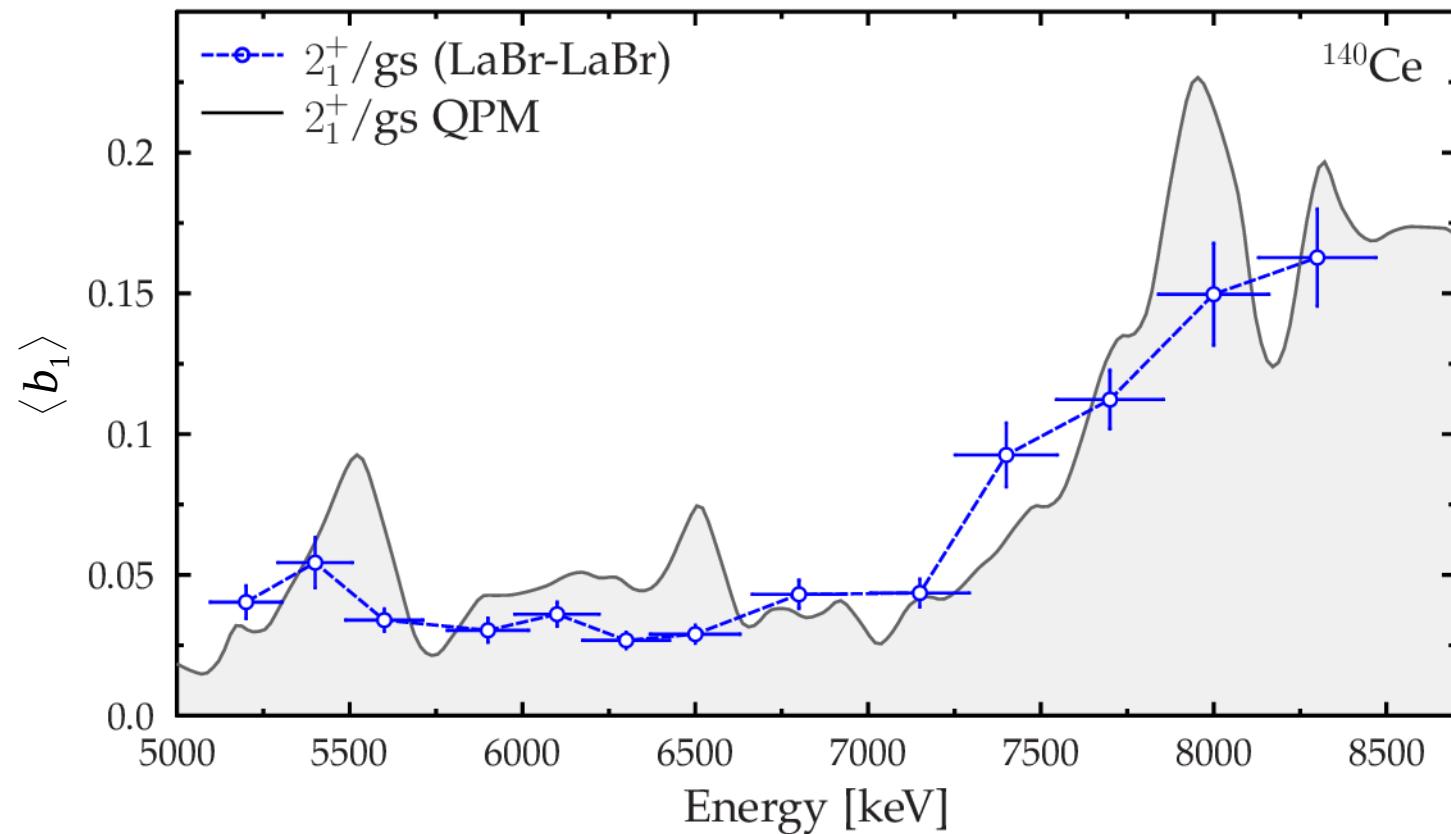


$^{140}\text{Ce} (\gamma, \gamma')$



Average branching ratio to first excited states

$$\langle b_1 \rangle = \frac{I_1}{I_0} = \frac{\sum_i \Gamma_0 \Gamma_1 / \Gamma}{\sum_i \Gamma_0^2 / \Gamma}$$



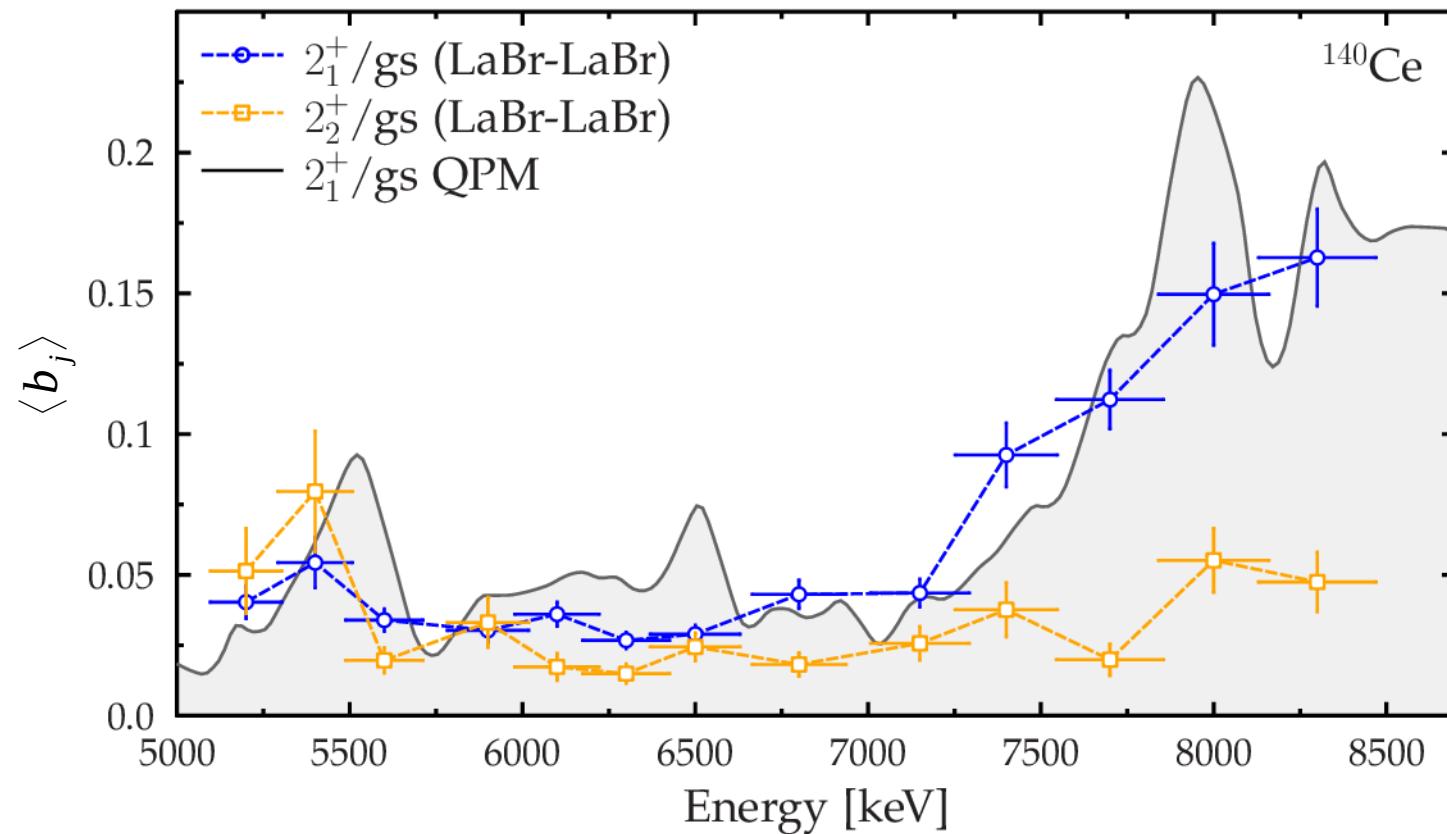
QPM: V.Yu. Ponomarev, priv. comm.

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



Average branching ratio to first excited states

$$\langle b_j \rangle = \frac{I_1}{I_0} = \frac{\sum_i \Gamma_0 \Gamma_j / \Gamma}{\sum_i \Gamma_0^2 / \Gamma}$$



QPM: V.Yu. Ponomarev, priv. comm.

^{140}Ce (γ, γ')



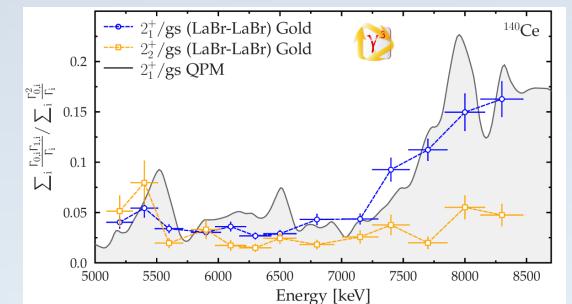
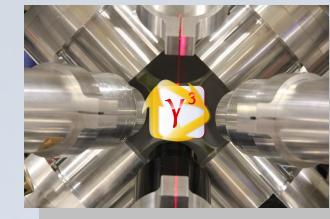
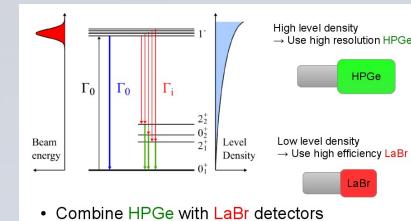
Using γ - γ Coincidences

- Determine branching ratios of single states (**Sensitivity 1-5%**)
- Average branching ratios (**Sensitivity down to 1%**)



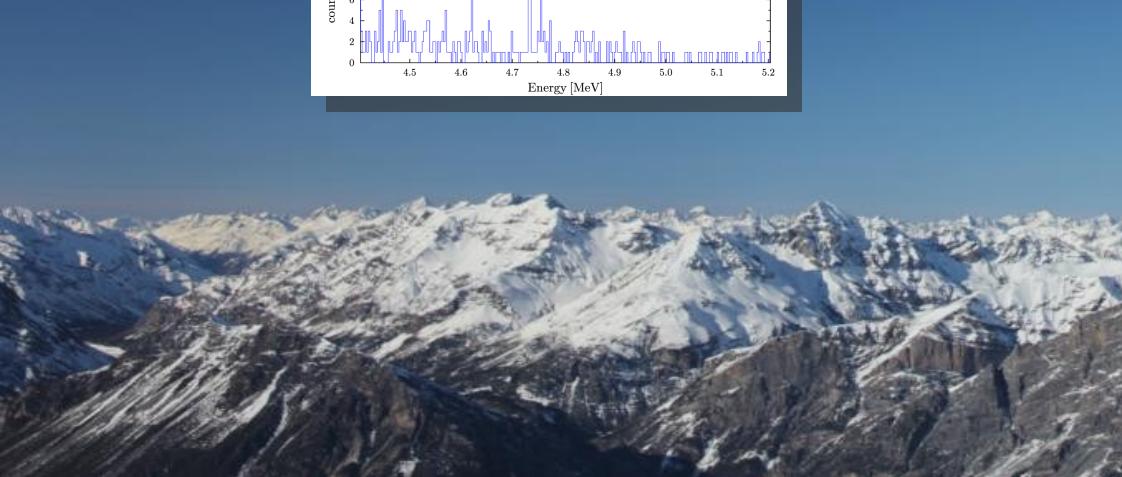
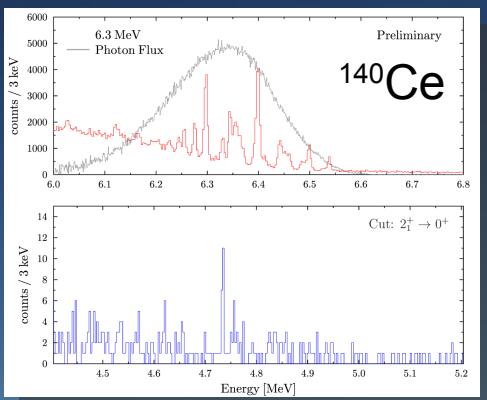
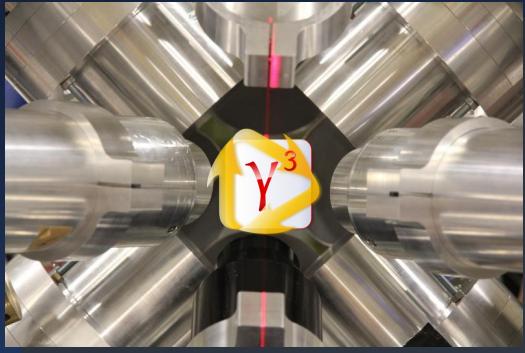
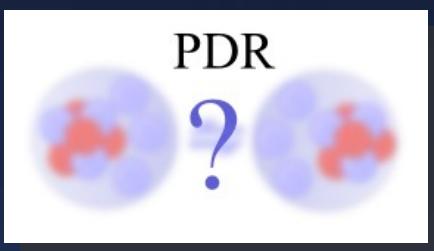
Summary

- γ - γ coincidence method to increase sensitivity for weak transitions
- New γ^3 setup at HLyS
- Now possible to measure single and average branching ratios
- Good agreement with QPM



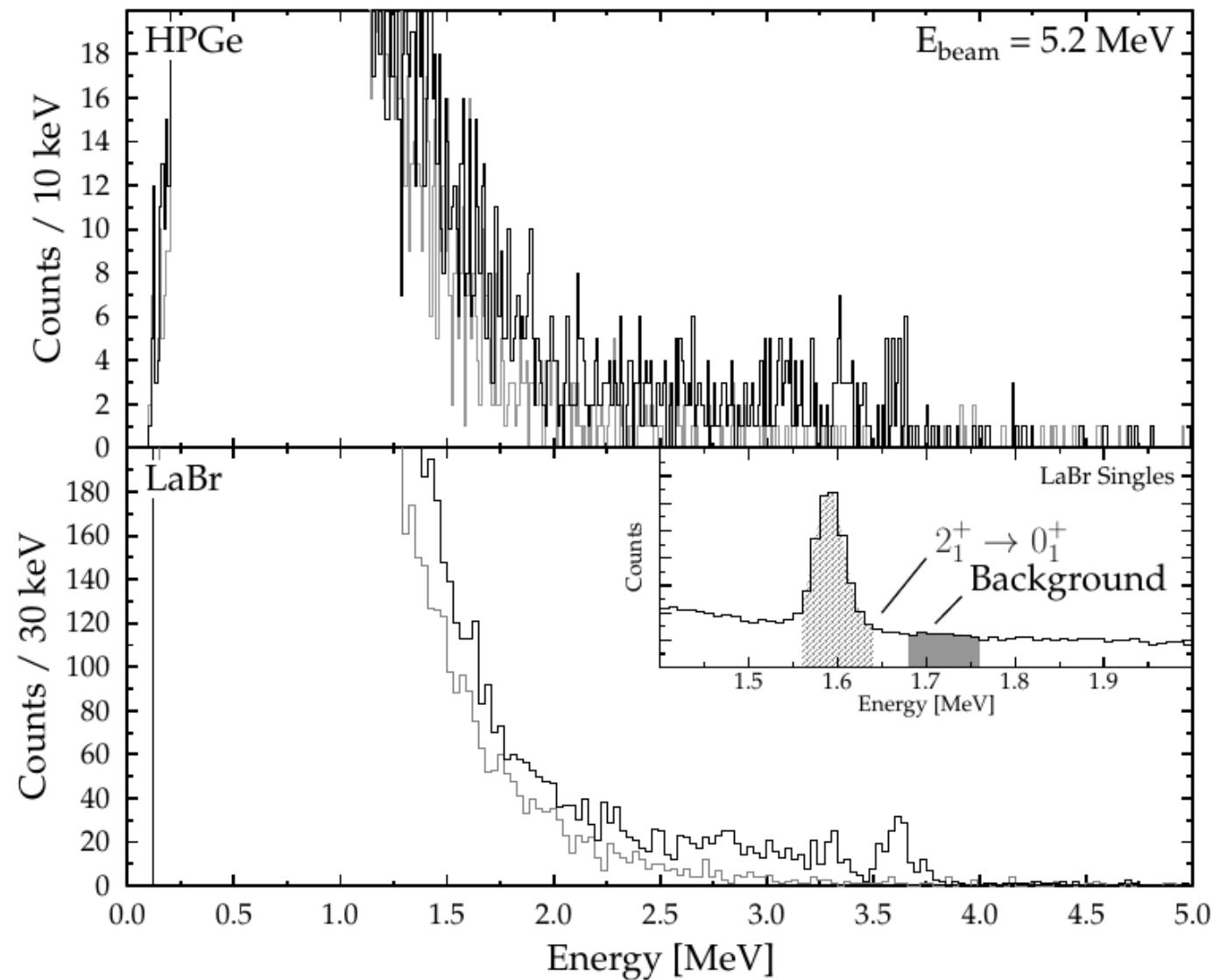
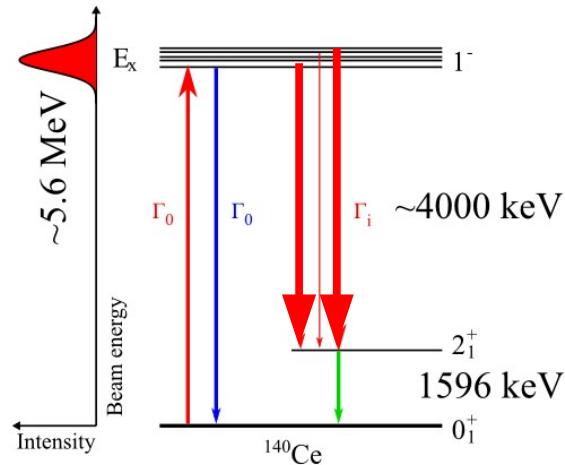
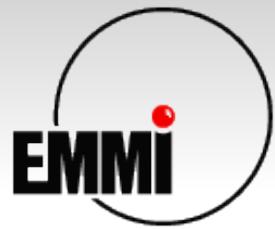


Collaboration

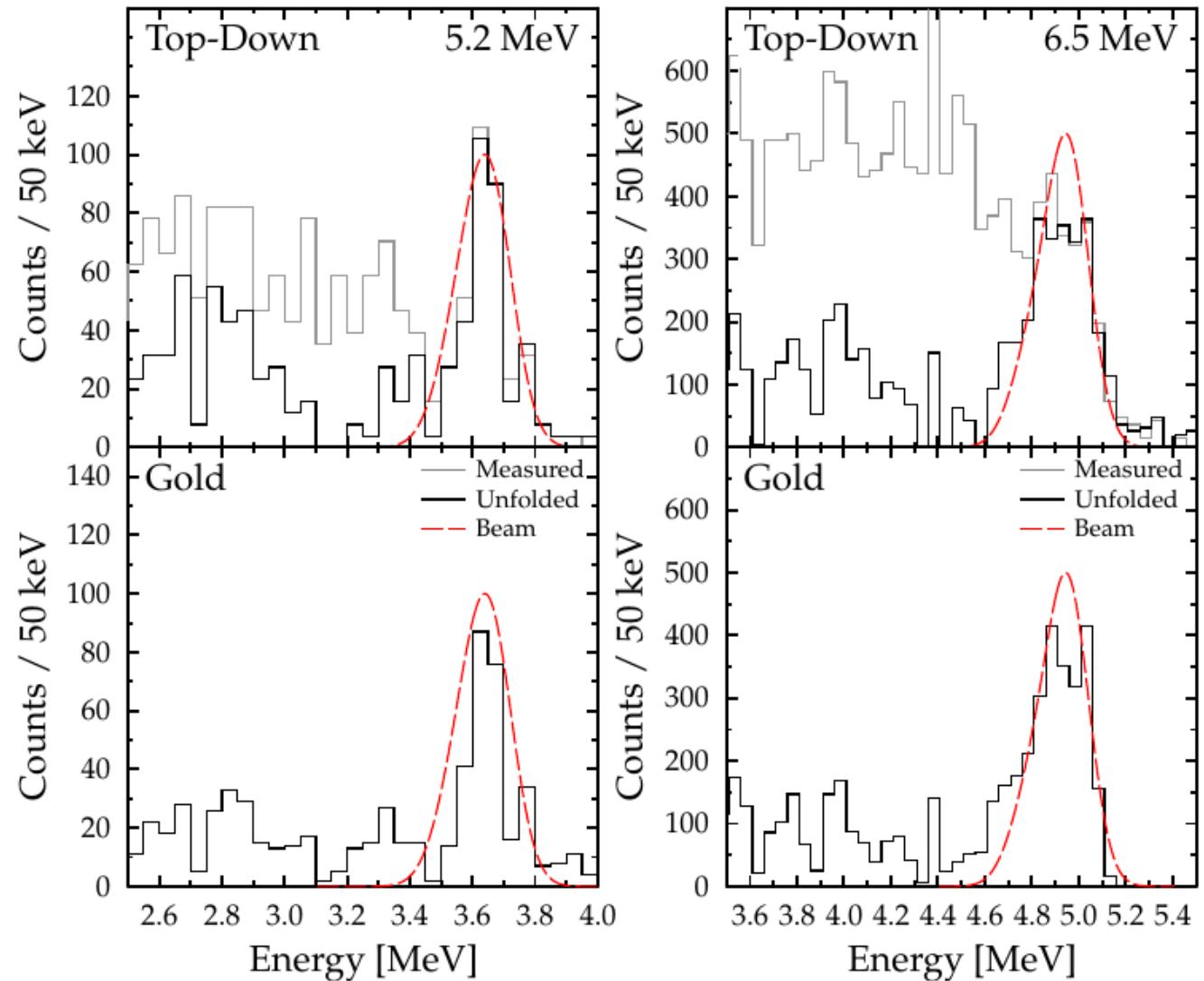
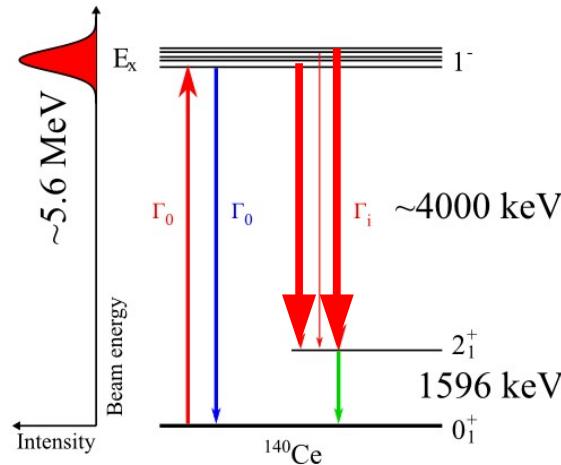


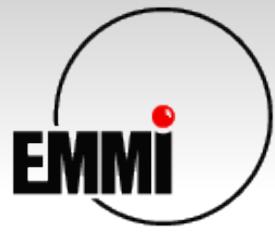
- **EMMI/GSI**
 - B.Löher, E.Fiori, J.Isaak, D.Savran, J.Silva
- **TU Darmstadt**
 - T.Aumann, J.Beller, M.Duchêne, M.Knörzer, N.Pietralla, M.Scheck, H.Scheit
- **Universität zu Köln (Cologne)**
 - V.Derya, J.Endres, A.Zilges
- **HlγS (Duke University)**
 - M.Bhike, M.Gooden, J.Kelley, A.Tonchev, W.Tornow, H.Weller
- **Yale University**
 - N.Cooper, P.Humby, V.Werner

^{140}Ce Energy Gate



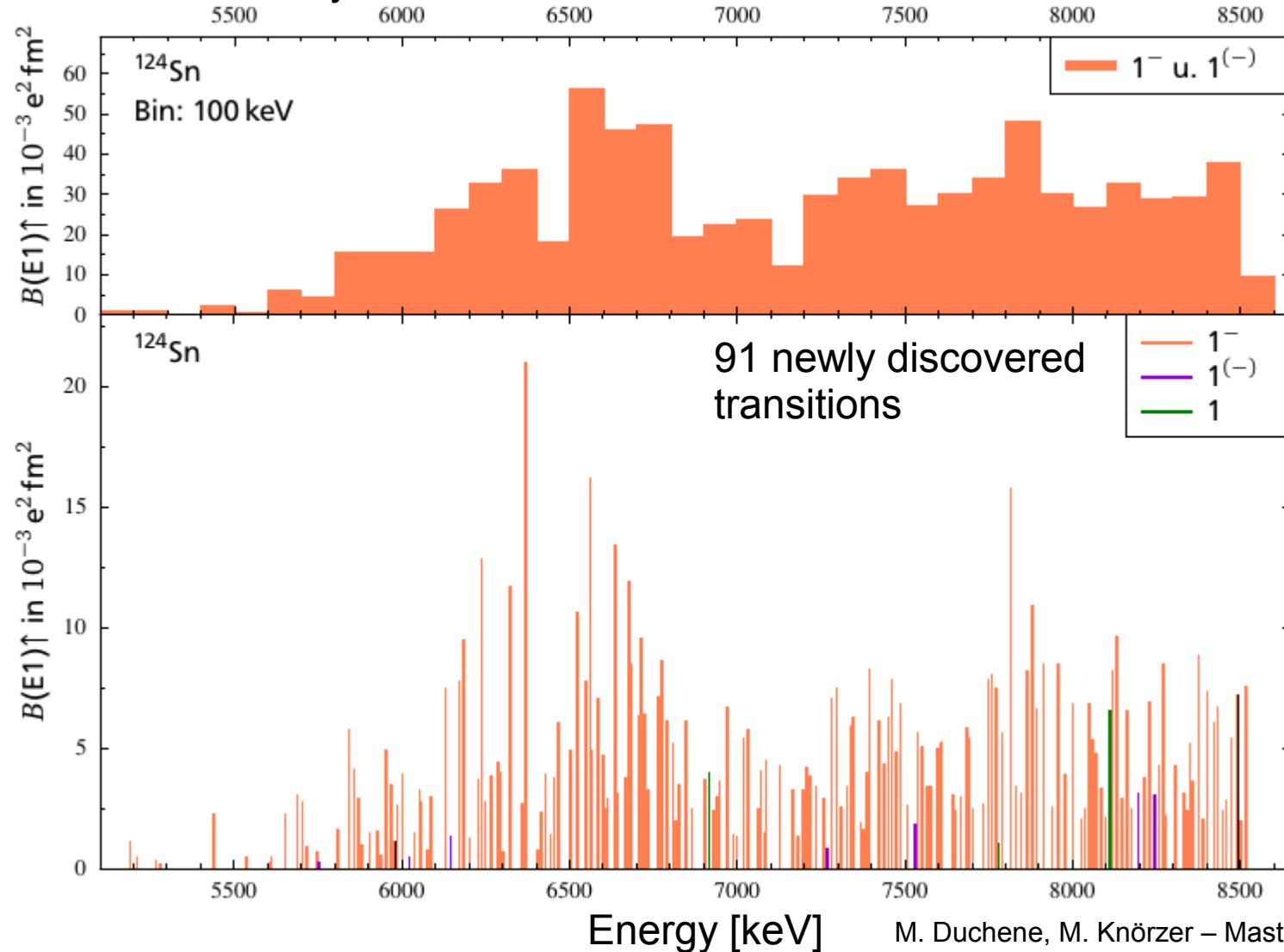
^{140}Ce LaBr Unfolded





More γ^3 results - ^{124}Sn

Parities and decay of the PDR in ^{124}Sn



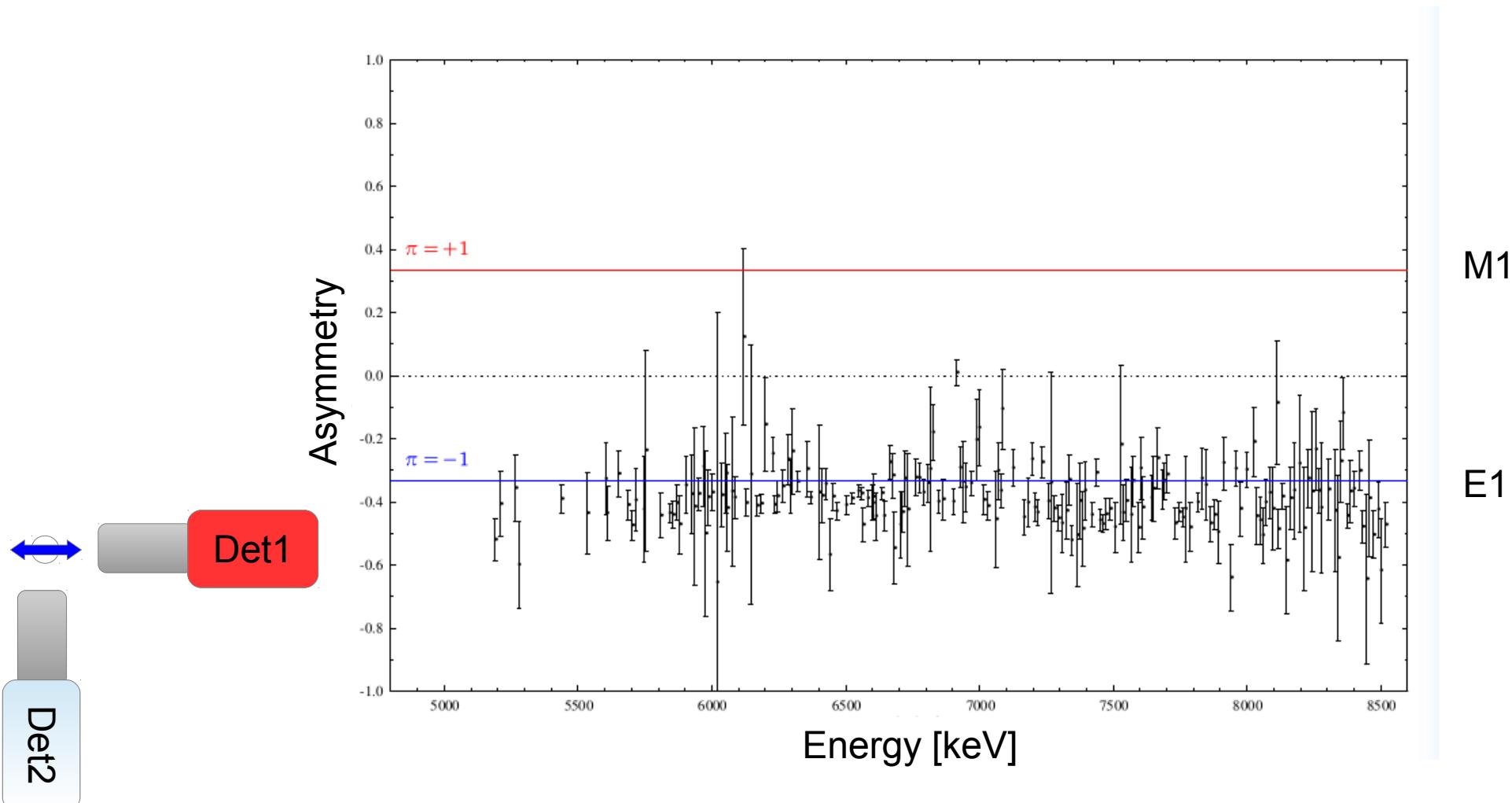
Energy [keV]

M. Duchene, M. Knörzer – Master Thesis

More γ^3 results - ^{124}Sn



Parities and decay of the PDR in ^{124}Sn

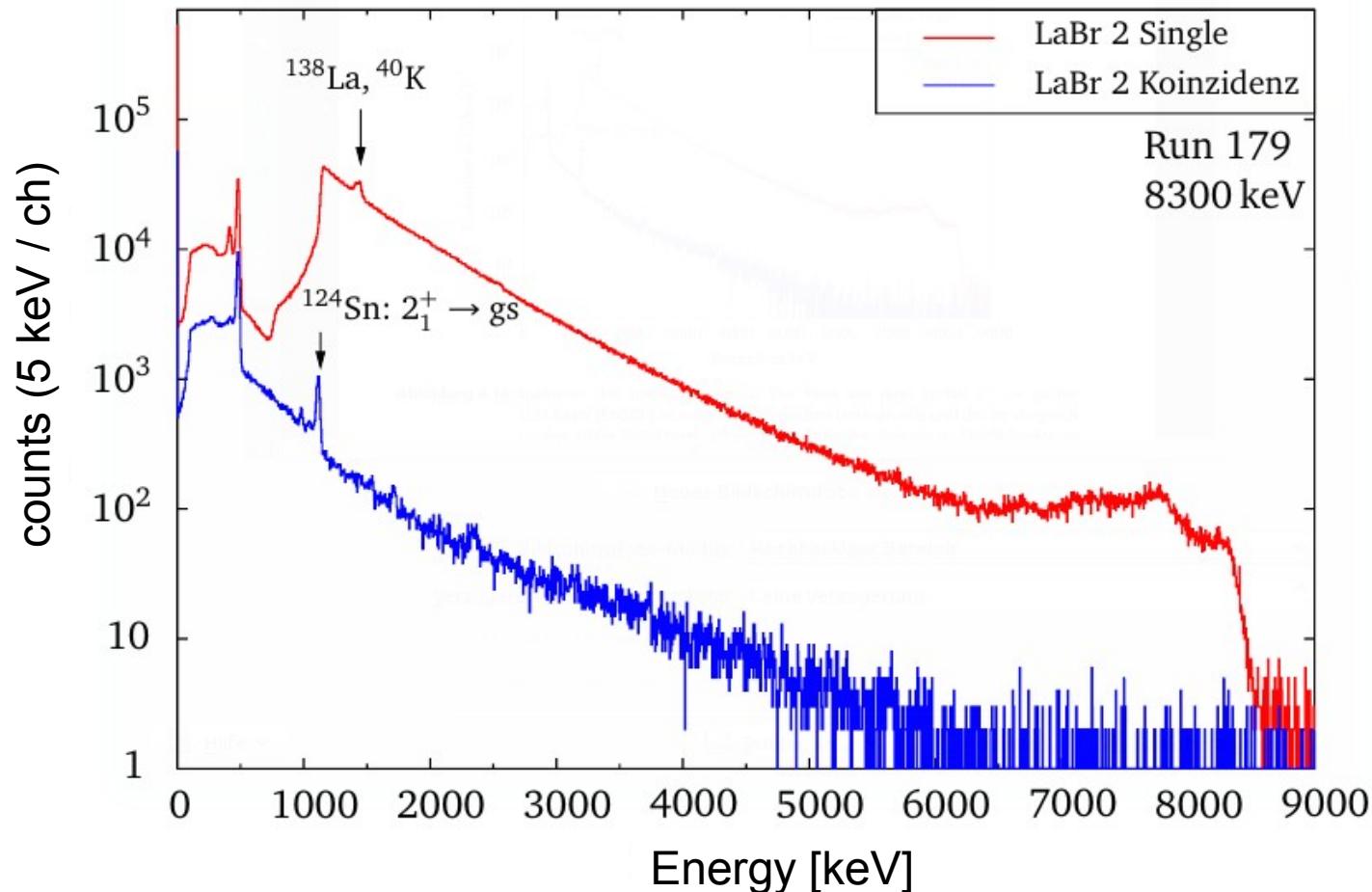


M. Duchene, M. Knörzer – Master Thesis



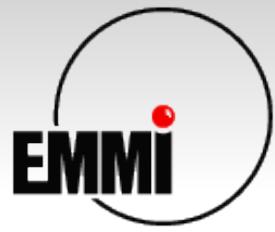
More γ^3 results - ^{124}Sn

Parities and decay of the PDR in ^{124}Sn

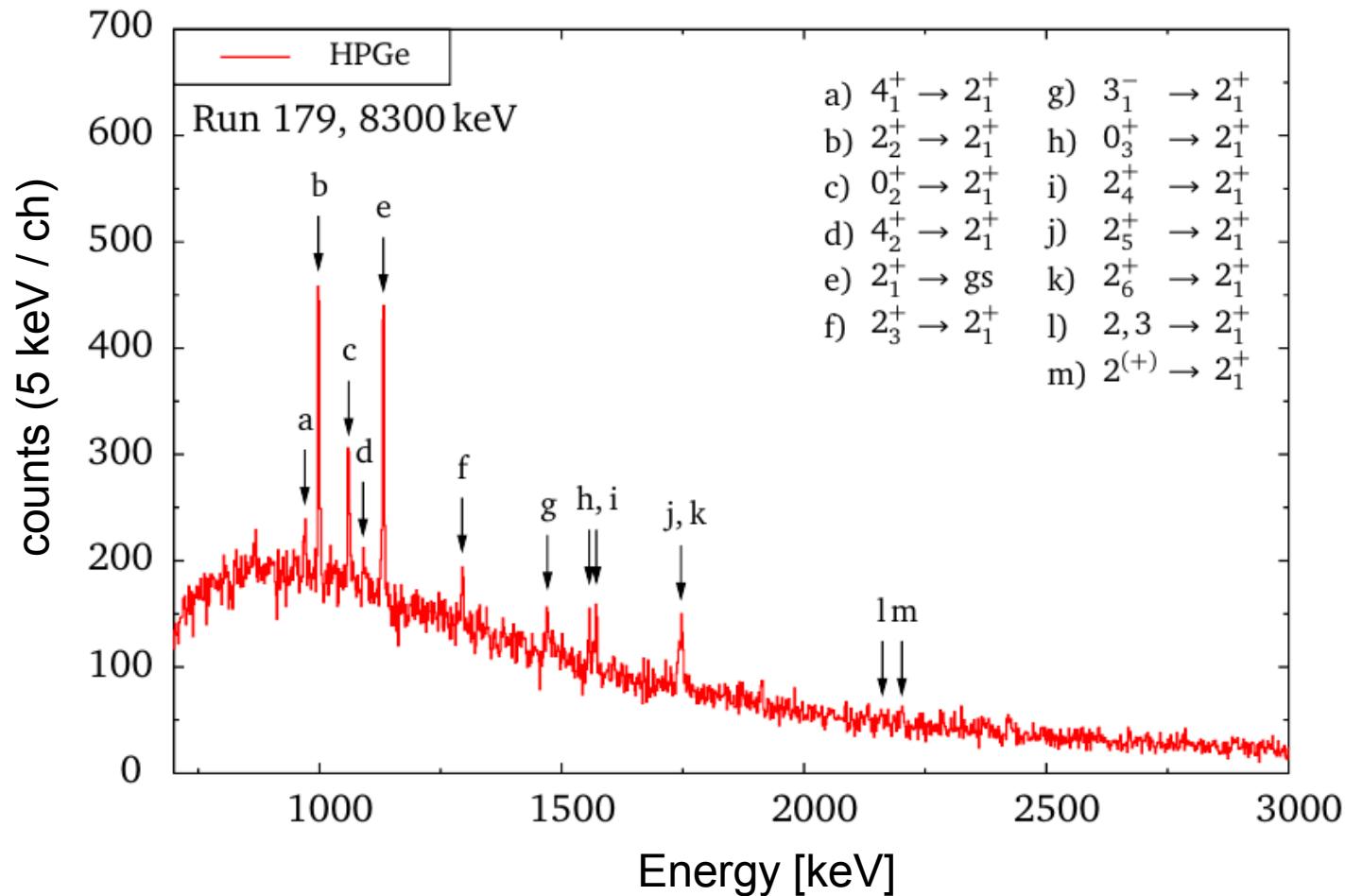


Energy gate on first $2^+ \rightarrow \text{gs}$ in LaBr

M. Duchene, M. Knörzer – Master Thesis



More γ^3 results - ^{124}Sn



Decays to 2^+ measured, but efficiency too small for primary transitions

M. Duchene, M. Knörzer – Master Thesis



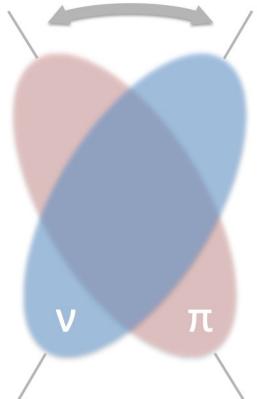
More γ^3 results - ^{156}Gd

Fragmentation of the Scissor's Mode

> 50 h beam at 3.07 MeV

Branching ratios to 4 excited states measured

Sensitivity for branchings **better than 0.3%**



J_j^π	J_k^π	$(E_j - E_k)$ [keV]	$R_{\text{exp}} = \Gamma_k / \Gamma_0$	R_{Lit} [Pitz <i>et al.</i> (1989)]
1_{sc}^+	0_1^+	3070	1.000(3)	
	2_1^+	2981	0.48(1)	0.59(6)
1_{sc}^+	0_1^+	3050	1.00(2)	
	2_1^+	2961	0.48(3)	0.36(16)
1_{sc}^+	0_1^+	3010	1.00(4)	
	2_1^+	2921	0.41(6)	0.48(21)
1_{sc}^+	0_1^+	2974	1.00(3)	
	2_1^+	2885	0.47(5)	0.41(7)