Investigation of low-lying dipole strengths using real photon-scattering experiments

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[3]GSI, Darmstadt, Germany
[4]Helmholtz-Zentrum Dresden-Rossendorf, Germany

Giant and Soft Modes of Excitation in Nuclear
Structure and Astrophysics

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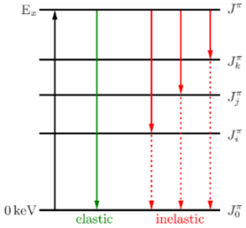
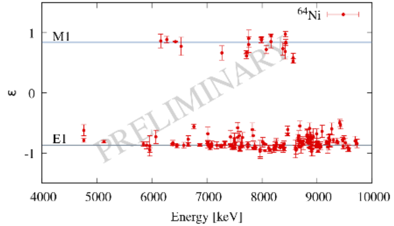
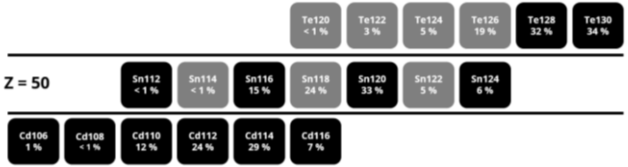
Outline

1. introduction to (γ,γ‘) experiments
   - method
   - photon sources
2. analysis procedure (example ^{64}Ni)
3. systematic (γ,γ‘) investigations
   - Z = 28 region
   - Z = 50 region
   - N = 82 region
4. summary







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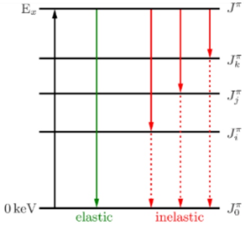
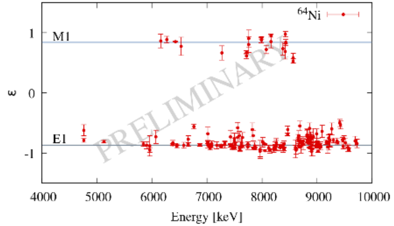
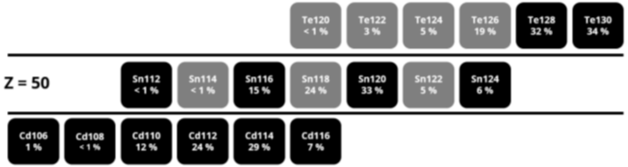
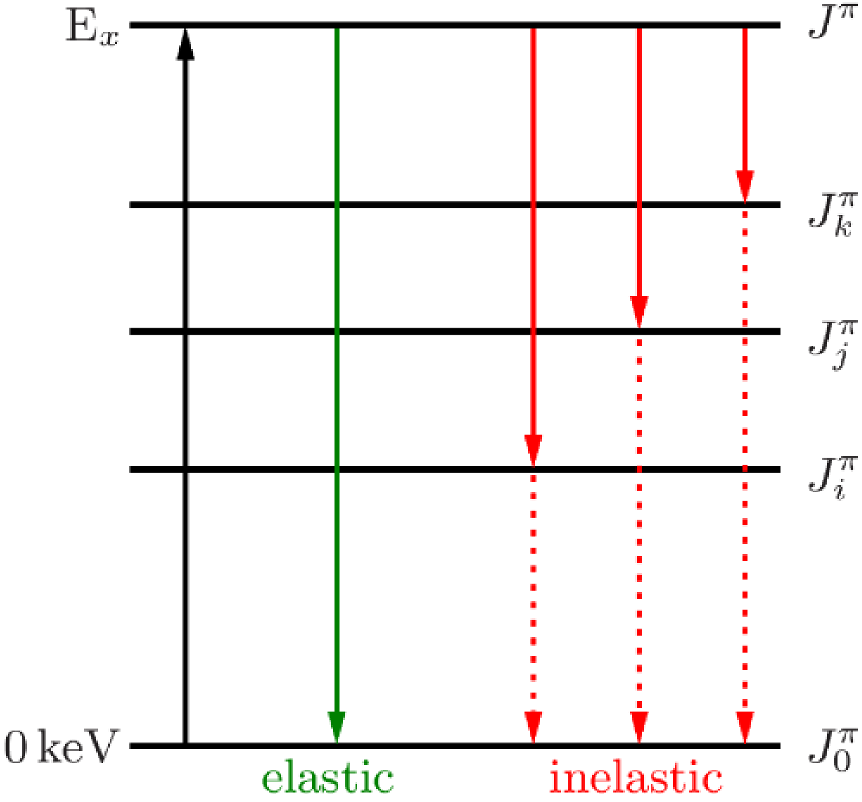






Real photon-scattering experiments

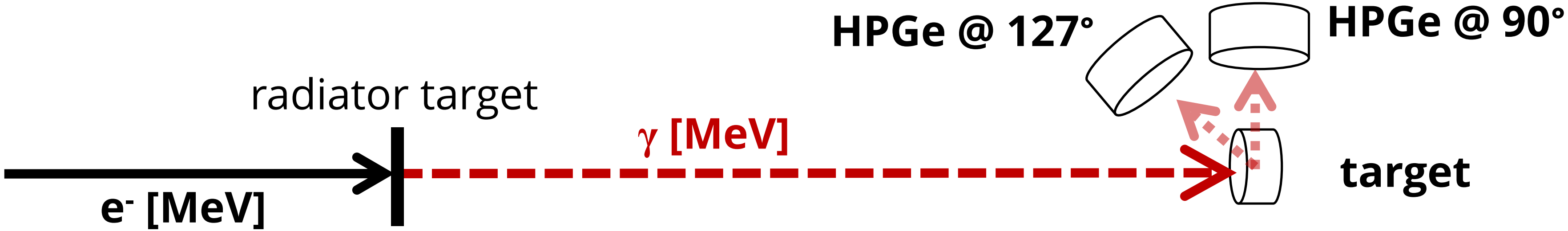
Nuclear Resonance Fluorescence (NRF) method

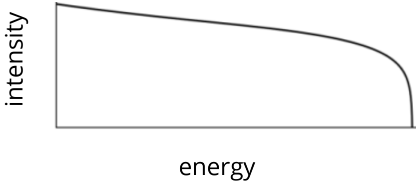


model-independent extraction of:

- level energies
- spin quantum numbers
- parity quantum numbers
- level lifetimes and total decay widths
- γ-decay branching ratios Γ_f/Γ_0
- …

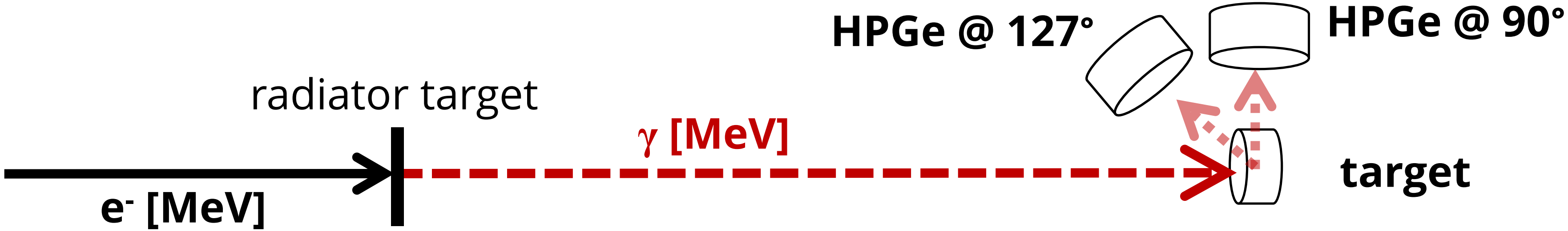
Photon source: Bremsstrahlung

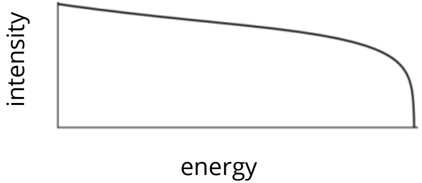




- mainly unpolarized, continuous photon flux
- multipole-order assignment

Photon source: Bremsstrahlung





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- multipole-order assignment
- simultaneous investigation of large energy range
- easy use of calibration standard for absolute photon-flux determination

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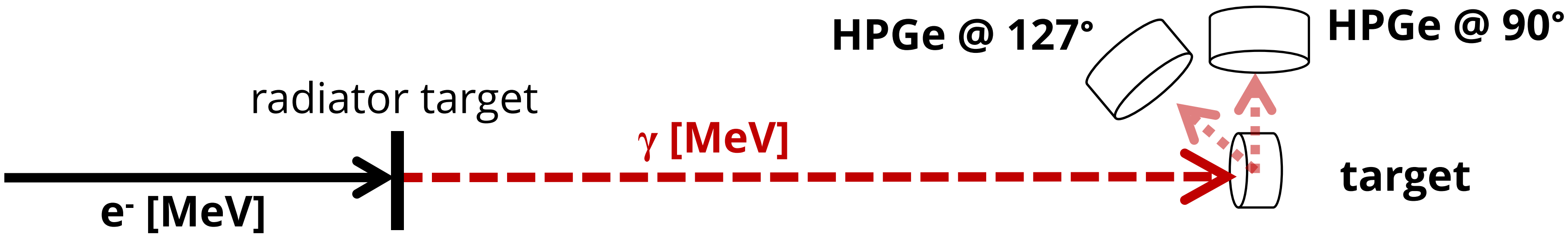
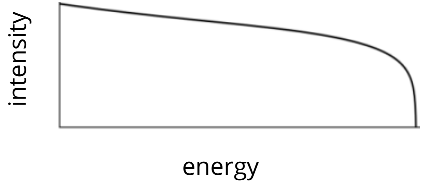
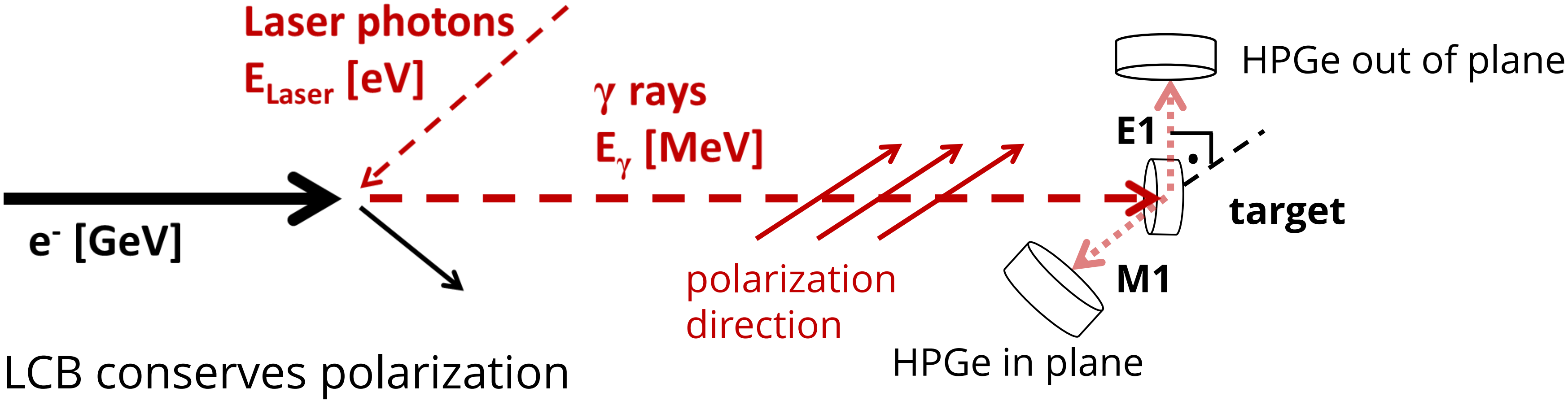




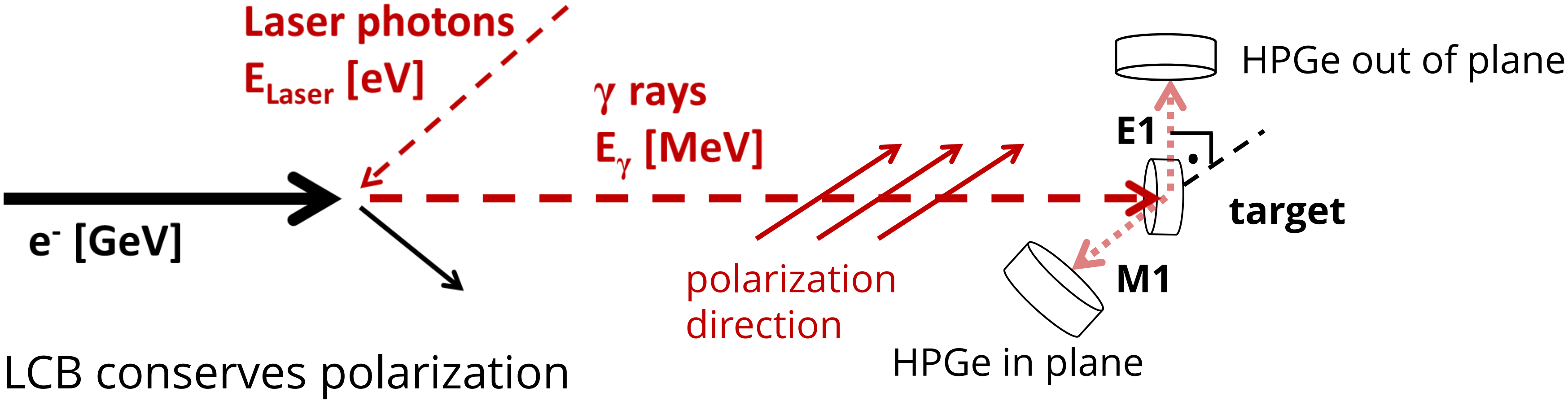
- mainly unpolarized, continuous photon flux
- multipole-order assignment
- simultaneous investigation of large energy range
- easy use of calibration standard for absolute photon-flux determination
- DHIPS (TU Darmstadt, Germany)
- γELBE (Helmholtz-Zentrum Dresden-Rossendorf, Germany)

Photon source: Laser-Compton-Backscattering (LCB)



- LCB conserves polarization

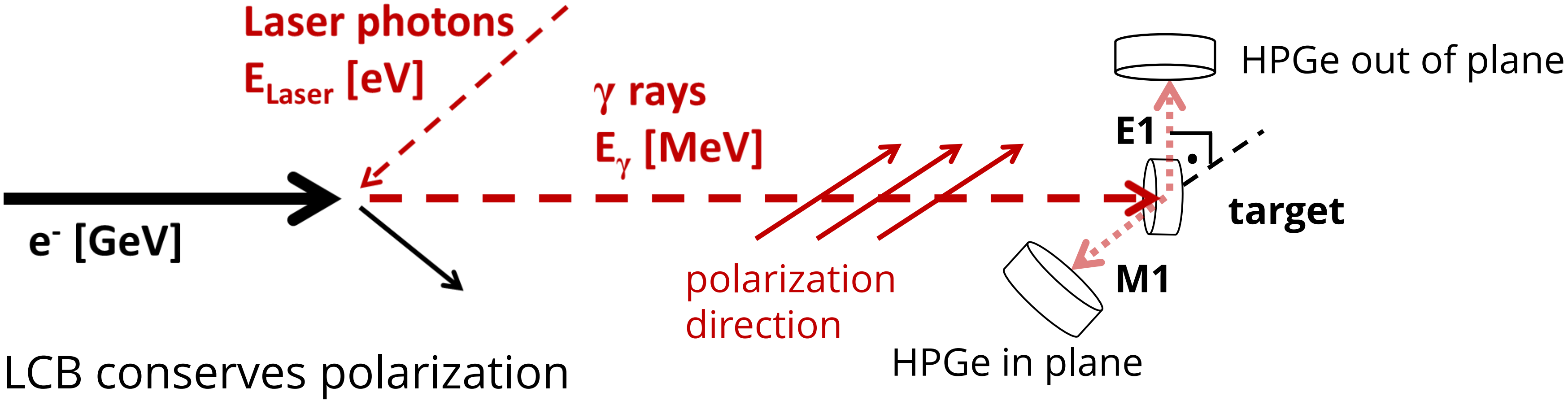
Photon source: Laser-Compton-Backscattering (LCB)



- LCB conserves polarization
- linearly-polarized photons

→ distinction between electric and magnetic transitions

Photon source: Laser-Compton-Backscattering (LCB)



Laser photons
E_{Laser} [eV]

γ rays
E_γ [MeV]

e^- [GeV]

polarization direction

HPGe out of plane

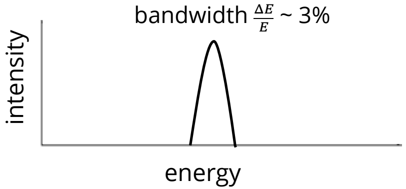
E1

target

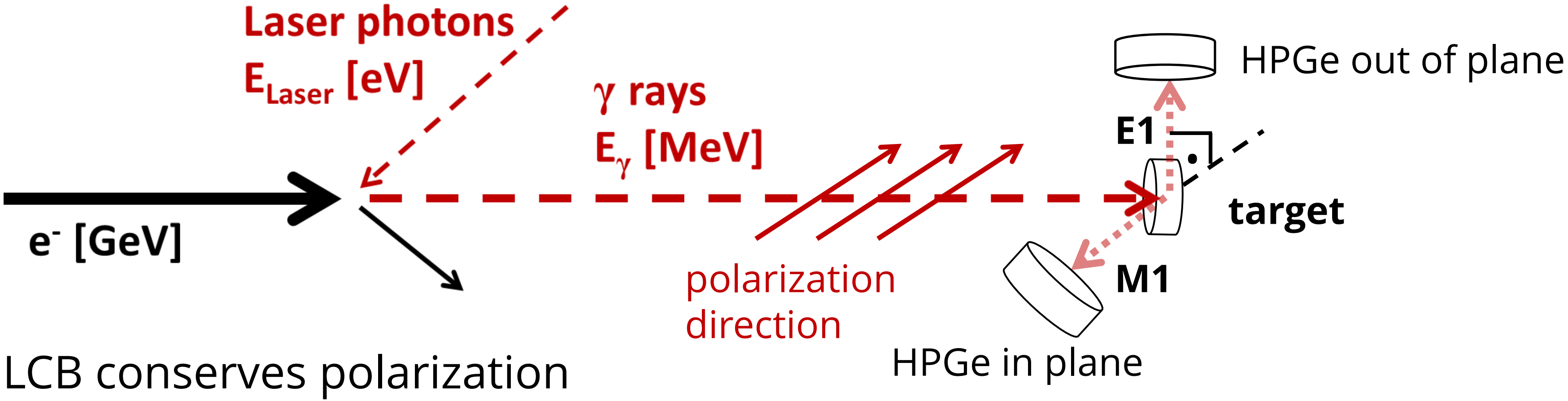
M1

HPGe in plane

- LCB conserves polarization
- linearly-polarized photons
  → distinction between electric and magnetic transitions
- quasi-monoenergetic γ-ray beam
  → γ-decay branching and unresolved strength



Photon source: Laser-Compton-Backscattering (LCB)



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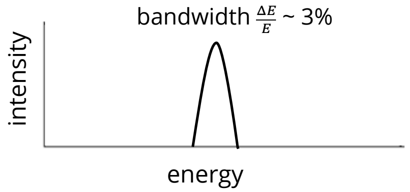
  → γ-decay branching and unresolved strength
- HIγS (Duke University, USA)



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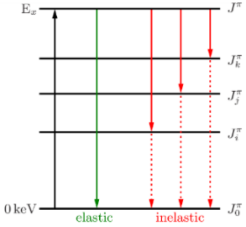

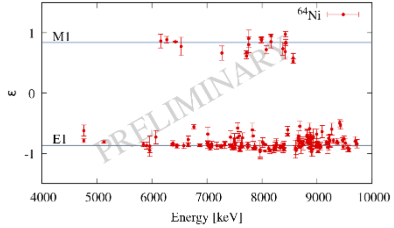

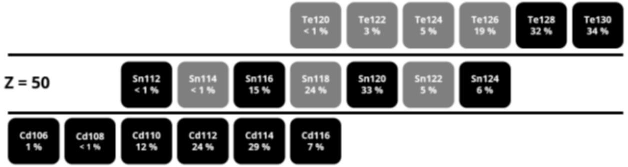

Example: Bremsstrahlung experiments on ^{64}Ni

- Bremsstrahlung measurements @ γELBE [1] (HZDR, Germany) with E_{max}= 7.3 MeV (LE) and 9.4 MeV (HE)
- ^{11}B as calibration standard
- absolute transition strengths can be extracted

[1] R. Schwengner *et al.*, NIM A **555** (2005) 211

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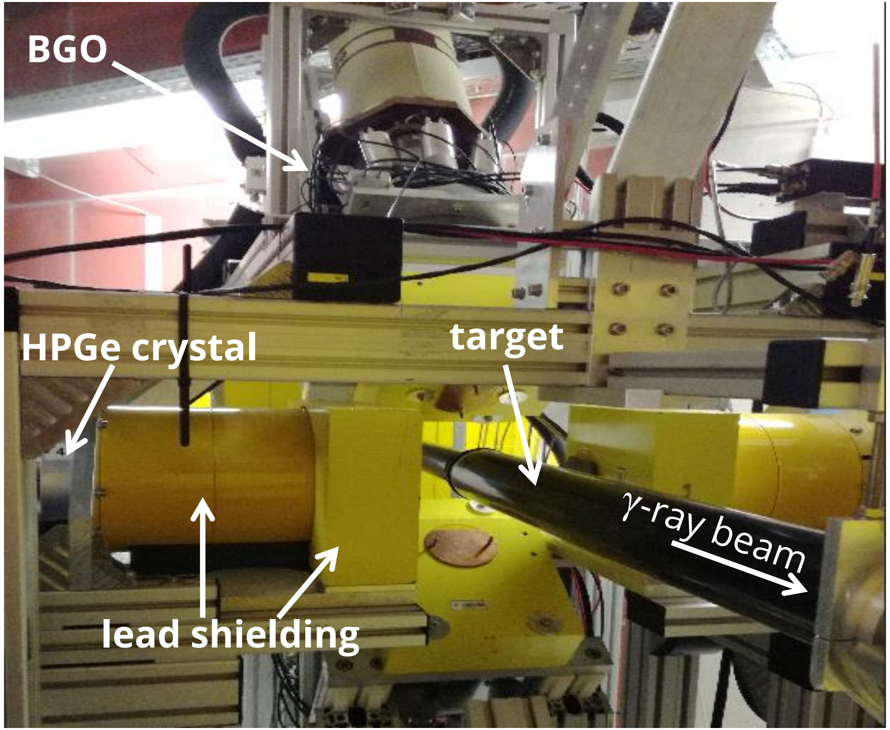
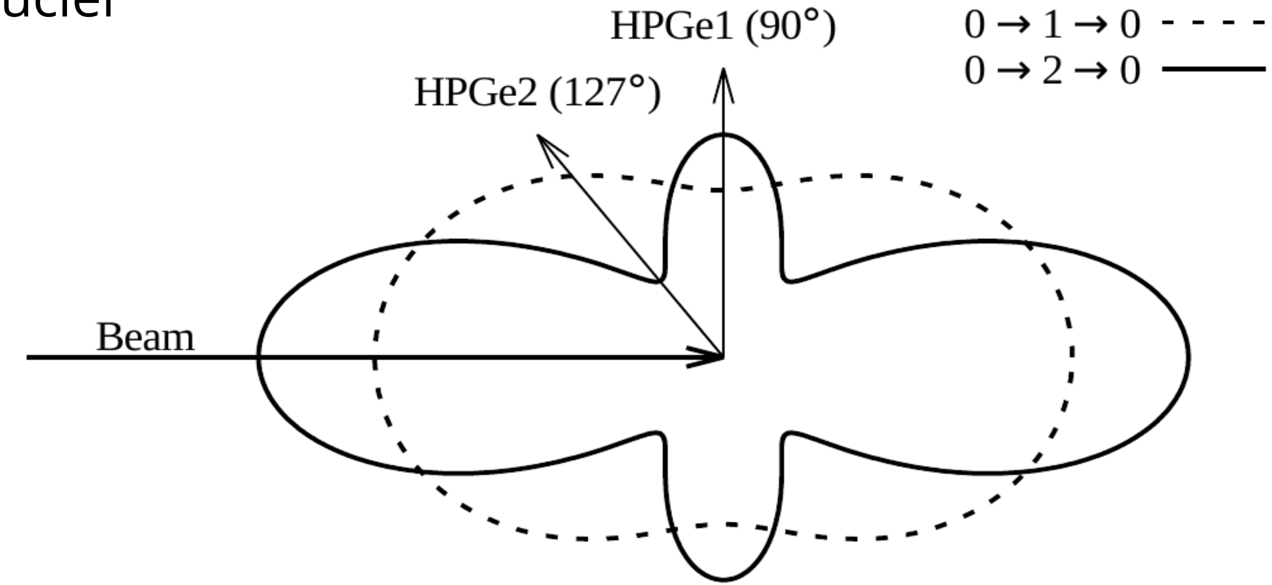
- ^{11}B as calibration standard
- absolute transition strengths can be extracted
- 4 Compton-shielded HPGe detectors @ θ = 90° and 127°
- multipole-order assignment



[1] R. Schwengner *et al.*, NIM A **555** (2005) 211

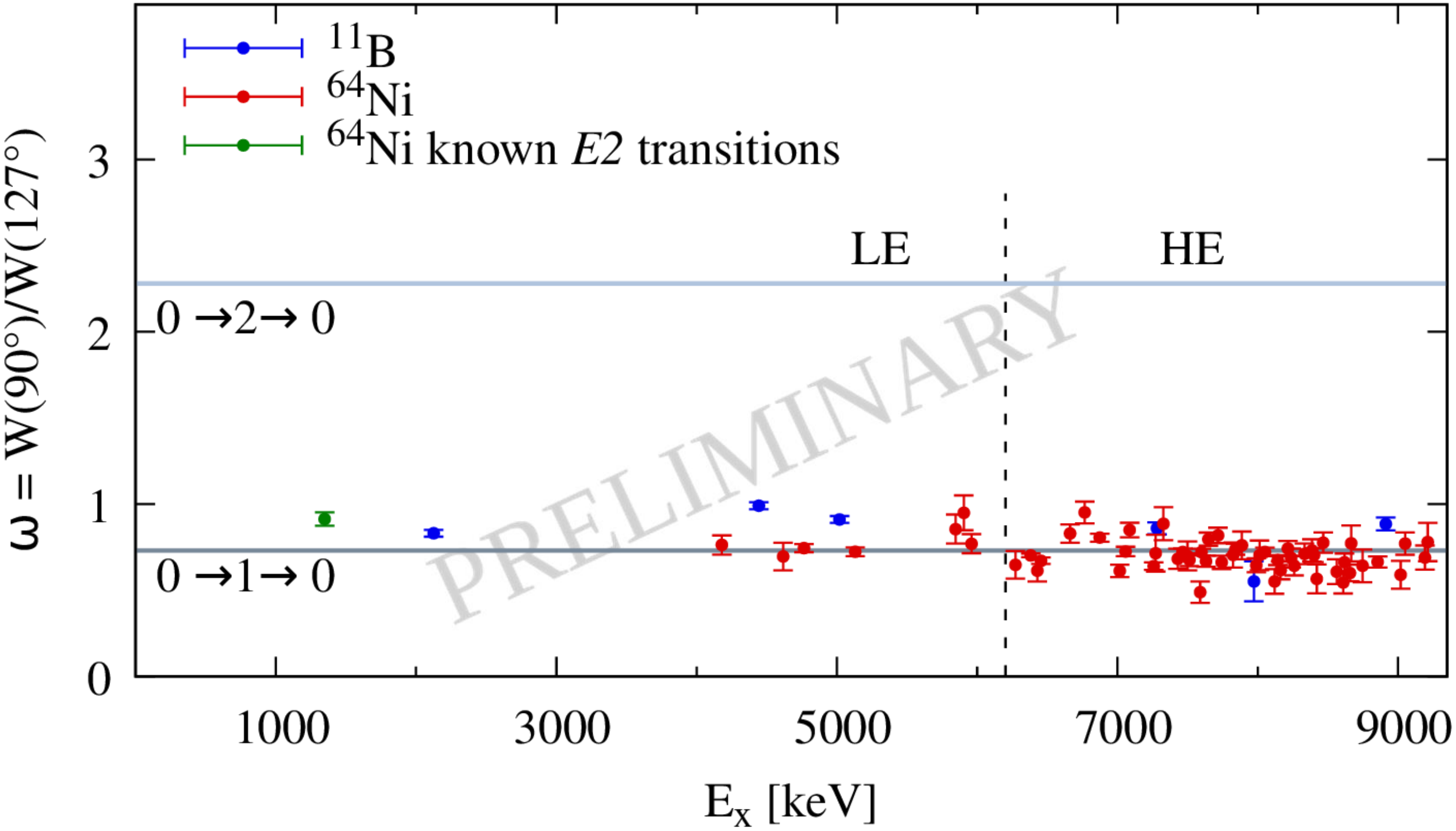
γELBE: Multipolarity determination

angular distributions of dipole and quadrupole excitations in even-even nuclei

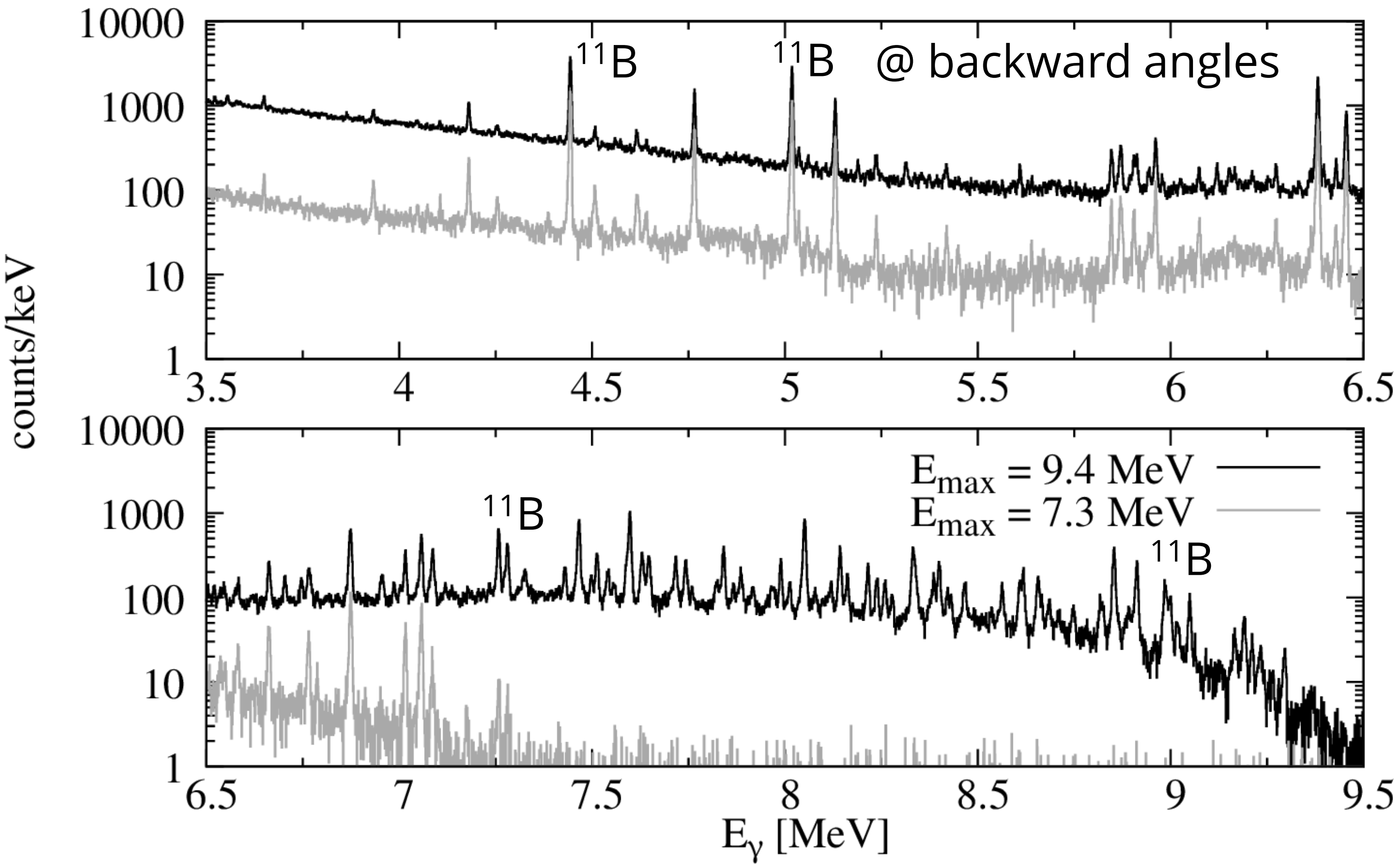


$$\omega = \frac{W(90^\circ)}{W(127^\circ)} = \begin{cases} 0.7 \text{ (dipole transition)} \\ 2.3 \text{ (quadrupole transition)} \end{cases}$$

Intensity ratios



Deexcitation spectra of bremsstrahlung experiment



^{11}B used as calibration standard

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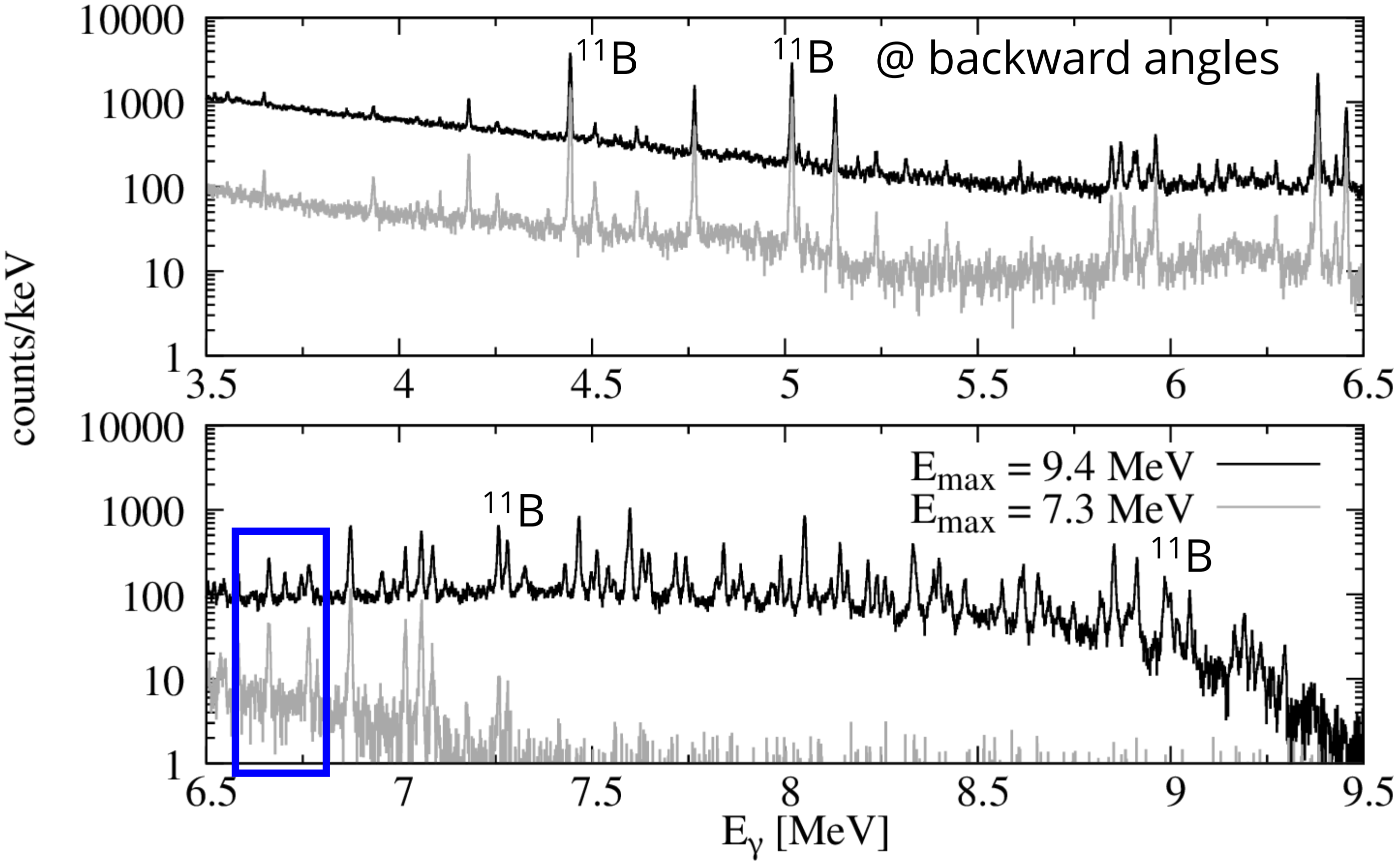
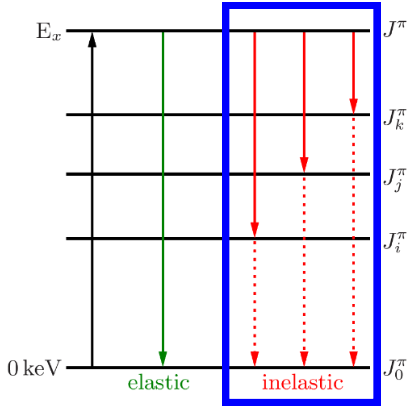
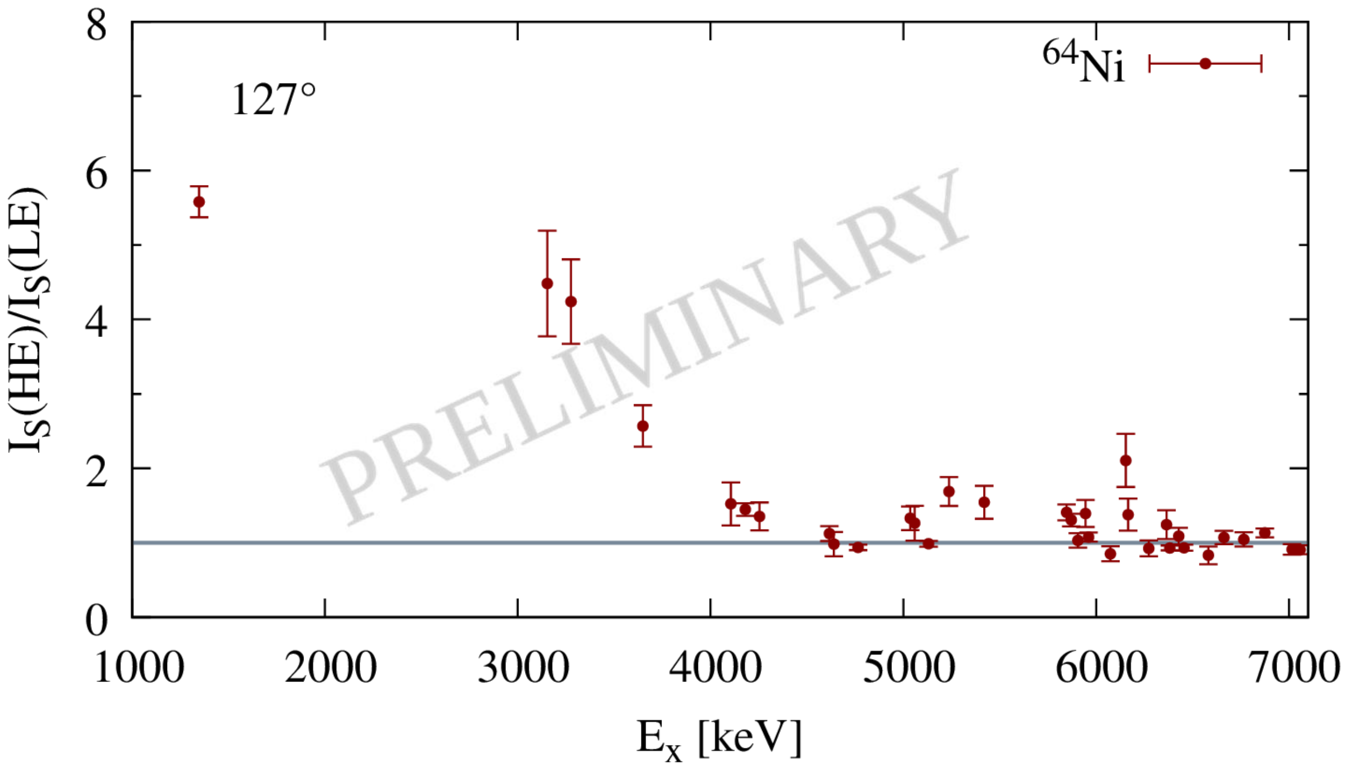


^{11}B used as calibration standard

investigation of inelastic decays



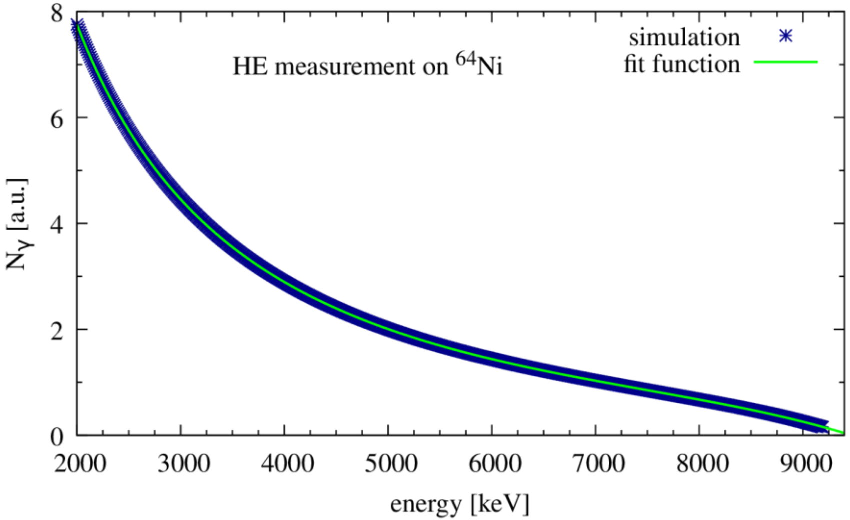
Intensity ratios between HE and LE measurement



decreasing feeding contribution with increasing energy

Absolute photon-flux determination @ γELBE

simulating photon-flux distribution



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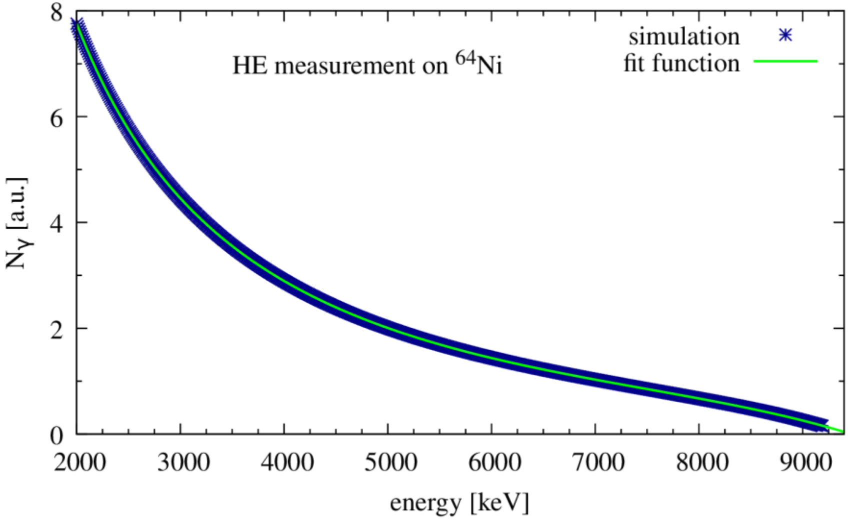
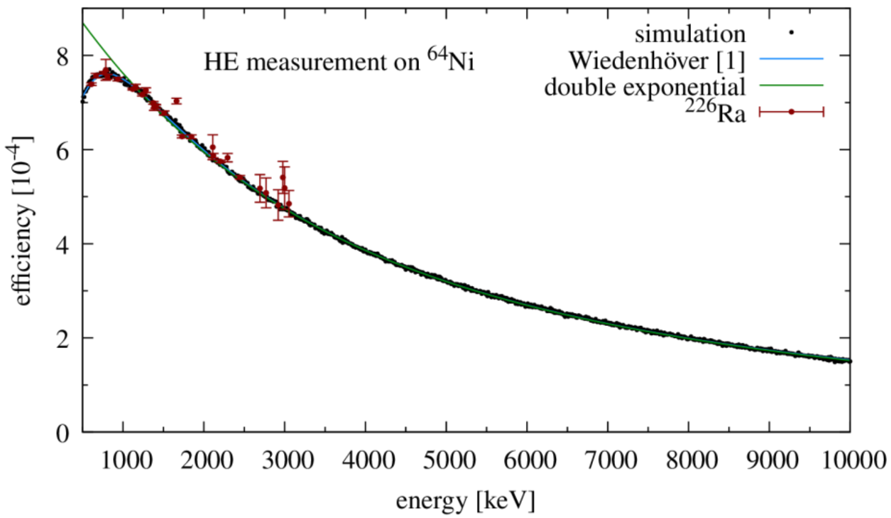


determining detection efficiencies



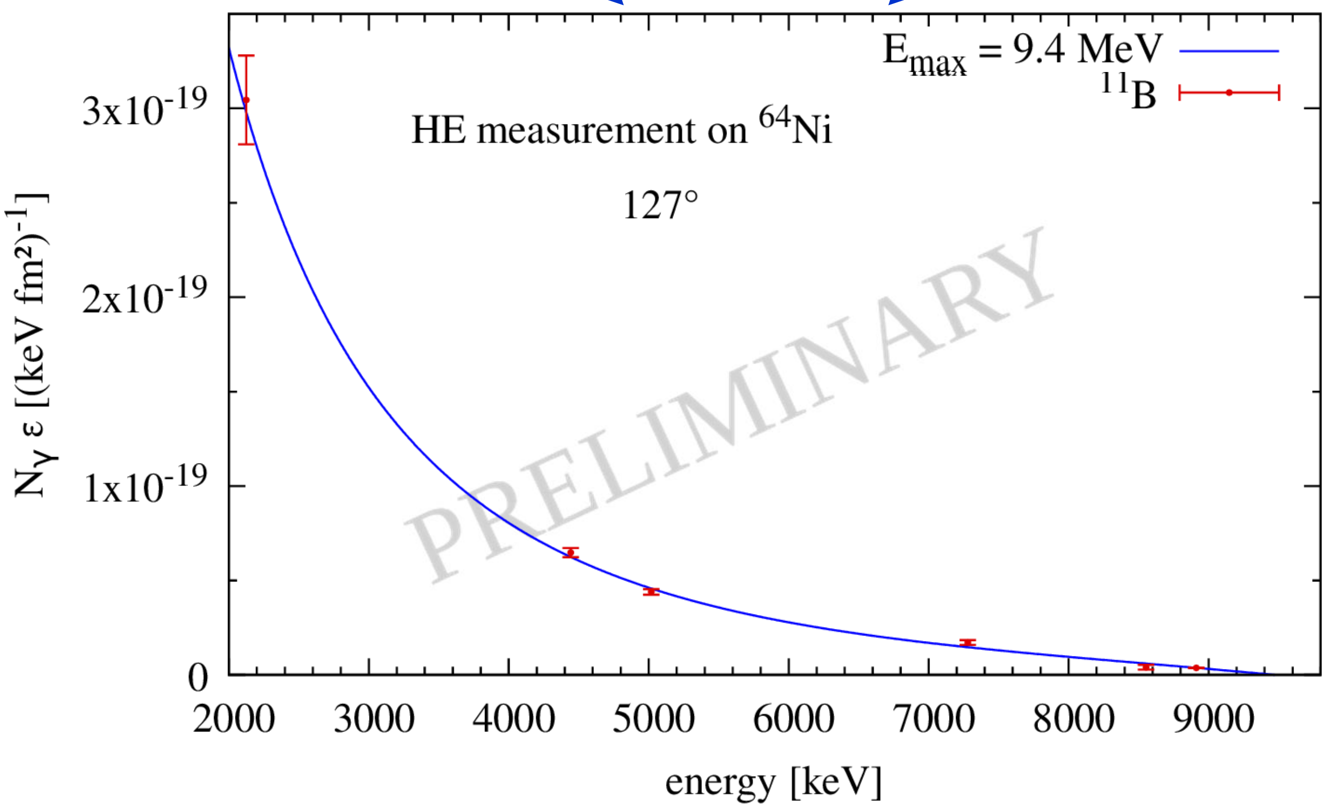
[1] I. Wiedenhöver, Dissertation (1994)

Absolute photon-flux determination @ γELBE

simulating photon-flux distribution

folding

determining detection efficiencies



Laser-Compton Backscattering (LCB) experiment on ^{64}Ni

- LCB experiments @ HIγS (Duke University, USA) [1] using 26 beam energies between 4.3 and 10.0 MeV

[1] H.R. Weller *et al.*, PPNP **62** (2009) 257

Laser-Compton Backscattering (LCB) experiment on ^{64}Ni

- LCB experiments @ HIγS (Duke University, USA) [1] using 26 beam energies between 4.3 and 10.0 MeV

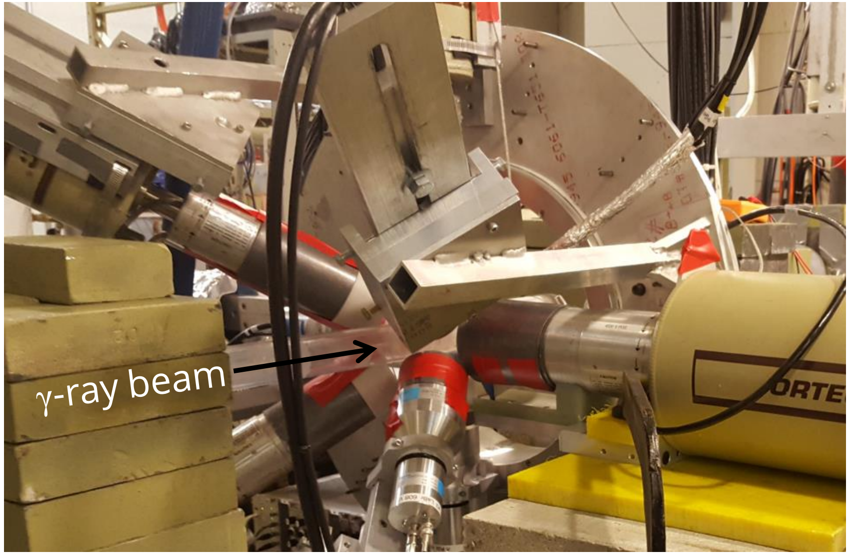
- γ^3 setup [2]:

  4 HPGe and 4 LaBr$_3$ detectors

- linearly-polarized photons

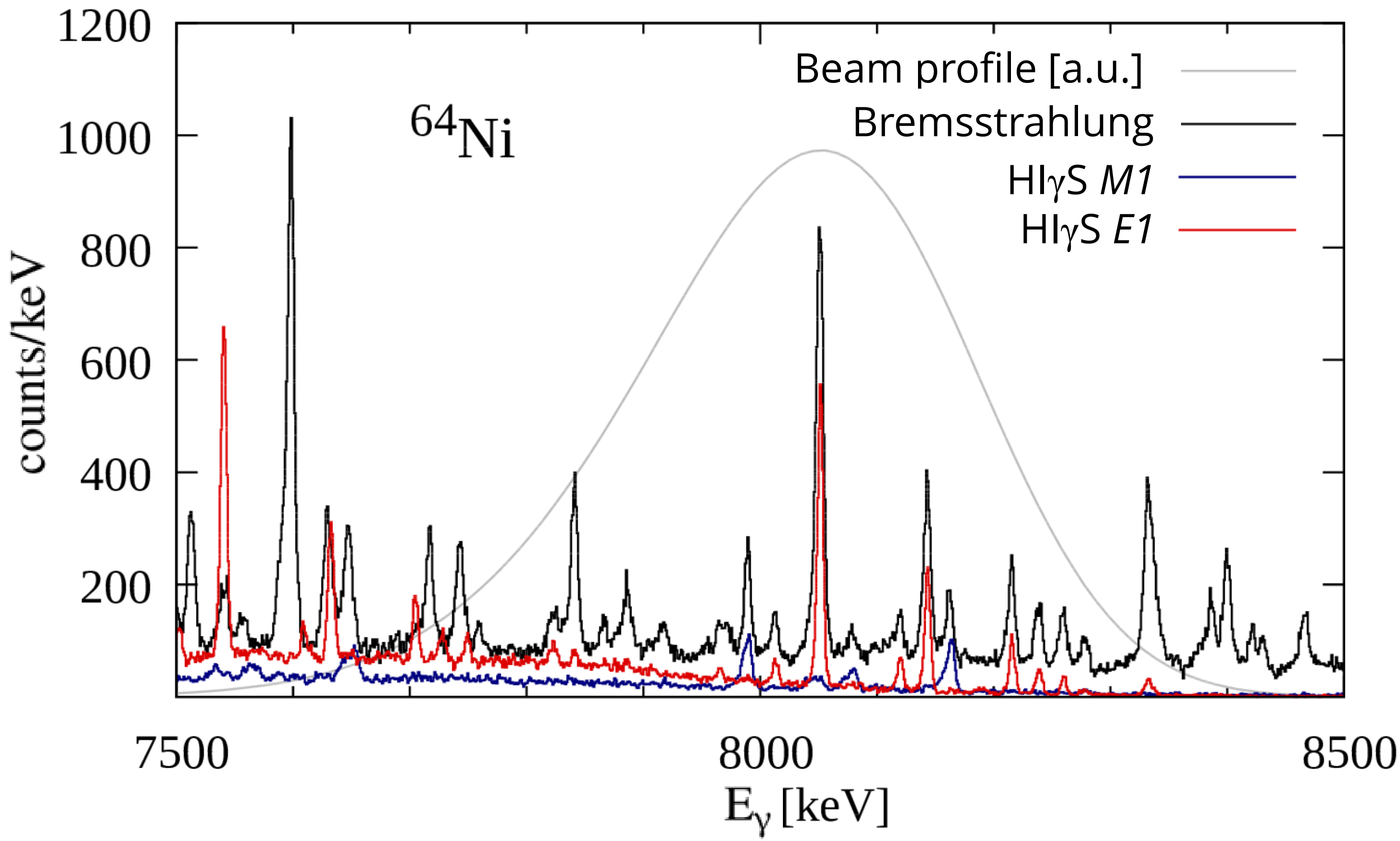
  → parity quantum number

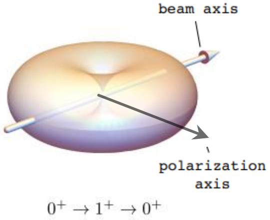
  assignment

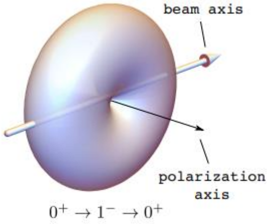


[1] H.R. Weller *et al.*, PPNP **62** (2009) 257
[2] B. Löher *et al.*, NIM A **723** (2013) 136

^{64}Ni – HIγS spectra (E_{beam} ~ 8 MeV)

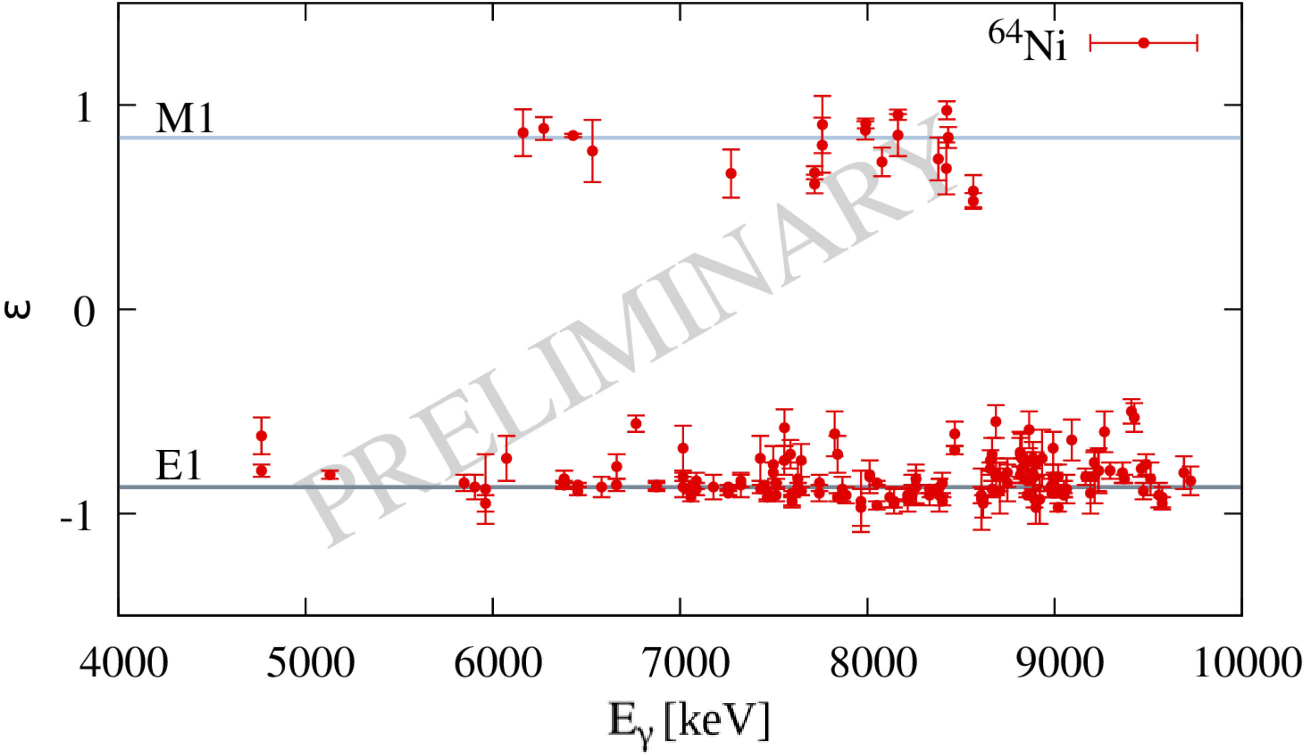


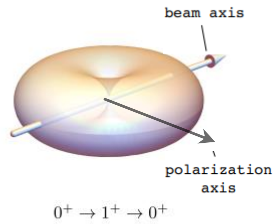


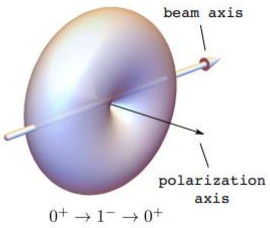


HIγS: Asymmetries

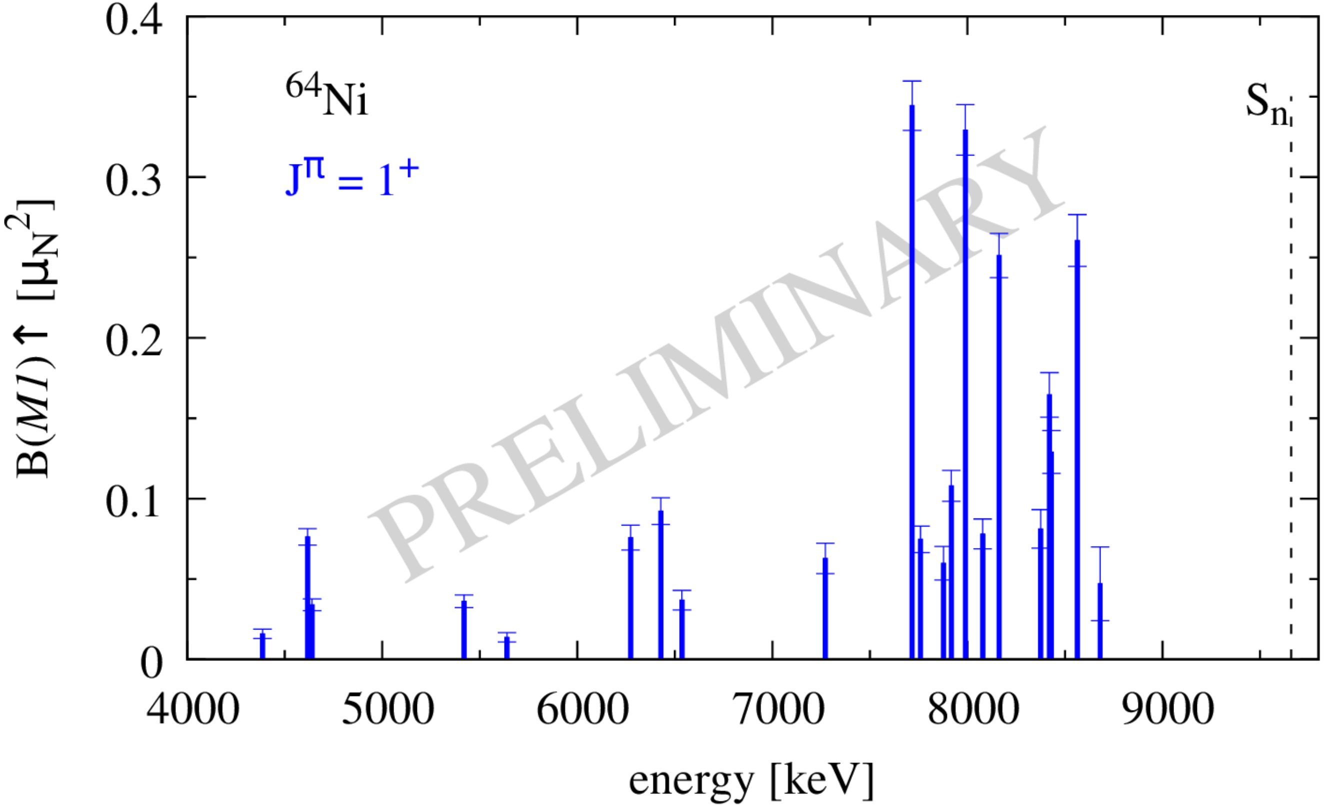
$$\varepsilon = \frac{(N_{\parallel} - N_{\perp})}{(N_{\parallel} + N_{\perp})} = \begin{cases} +1 \text{ (magnetic dipole excitation)} \\ -1 \text{ (electric dipole excitation)} \end{cases}$$







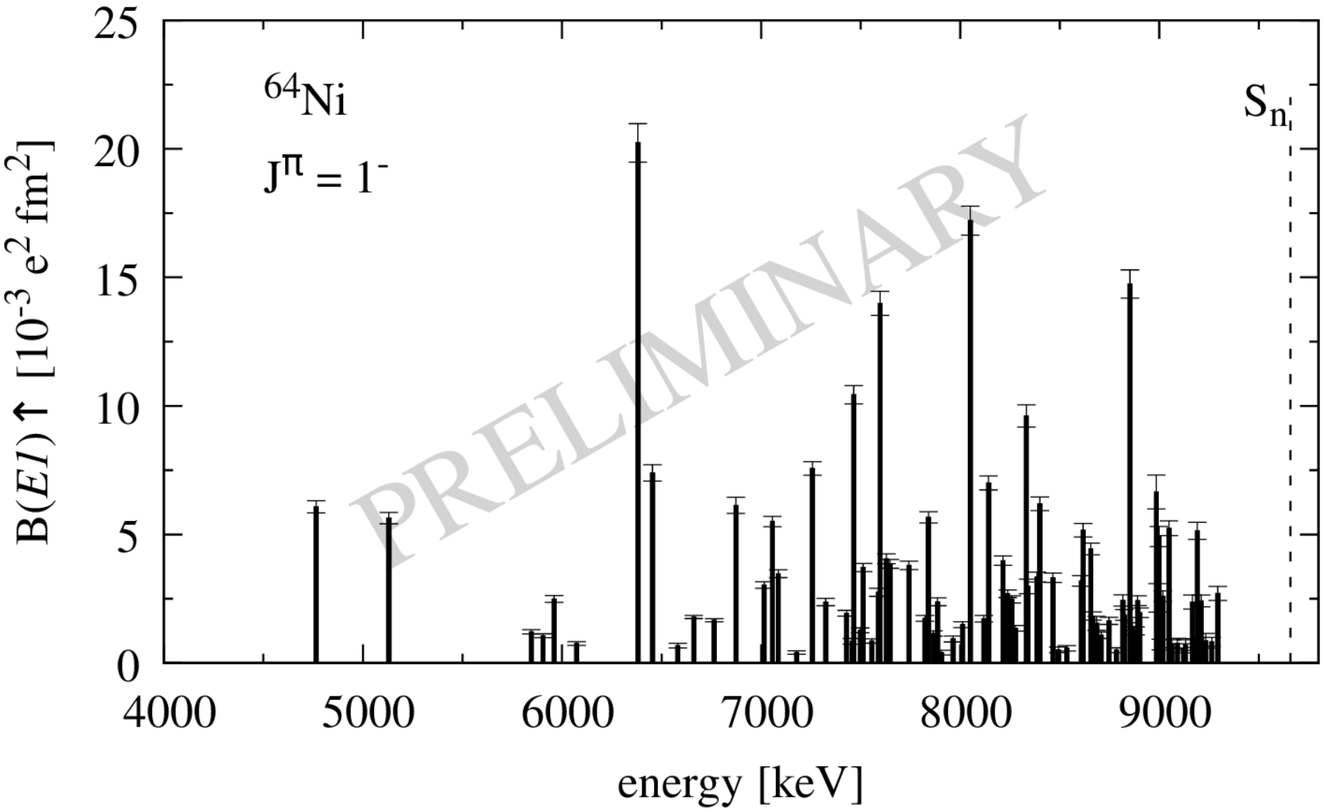
Combination of complementary experiments



4 - 9.3 MeV:

21 $J^{\pi} = 1^+$ states

Combination of complementary experiments



4 - 9.3 MeV:

21 $J^\pi = 1^+$ states

101 $J^\pi = 1^-$ states

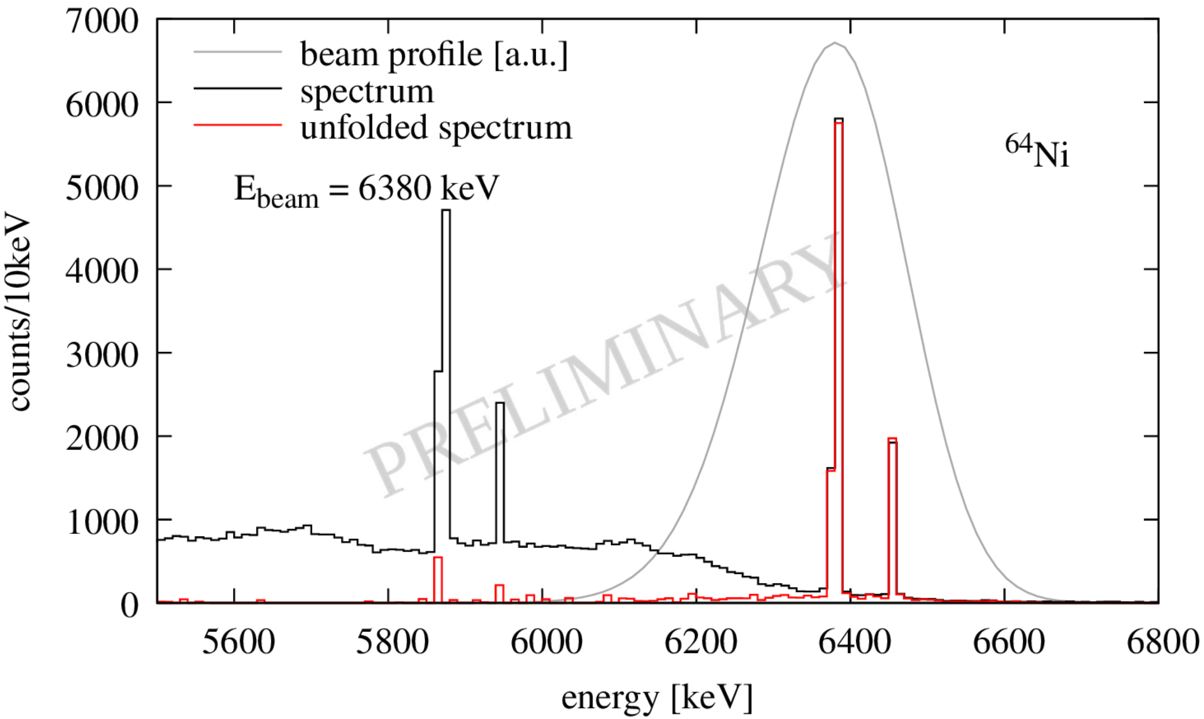
unknown parity:

9 $J^\pi = 1$ states

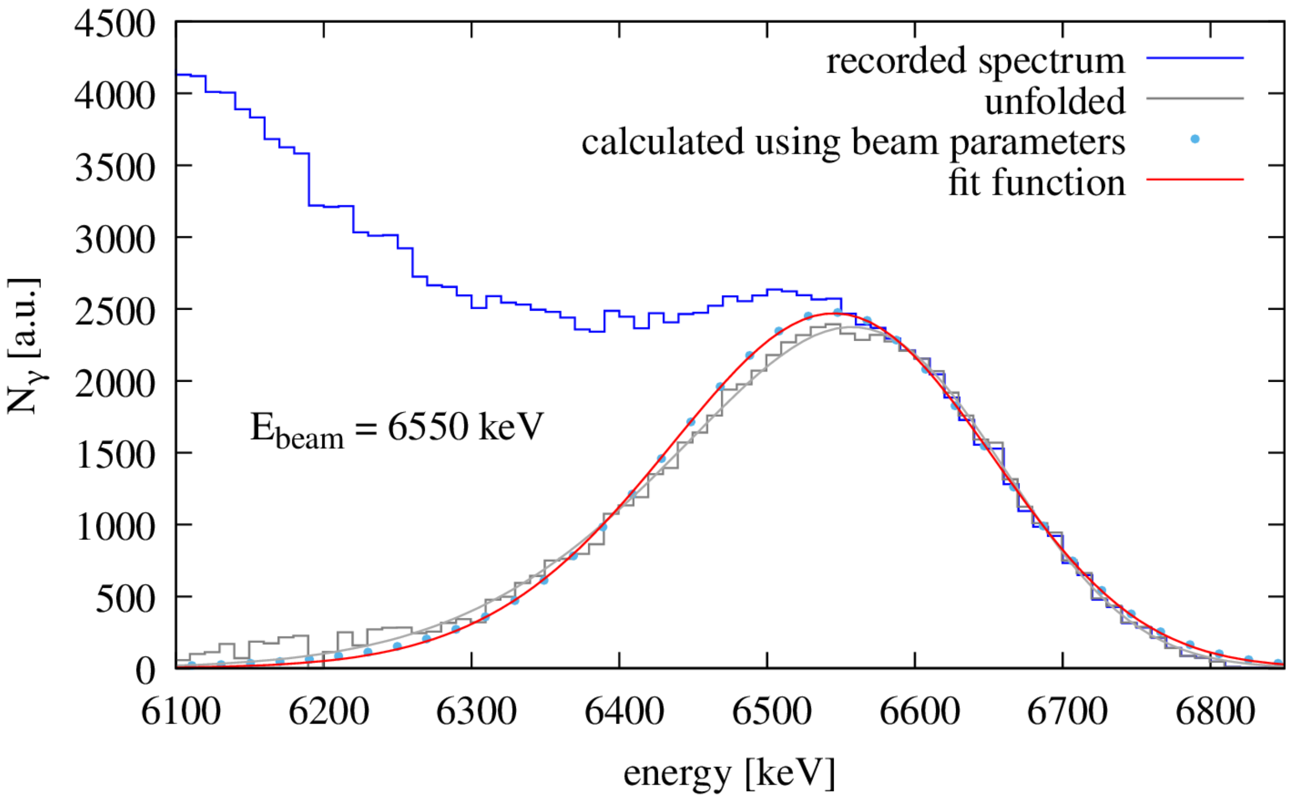
HIγS: Elastic cross section $\sigma_{\gamma\gamma}$

elastic cross section including unresolved transitions

$$\sigma_{\gamma\gamma} = \frac{A(total)}{N_T \cdot W \cdot \bar{\varepsilon} \cdot \int_0^\infty N_\gamma \, dE_\gamma}$$



HIγS: Absolute photon-flux determination

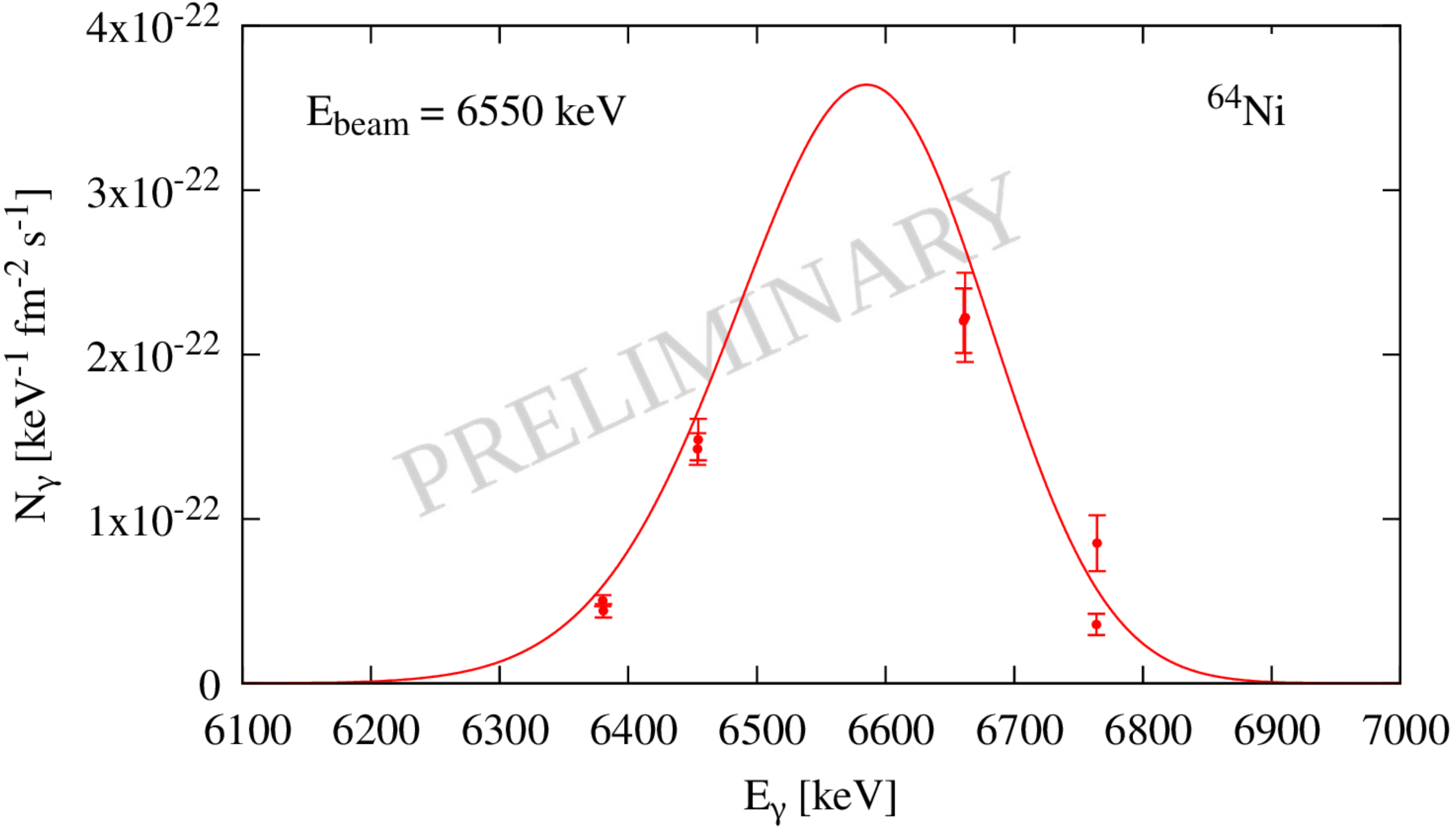


beam detector monitors photon-flux distribution before each measurement

→ deconvolution of spectrum

→ beam profile scaled to known transitions of target nucleus

HIγS: Absolute photon-flux determination



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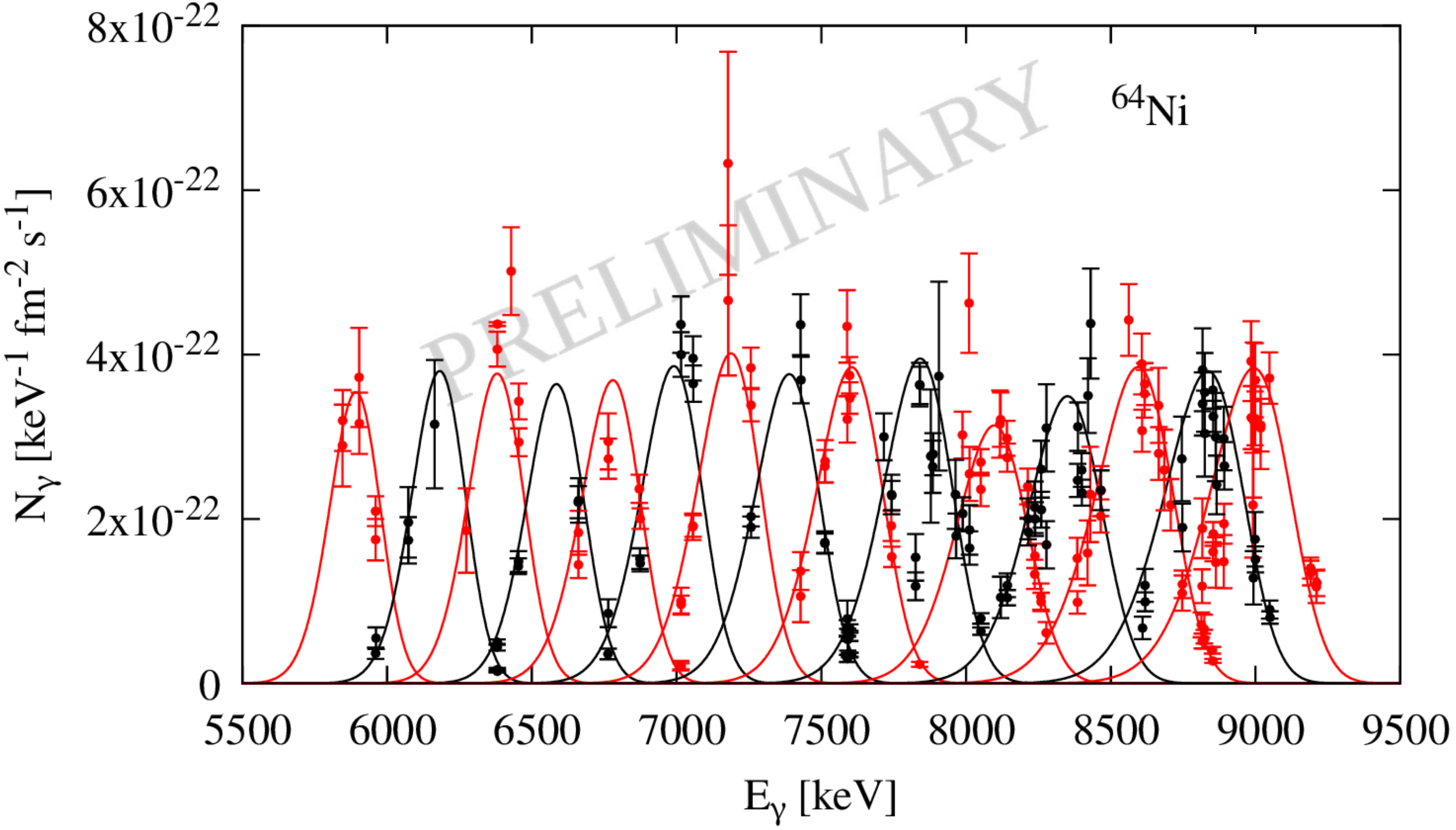
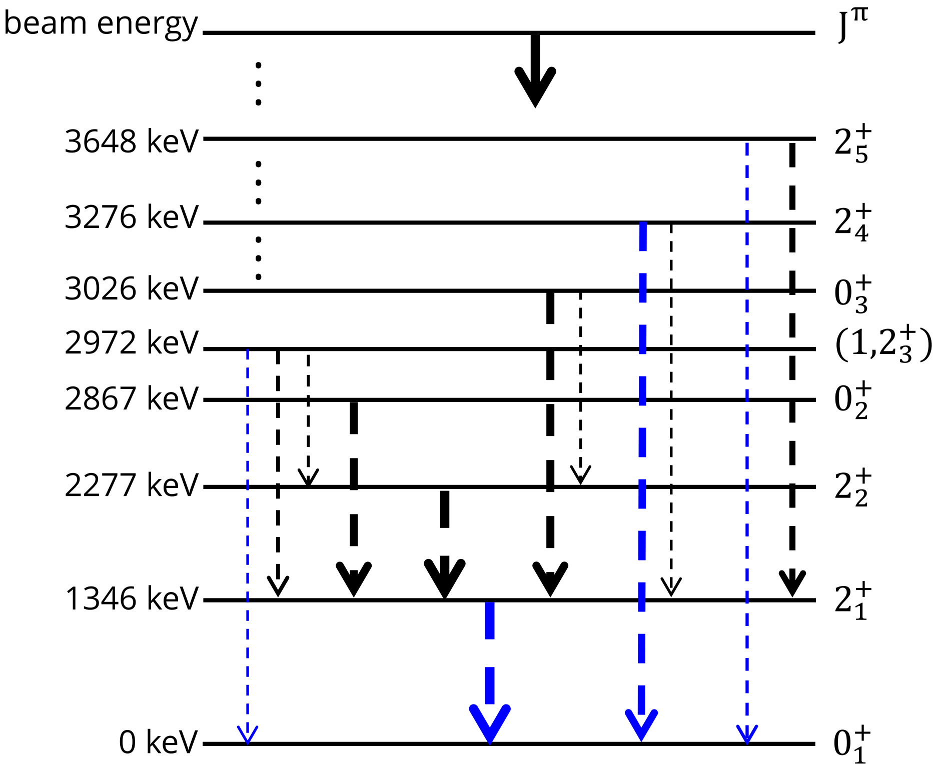


HIγS: Inelastic cross section $\boldsymbol{\sigma_{\gamma\gamma'}}$

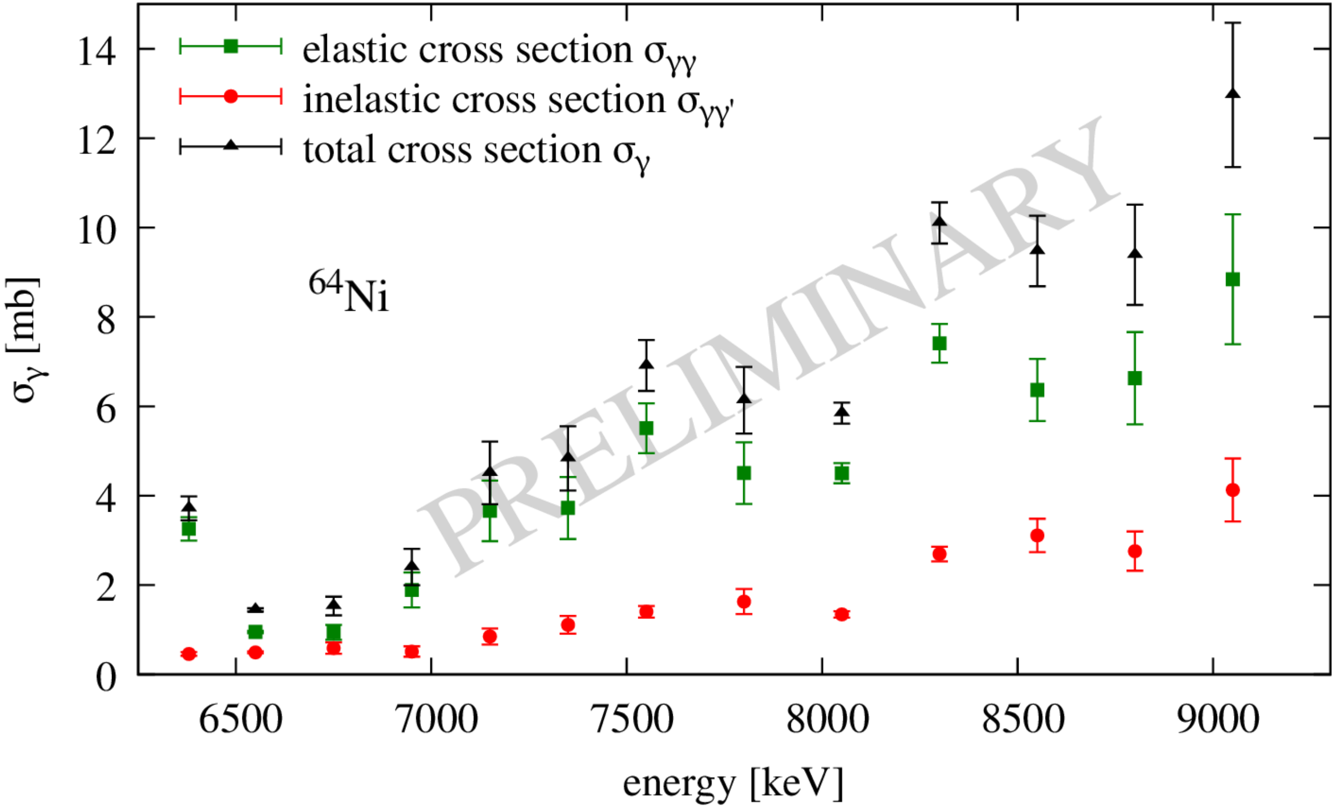
inelastic cross section estimation using first excited states in ^{64}Ni

$$\sigma_{\gamma\gamma'} = \frac{A(2^+)}{\mathrm{N_T} \cdot \overline{\mathrm{W}} \cdot \varepsilon(2^+) \cdot \int_0^\infty \mathrm{N}_\gamma \, \mathrm{dE}_\gamma}$$

ground-state decay observed in deexcitation spectra



HIγS: Photoabsorption cross section $\sigma_\gamma = \sigma_{\gamma\gamma} + \sigma_{\gamma\gamma'}$



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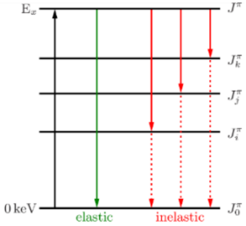
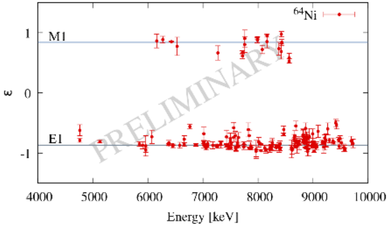
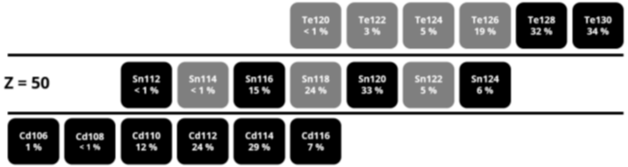
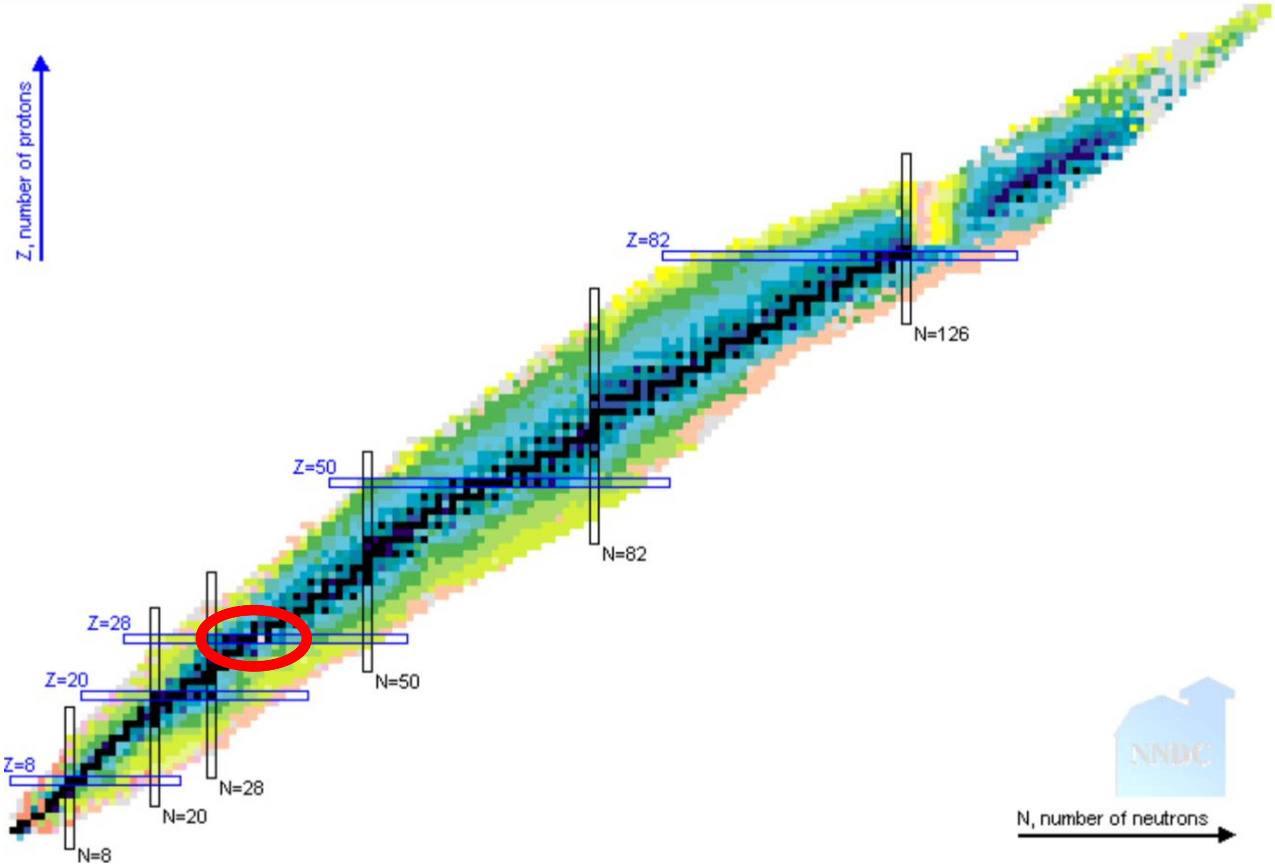






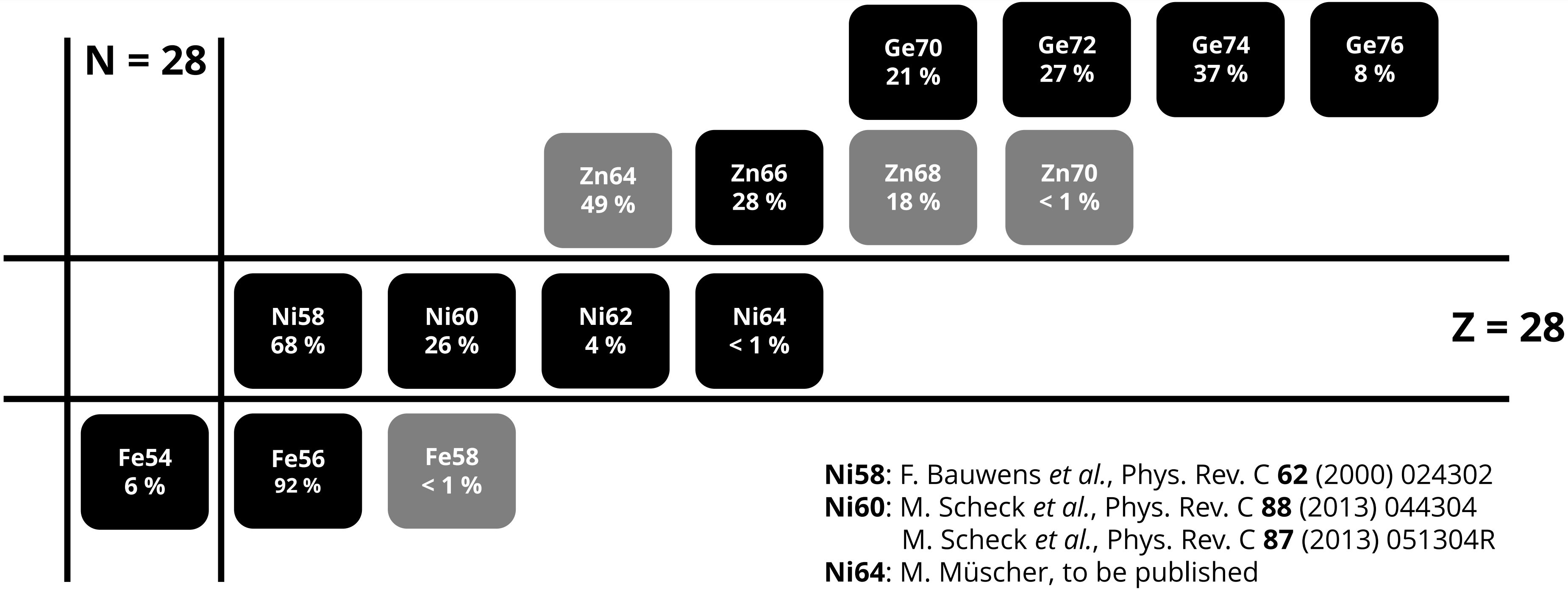
						Te120 < 1 %	Te122 3 %	Te124 5 %	Te126 19 %	Te128 32 %	Te130 34 %
Z = 50			Sn112 < 1 %	Sn114 < 1 %	Sn116 15 %	Sn118 24 %	Sn120 33 %	Sn122 5 %	Sn124 6 %		
	Cd106 1 %	Cd108 < 1 %	Cd110 12 %	Cd112 24 %	Cd114 29 %	Cd116 7 %					

Systematic (γ,γ‘) investigations



picture taken from nndc

Electric dipole response in the Z = 28 region



N = 28

Ge70
21 %

Ge72
27 %

Ge74
37 %

Ge76
8 %

Zn64
49 %

Zn66
28 %

Zn68
18 %

Zn70
< 1 %

Ni58
68 %

Ni60
26 %

Ni62
4 %

Ni64
< 1 %

Z = 28

Fe54
6 %

Fe56
92 %

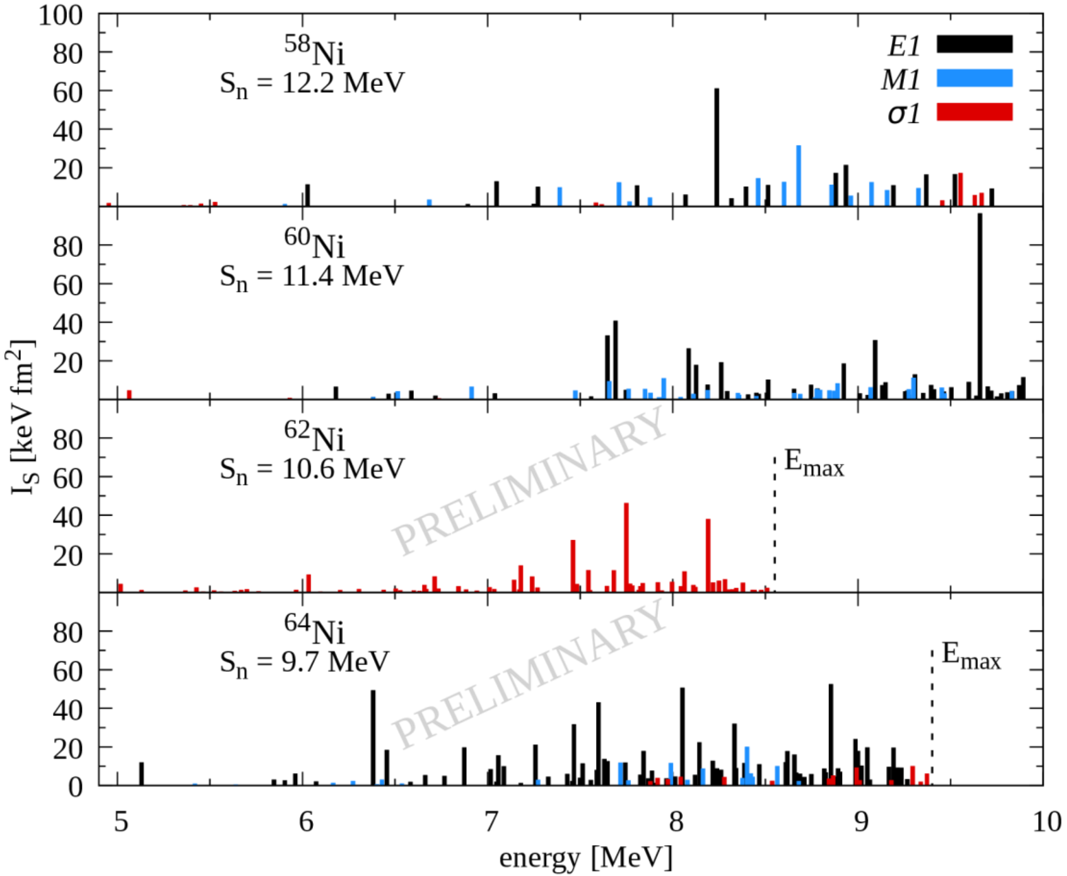
Fe58
< 1 %

Ni58: F. Bauwens *et al.*, Phys. Rev. C **62** (2000) 024302
Ni60: M. Scheck *et al.*, Phys. Rev. C **88** (2013) 044304
M. Scheck *et al.*, Phys. Rev. C **87** (2013) 051304R
Ni64: M. Müscher, to be published

Fe54: R. Schwengner *et al.*, Phys. Rev. C **101** (2020) 064303
Fe56: T. Shizuma *et al.*, Phys. Rev. C **87** (2013) 024301
F. Bauwens *et al.*, Phys. Rev. C **62** (2000) 024302

Zn66: R. Schwengner *et al.*, Phys. Rev. C **103** (2021) 024312
Ge74: R. Massarczyk *et al.*, Phys. Rev. C **92** (2015) 044309
Ge76: R. Schwengner *et al.*, Phys. Rev. C **105** (2022) 024303
Ge isotopes: A. Jung *et al.*, Nucl. Phys. A **584** (1995) 103

Comparison Z = 28 isotopes



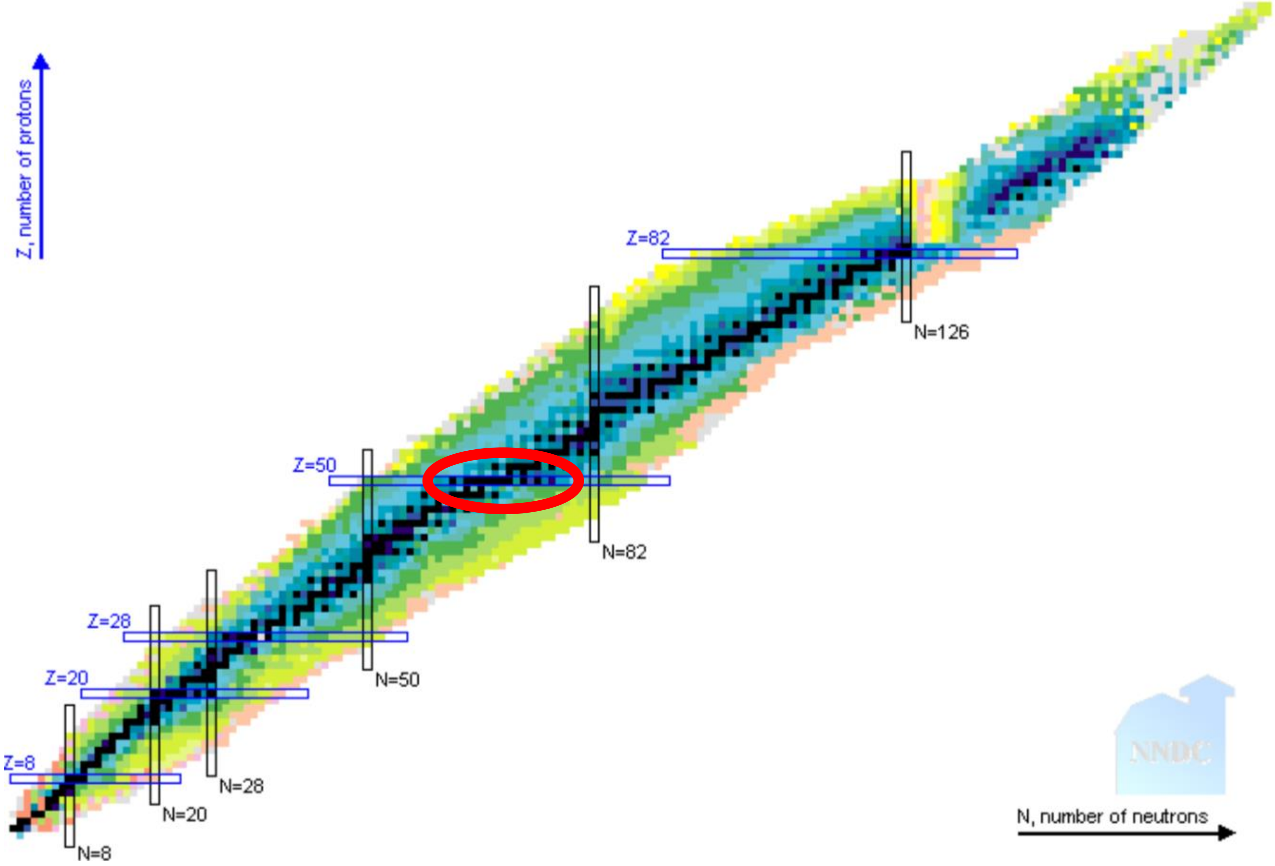
NRF experiments on ^{62}Ni already performed at HIγS

state-to-state analysis:

increasing fragmentation of dipole strength with increasing neutron excess

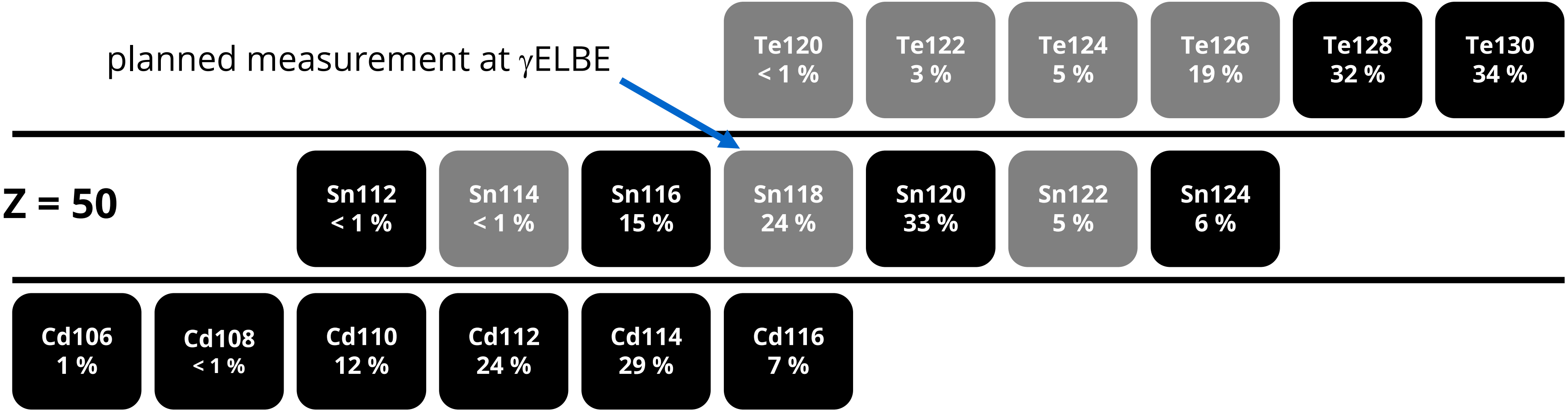
F. Bauwens *et al.*, Phys. Rev. C **62** (2000) 024302
M. Scheck *et al.*, Phys. Rev. C **88** (2013) 044304
M. Scheck *et al.*, Phys. Rev. C **87** (2013) 051304R
T. Schüttler, private communication (2022)

Systematic (γ,γ‘) investigations



picture taken from nndc

Electric dipole response in the Z = 50 region



planned measurement at γELBE

						Te120 < 1 %	Te122 3 %	Te124 5 %	Te126 19 %	Te128 32 %	Te130 34 %
Z = 50			Sn112 < 1 %	Sn114 < 1 %	Sn116 15 %	Sn118 24 %	Sn120 33 %	Sn122 5 %	Sn124 6 %		
	Cd106 1 %	Cd108 < 1 %	Cd110 12 %	Cd112 24 %	Cd114 29 %	Cd116 7 %					

recently measured at HIγS and at γELBE

Sn112/120: B. Özel-Tashenov *et al.*, Phys. Rev. C **62** (2000) 024302
Sn112: I. Pysmenetska *et al.*, Phys. Rev. C **73** (2006) 017302
Sn116/124: K. Govaert *et al.*, Phys. Rev. C **57** (1998) 2229
Sn120: M. Müscher *et al.*, Phys. Rev. C 102 (2020) 014317

Cd106: A. Linnemann *et al.*, Phys. Rev. C **75** (2007) 024310
Cd108: A. Gade *et al.*, Phys. Rev. C **67** (2003) 034304
Cd110-116: C. Kohstall *et al.*, Phys. Rev. C **72** (2005) 034302
Cd114: R. Massarczyk *et al.*, Phys. Rev. C 93 (2016) 014301

Te128/130: J. Isaak *et al.*, Phys. Rev. C **103** (2021) 044317
J. Isaak *et al.*, Phys. Lett. B **788** (2019) 225

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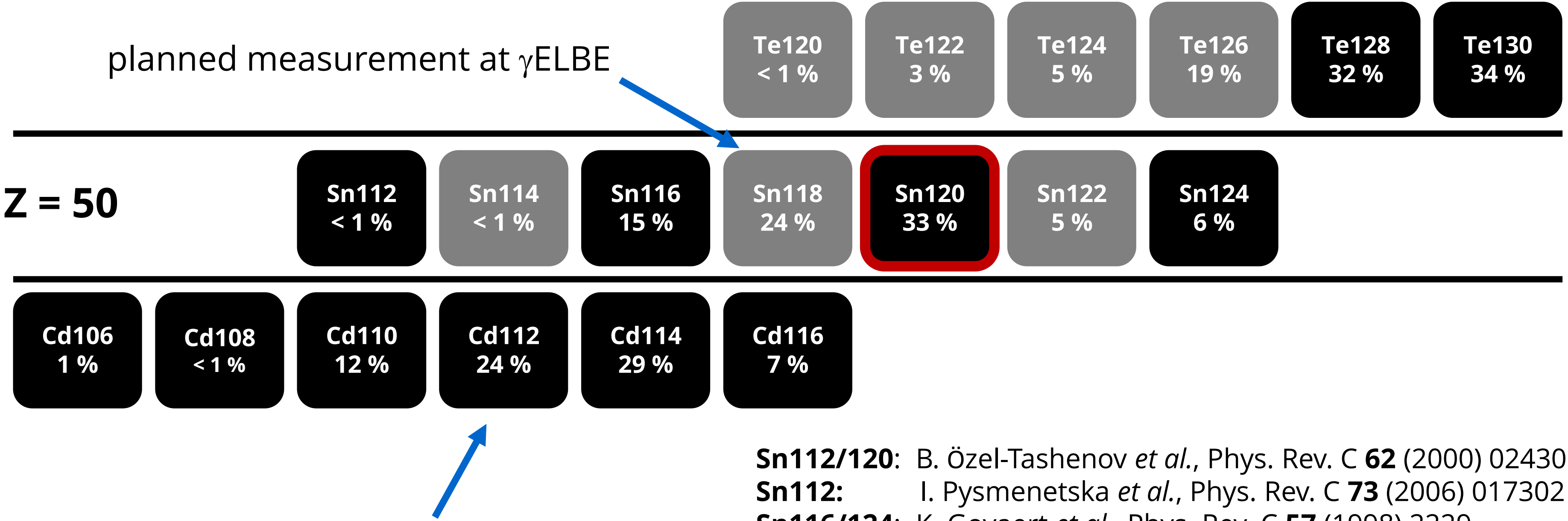

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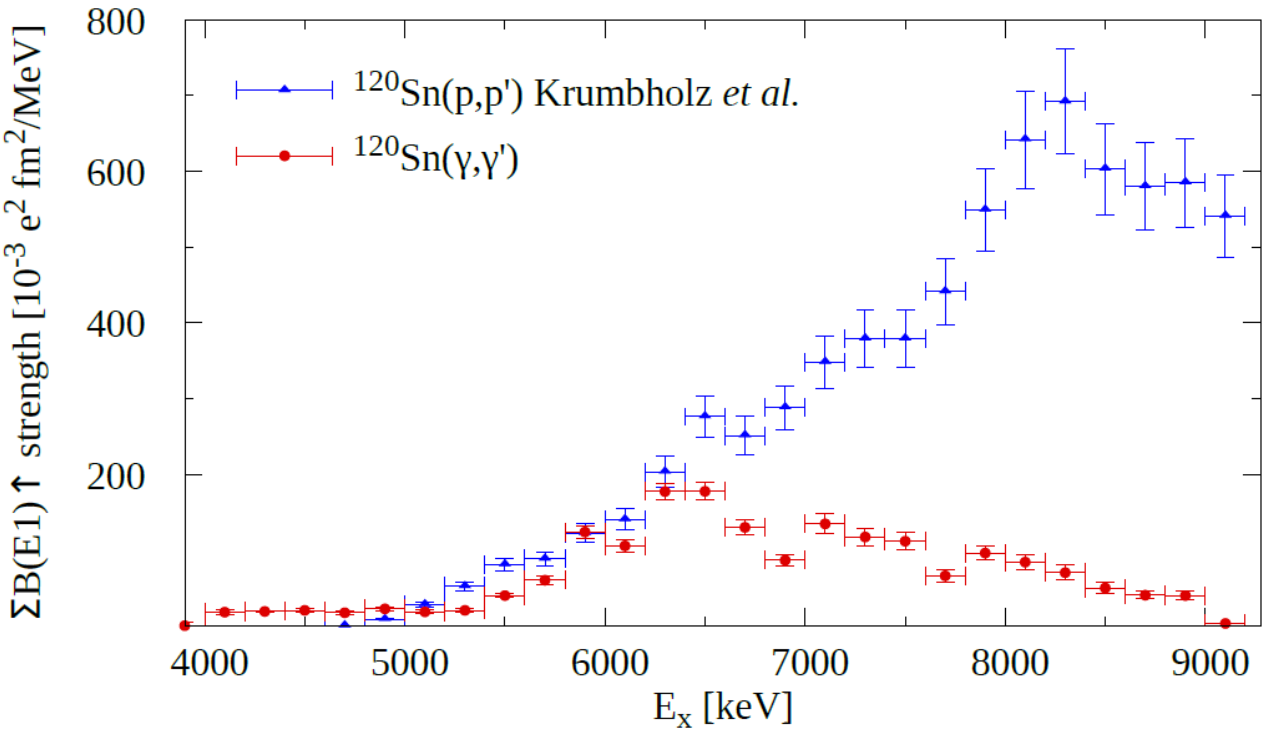
Case I: ^{120}Sn

deviations between (p,p‘) and (γ,γ‘)-bremsstrahlung results above 6.5 MeV

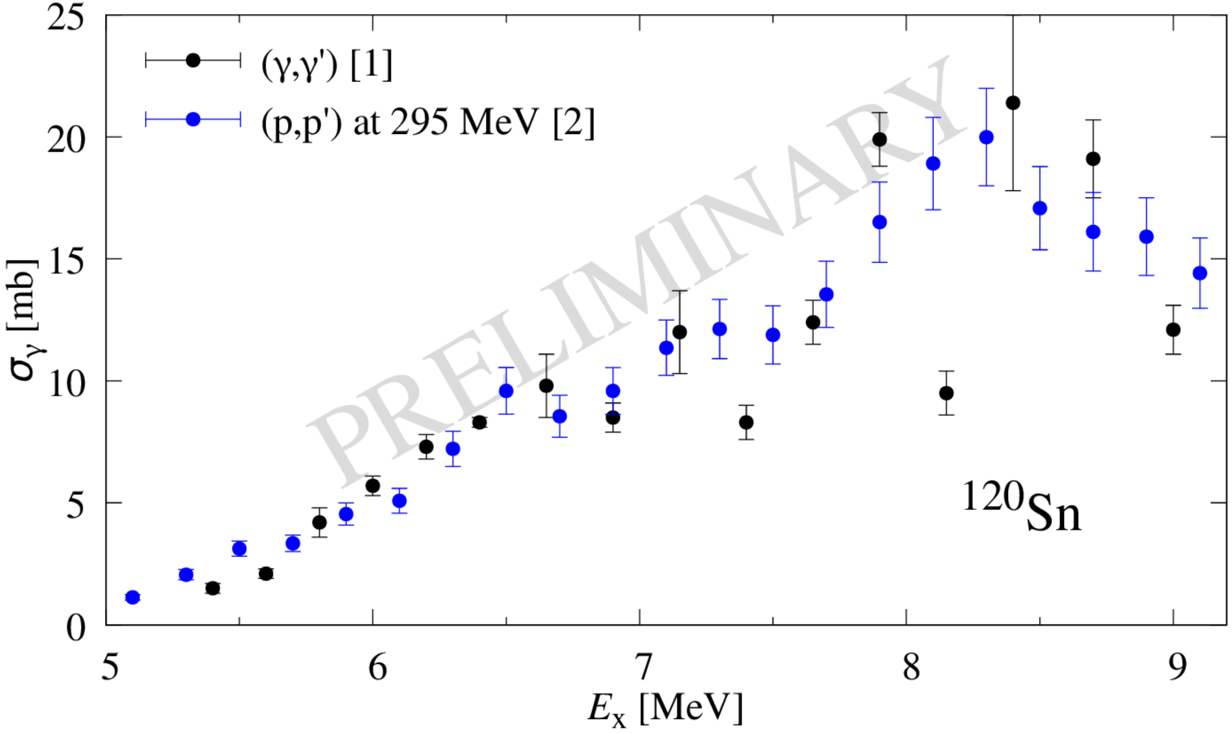


M. Müscher *et al.*, Phys. Rev. C **102** (2020) 014317

Case I: ^{120}Sn

deviations between (p,p‘) and (γ,γ‘)-bremsstrahlung results above 6.5 MeV

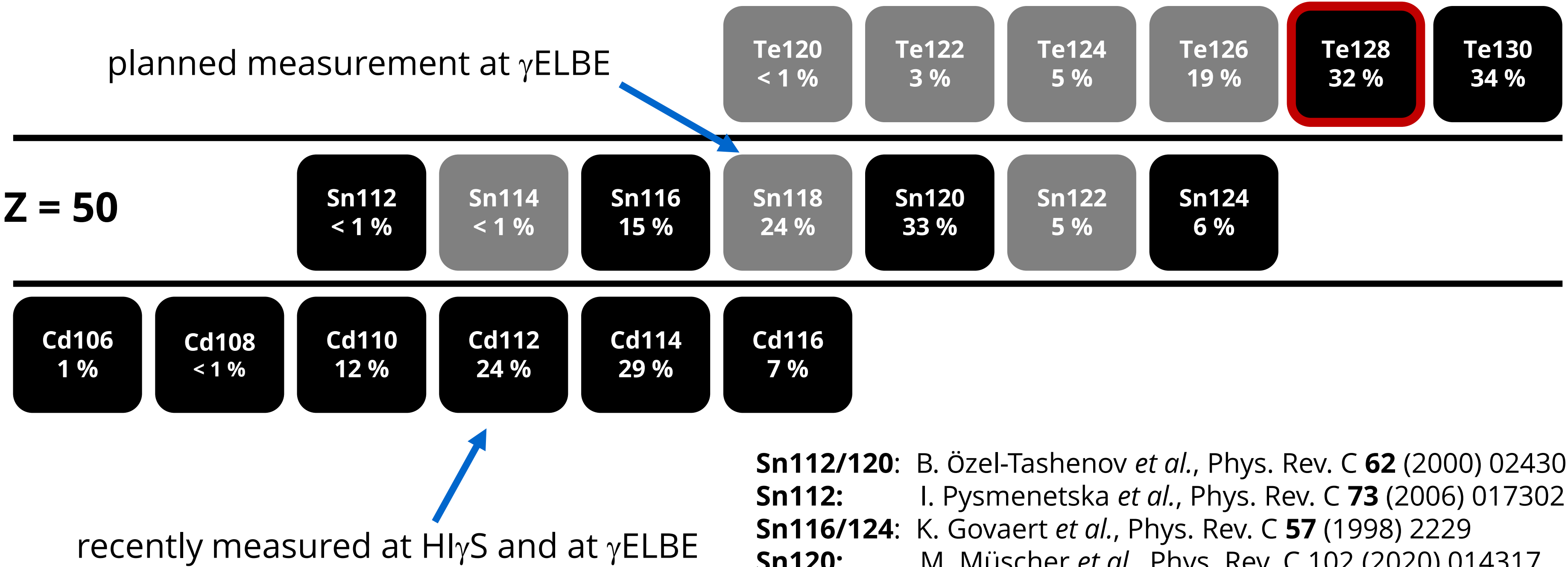
→ solved by taking unresolved transitions and inelastic decays into account in (γ,γ‘) data



[1] P. Kuchenbrod, Master’s thesis, TU Darmstadt (2022)

[2] S. Bassauer *et al.*, Phys. Lett. B **810** (2020) 135804

Electric dipole response in the Z = 50 region



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J. Isaak *et al.*, Phys. Lett. B **788** (2019) 225

Case II: ^{128}Te

test of generalized Brink-Axel hypothesis:

(photoabsorption and photon-emission process can be treated equivalently)

→ photon-strength function (PSF) for both processes same:

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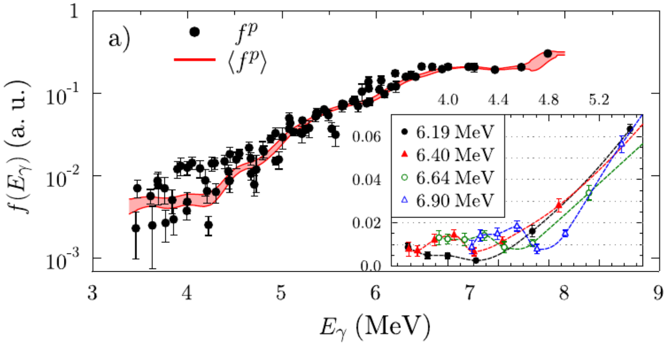
1. linked to average γ-decay intensity to lower-lying excited levels (f^p)



J. Isaak *et al.*, Phys. Lett. B **788** (2019) 225

Case II: ^{128}Te

test of generalized Brink-Axel hypothesis:

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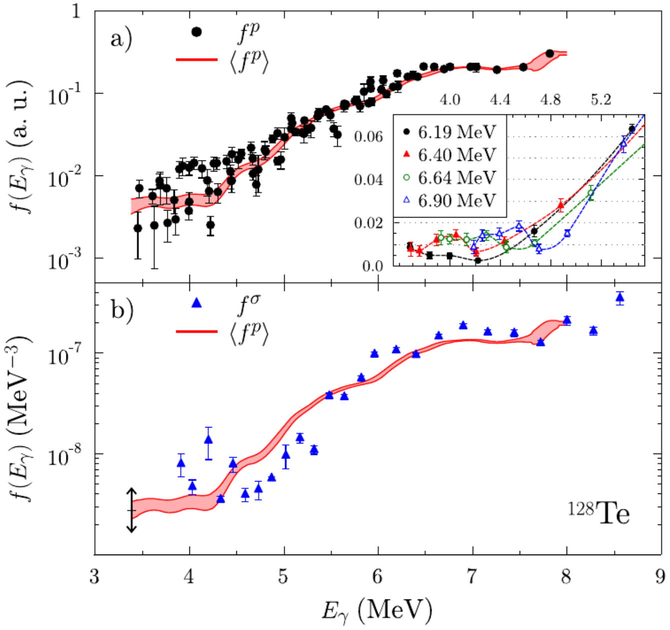
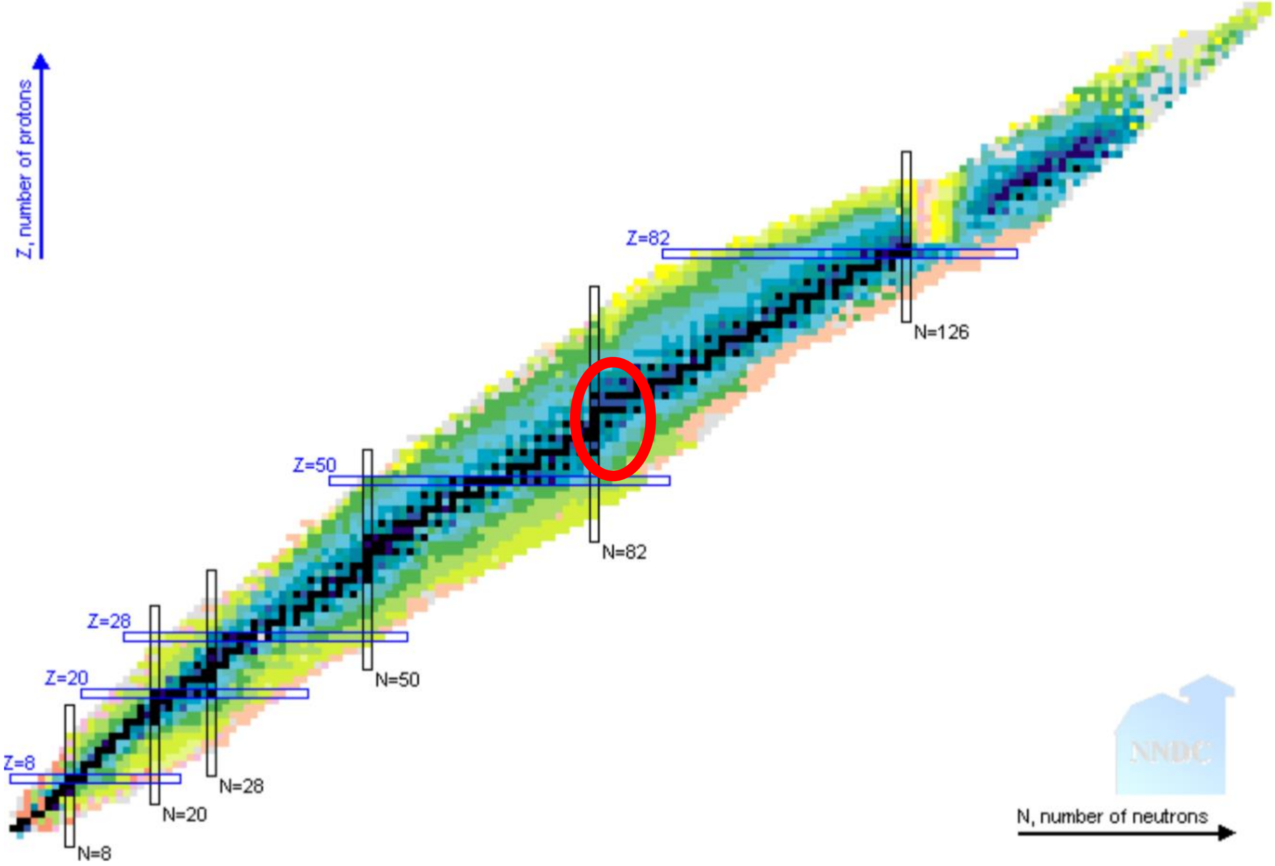
→ photon-strength function (PSF) for both processes same:

1. linked to average γ-decay intensity to lower-lying excited levels (f^p)
2. calculated from average photoabsorption cross section (f^σ)



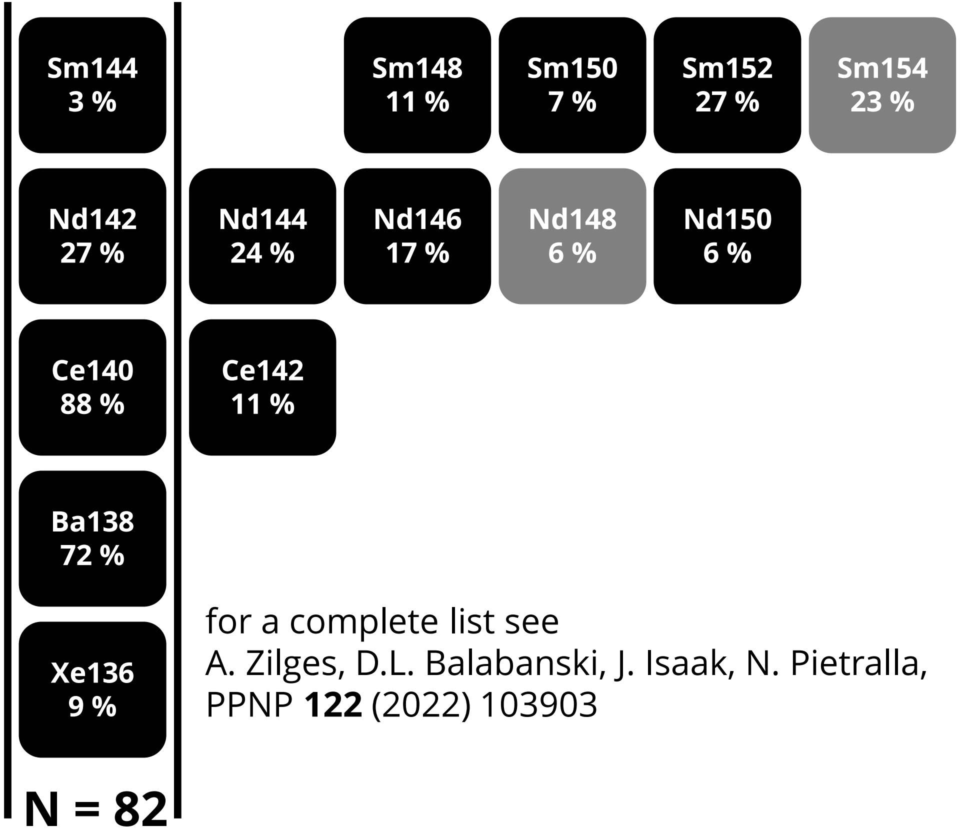
J. Isaak *et al.*, Phys. Lett. B **788** (2019) 225

Systematic (γ,γ‘) investigations



picture taken from nndc

Electric dipole response in the N = 82 region



Sm144 **3 %**		**Sm148** **11 %**	**Sm150** **7 %**	**Sm152** **27 %**	**Sm154** **23 %**
Nd142 **27 %**	**Nd144** **24 %**	**Nd146** **17 %**	**Nd148** **6 %**	**Nd150** **6 %**	
Ce140 **88 %**	**Ce142** **11 %**				
Ba138 **72 %**					
Xe136 **9 %**					
N = 82					

for a complete list see
A. Zilges, D.L. Balabanski, J. Isaak, N. Pietralla,
PPNP **122** (2022) 103903

Xe124-136: H. Von Garrel *et al.*, Phys. Rev. C **73** (2006) 054315
Xe136: D. Savran *et al.*, Phys. Rev. Lett. **100** (2008) 232501
D. Savran *et al.*, Phys. Rev. C. **84** (2011) 2024326

Ba138: N. Pietralla *et al.*, Phys. Rev. Lett. **88** (2001) 012502

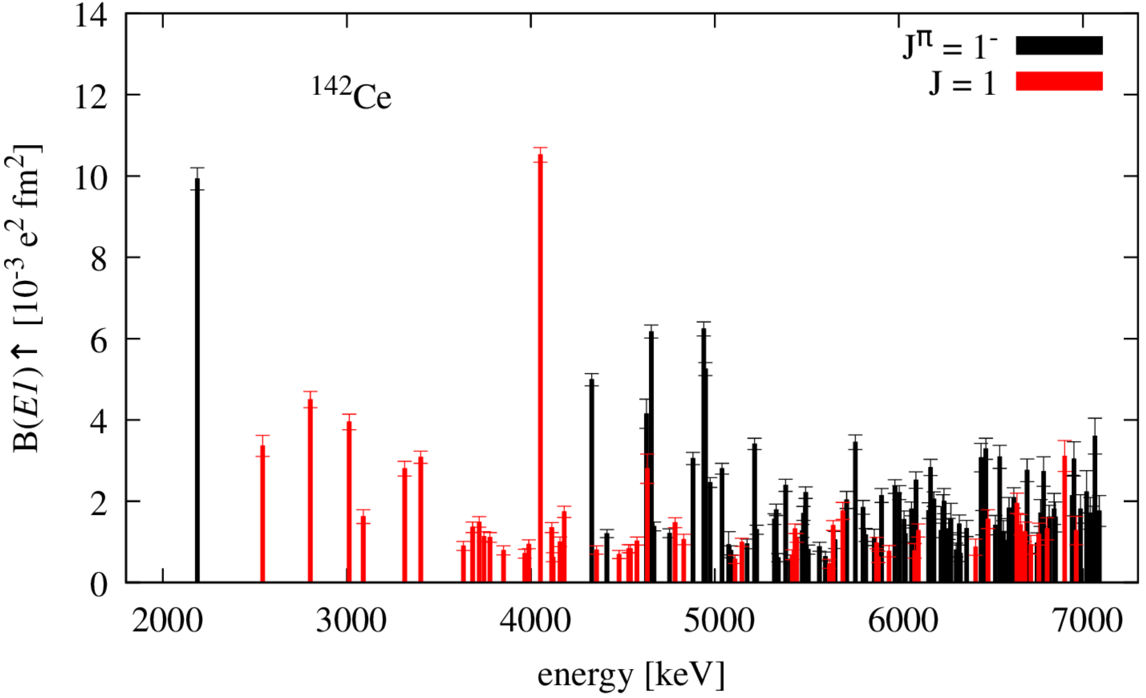
Ce140: C. Romig *et al.*, Phys. Lett. B **744** (2015) 369
V. Derya *et al.*, Phys. Rev. C **93** (2016) 034311
B. Löher *et al.*, Phys. Lett. B **756** (2016) 72
Ce142: A. Gade et al., Phys. Rev. 69 (2004) 054321
M. Müscher, Master‘s thesis (2018)
J. Sieber, Bachelor‘s thesis (2019)

Nd142: C.T. Angell *et al.*, Phys. Rev. C **86** (2012) 051302R
Nd144: F. Kluwig, Master‘s thesis (2022)
Nd146: K. Meul, Bachelor‘s thesis (2021)
Nd150: O. Papst, to be published
Nd150/Sm150: J. Kleemann *et al.*, Phys. Rev. C **104** (2021) L061302

Sm148: T. C. Li *et al.*, Phys. Rev. C **71** (2005) 044318
Sm152: K. E. Ide *et al.*, Phys. Rev. C **103** (2021) 054302

Ba138 - Sm144: S. Volz *et al.*, Nucl. Phys. A **779** (2006) 1
A. Zilges *et al.*, PPNP **55** (2005) 408
Ba138/Ce140/Sm144: A Zilges *et al.*, Phys. Lett. B **542** (2002) 43

^{142}Ce – B(*E1*) strength



4 - 7.1 MeV:

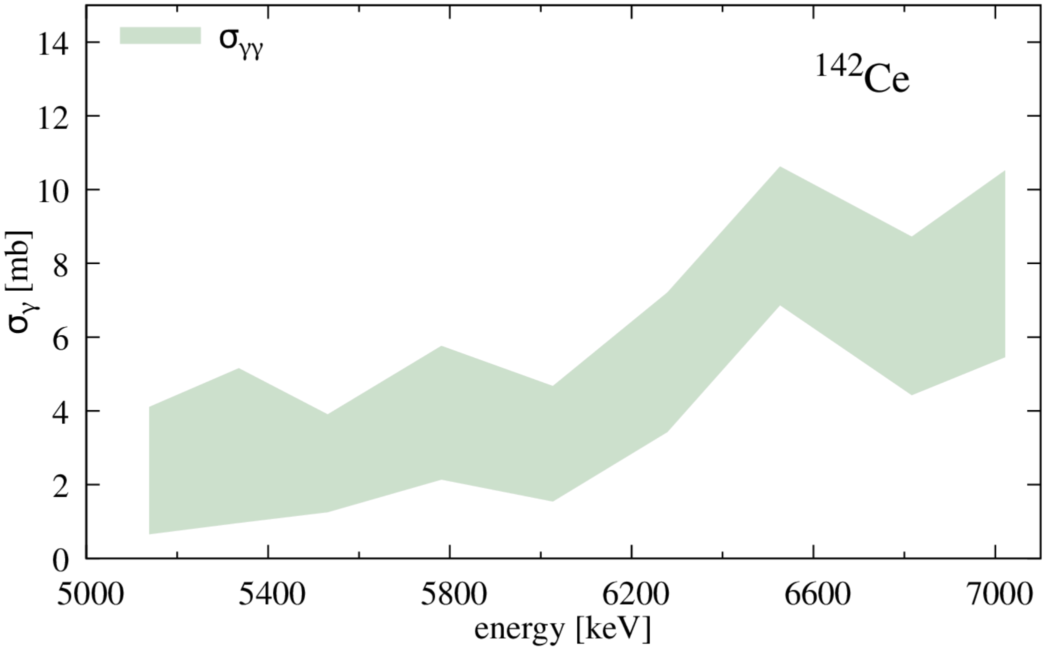
only $J^{\pi} = 1^{-}$ states observed

high fragmentation of strength

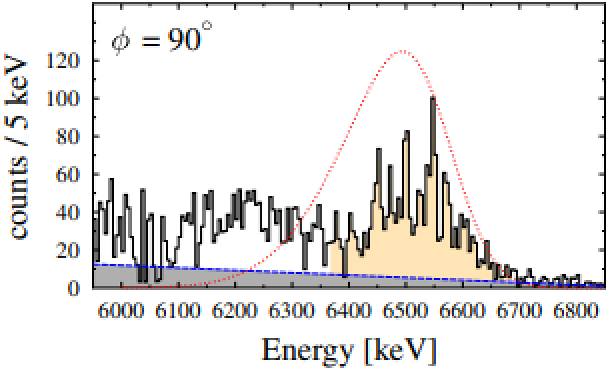
experimental sensitivity limit for state-to-state analysis reached

M. Müscher, to be published

^{142}Ce – photoabsorption cross section

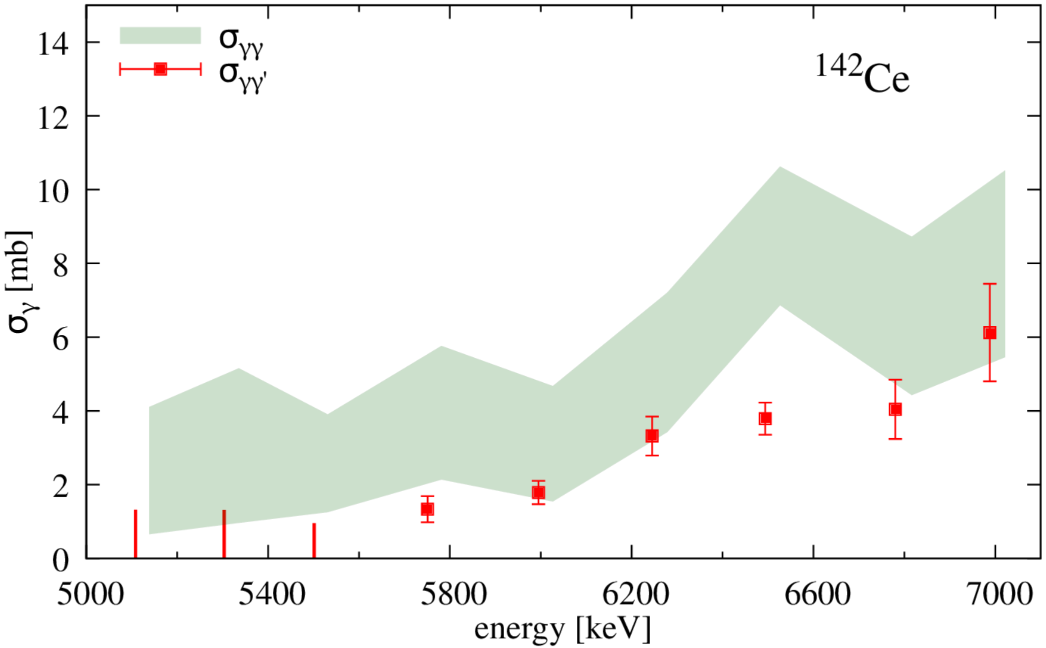


elastic cross section $\sigma_{\gamma\gamma}$:



M. Müscher, to be published

^{142}Ce – photoabsorption cross section



M. Müscher, to be published

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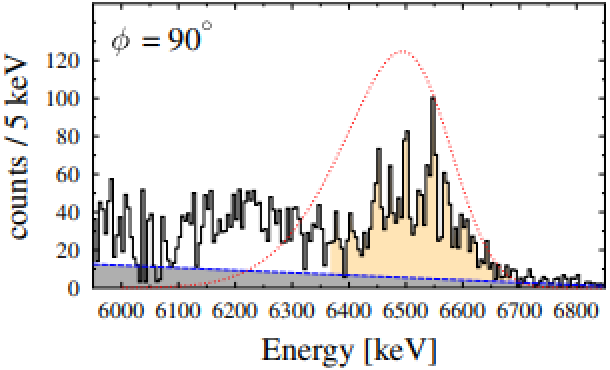
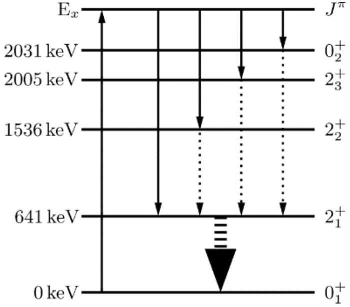
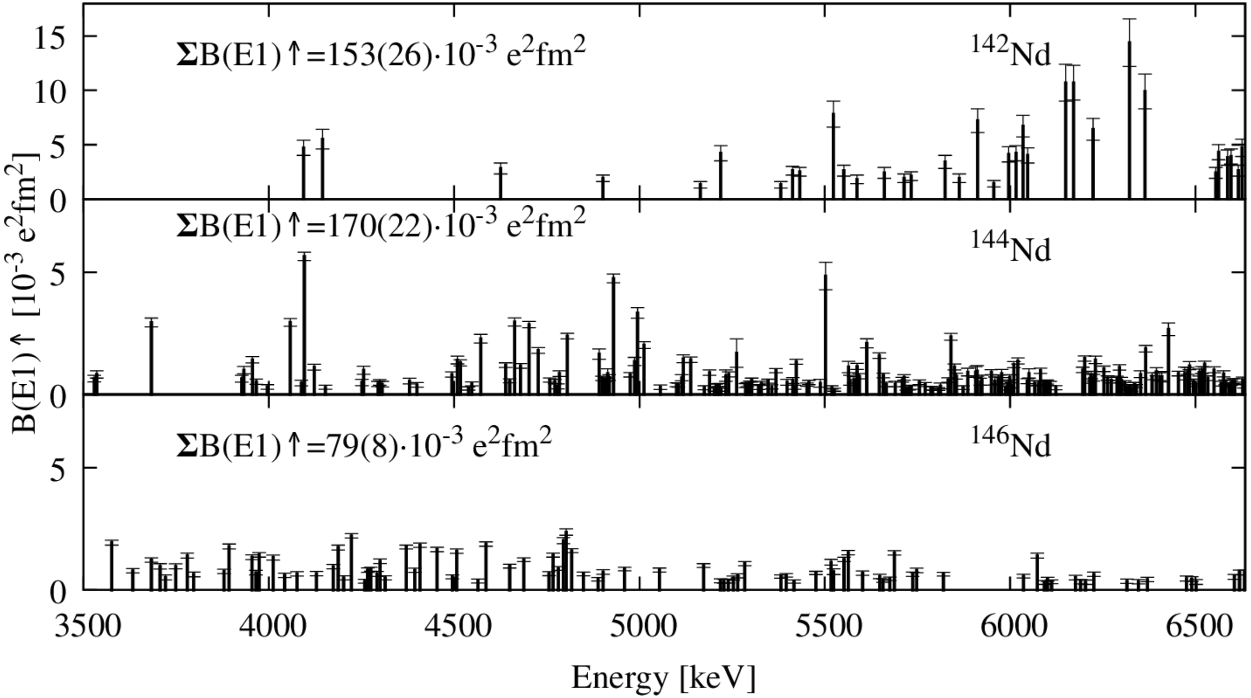


inelastic cross section $\sigma_{\gamma\gamma'}$:



Nd-isotopic chain – B(*E1*) strengths



fragmentation increases with increasing neutron excess

unresolved strength and γ-decay branchings not included

Nd142: S. Volz *et al.*, Nucl. Phys. A **779** (2006) 1
Nd144: F. Kluwig, Master‘s thesis, University of Cologne (2022)
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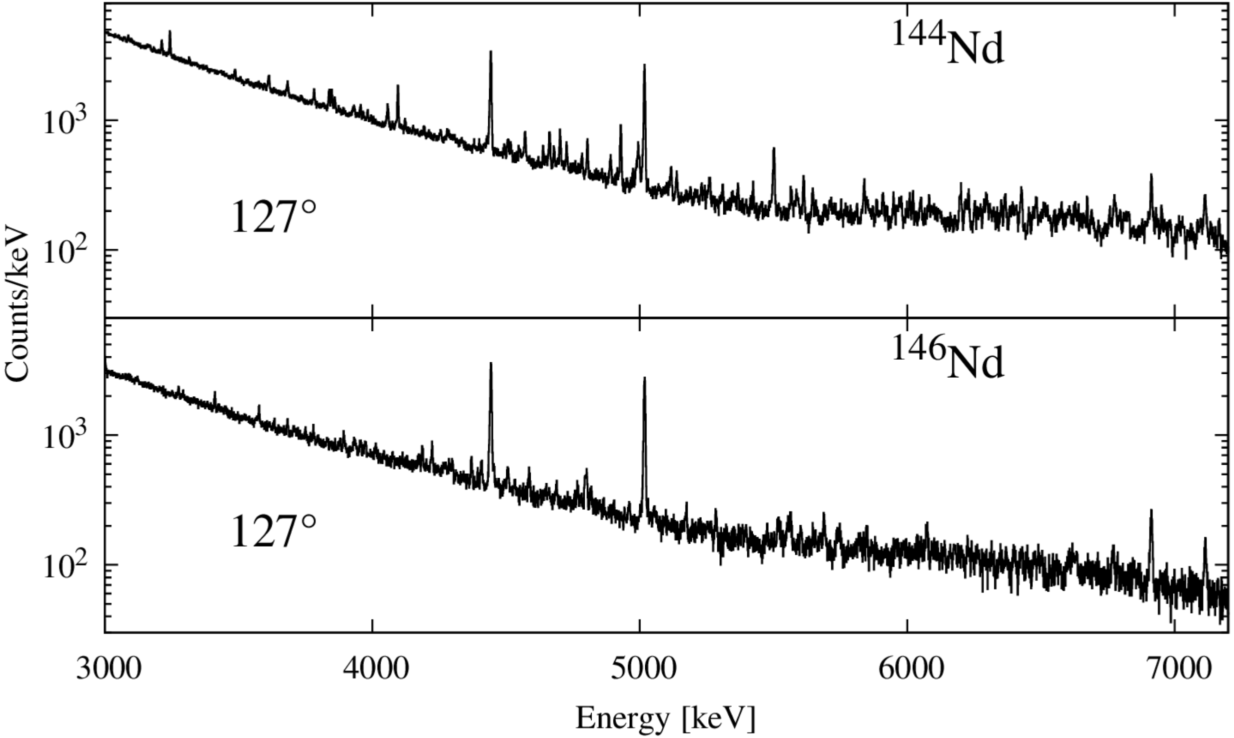


fragmentation increases with increasing neutron excess

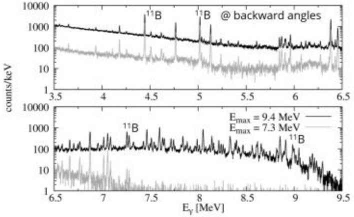
unresolved strength and γ-decay branchings not included

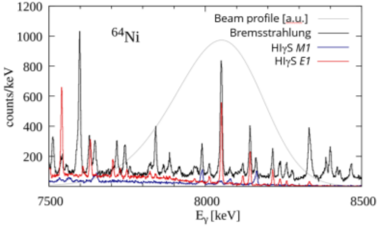
^{146}Nd just investigated up to 6.5 MeV due to high fragmentation

Nd142: S. Volz *et al.*, Nucl. Phys. A **779** (2006) 1
Nd144: F. Kluwig, Master's thesis, University of Cologne (2022)
Nd146: K. Meul, Bachelor's thesis, University of Cologne (2021)

Summary

- complementary NRF experiments
    - bremsstrahlung
    - Laser-Compton-Backscattering





Summary

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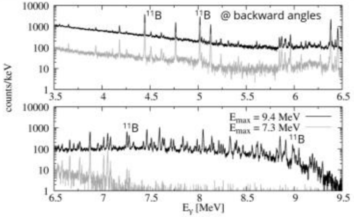
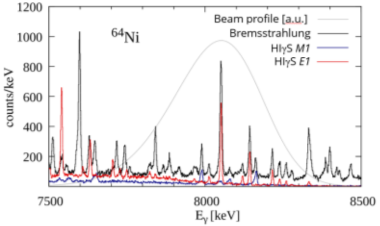
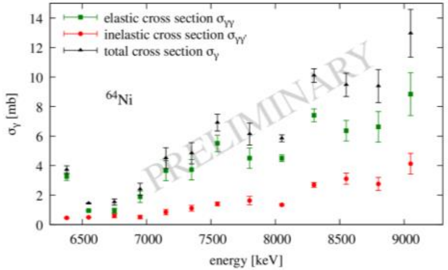
- (γ,γ‘) data well suited to investigate different topics of nuclear physics







Summary

- complementary NRF experiments
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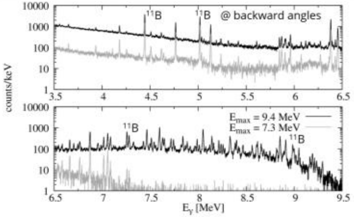
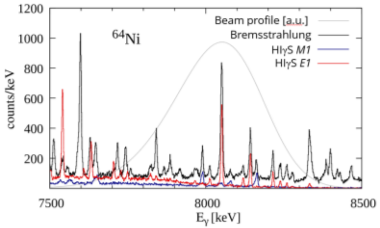
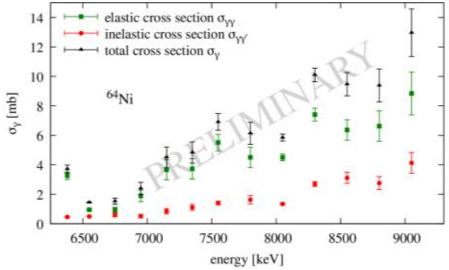
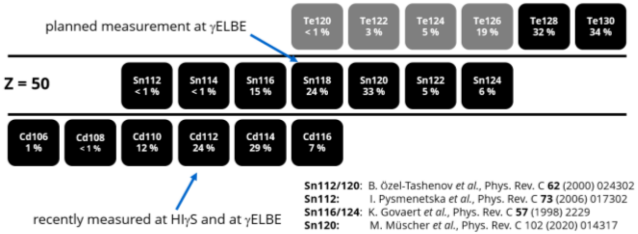
- (γ,γ‘) data well suited to investigate different topics of nuclear physics
- systematic NRF studies in isotopic and isotonic chains to investigate low-lying dipole response
  - Z = 28
  - Z = 50
  - N = 82









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Cd114: R. Massarczyk *et al.*, Phys. Rev. C 93 (2016) 014301