Nuclear Photonics

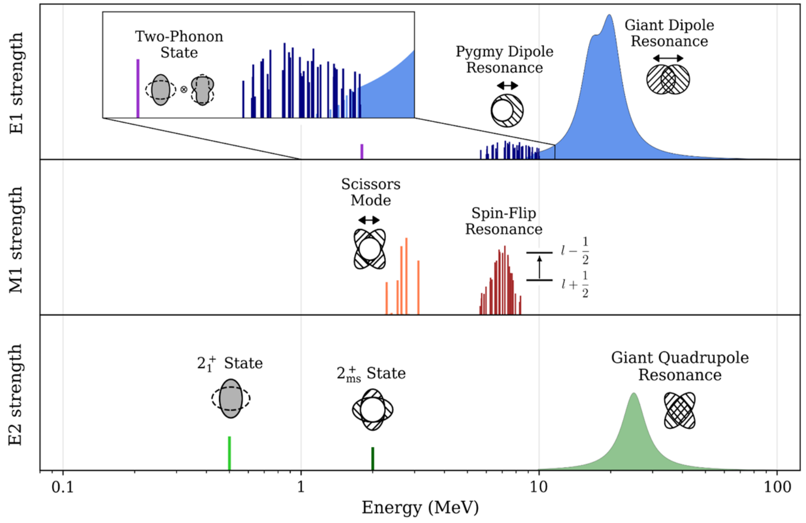
TECHNISCHE UNIVERSITÄT DARMSTADT

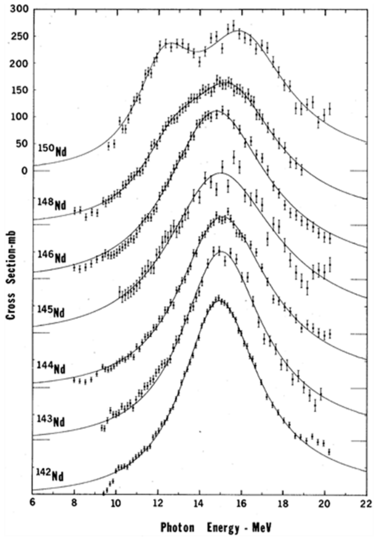
ENERGY-RESOLVED PHOTORESPONSE OF THE NUCLEAR GIANT DIPOLE RESONANCE:

Circumstantial Evidence for its Sub-Zeptosecond Lifetime

Dr. Jörn Kleemann

Professor Dr. Norbert Pietralla (TU Darmstadt)





PHYSICS REPORTS (Review Section of Physics Letters) 166, No. 3 (1988) 125–193. North-Holland, Amsterdam

DAMPING OF HIGH-LYING SINGLE-PARTICLE MODES IN HEAVY NUCLEI

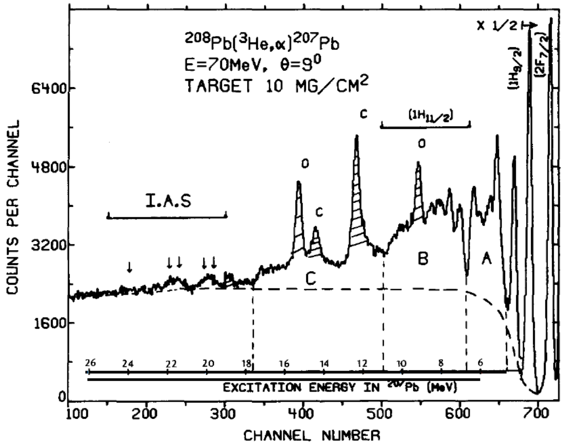
S. GALÈS
Institut de Physique Nucléaire, BP No. 1, 91406 Orsay Cedex, France

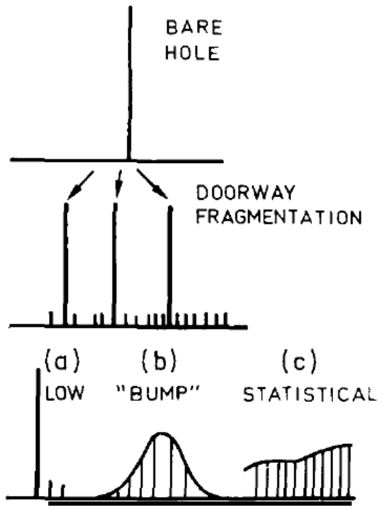
Ch. STOYANOV
Bulgarian Academy of Sciences, Institute of Nuclear Research and Nuclear Energy, 72 Boulevard Lenin, 1784 Sofia, Bulgaria

and

A.I. VDOVIN
Laboratory of Theoretical Physics, Joint Institute for Nuclear Research, 141 980 Dubna near Moscow, USSR

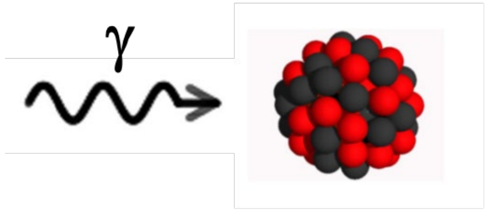
Received January 1988





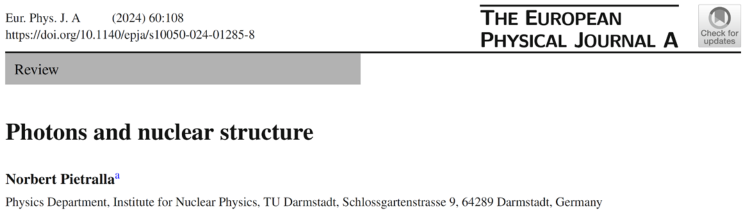
Bucharest, Marriott Hotel, Lobby
7.7.2016, ~23:30 h

UEFA-Euro 2016 Semi-Final
Germany – France: 0:2
(2nd goal by Antoine Griezmann)



What happens ?

Figure to the right from:



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https://doi.org/10.1140/epja/s10050-024-01285-8
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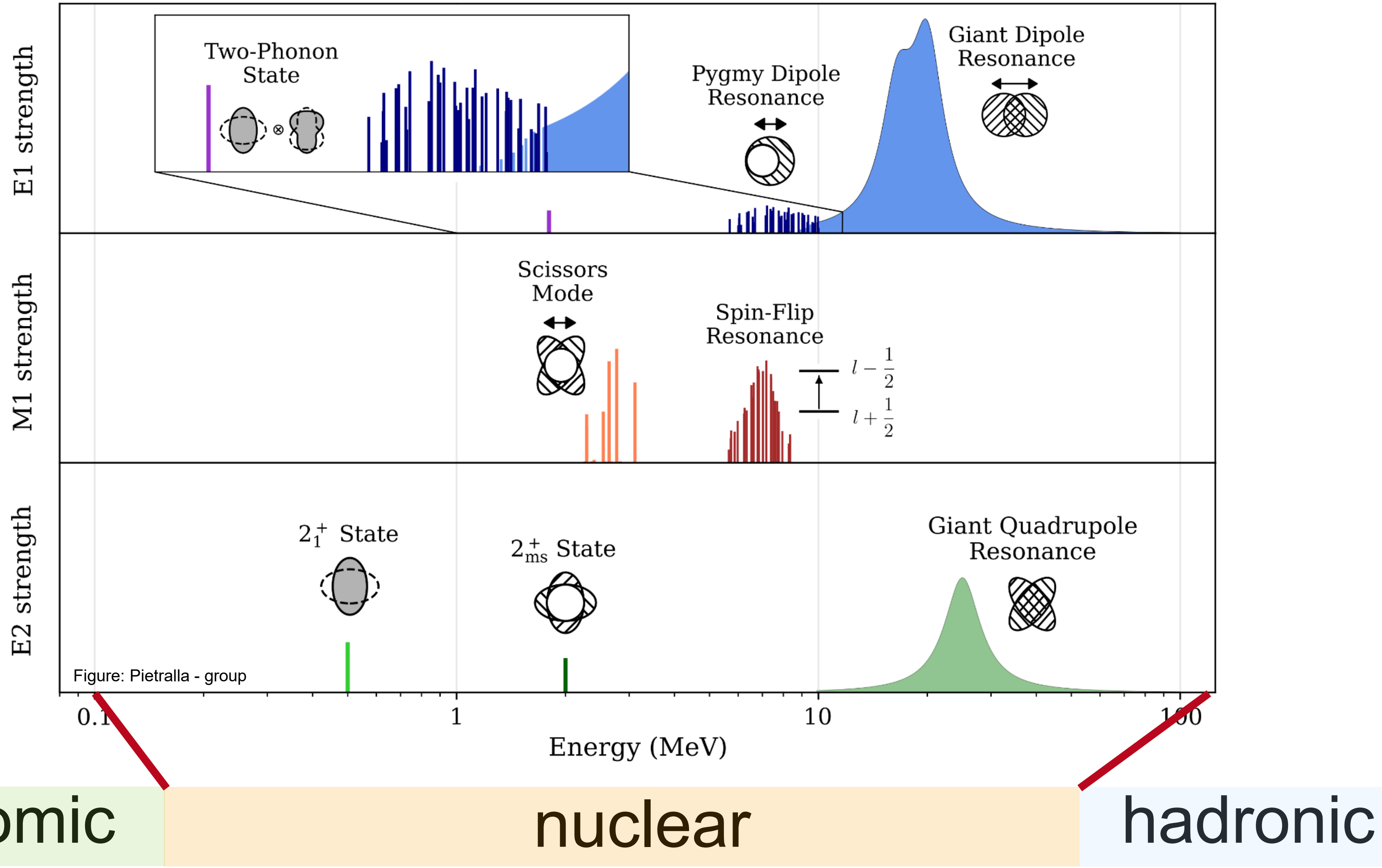
Review

Photons and nuclear structure

Norbert Pietralla[a]
Physics Department, Institute for Nuclear Physics, TU Darmstadt, Schlossgartenstrasse 9, 64289 Darmstadt, Germany



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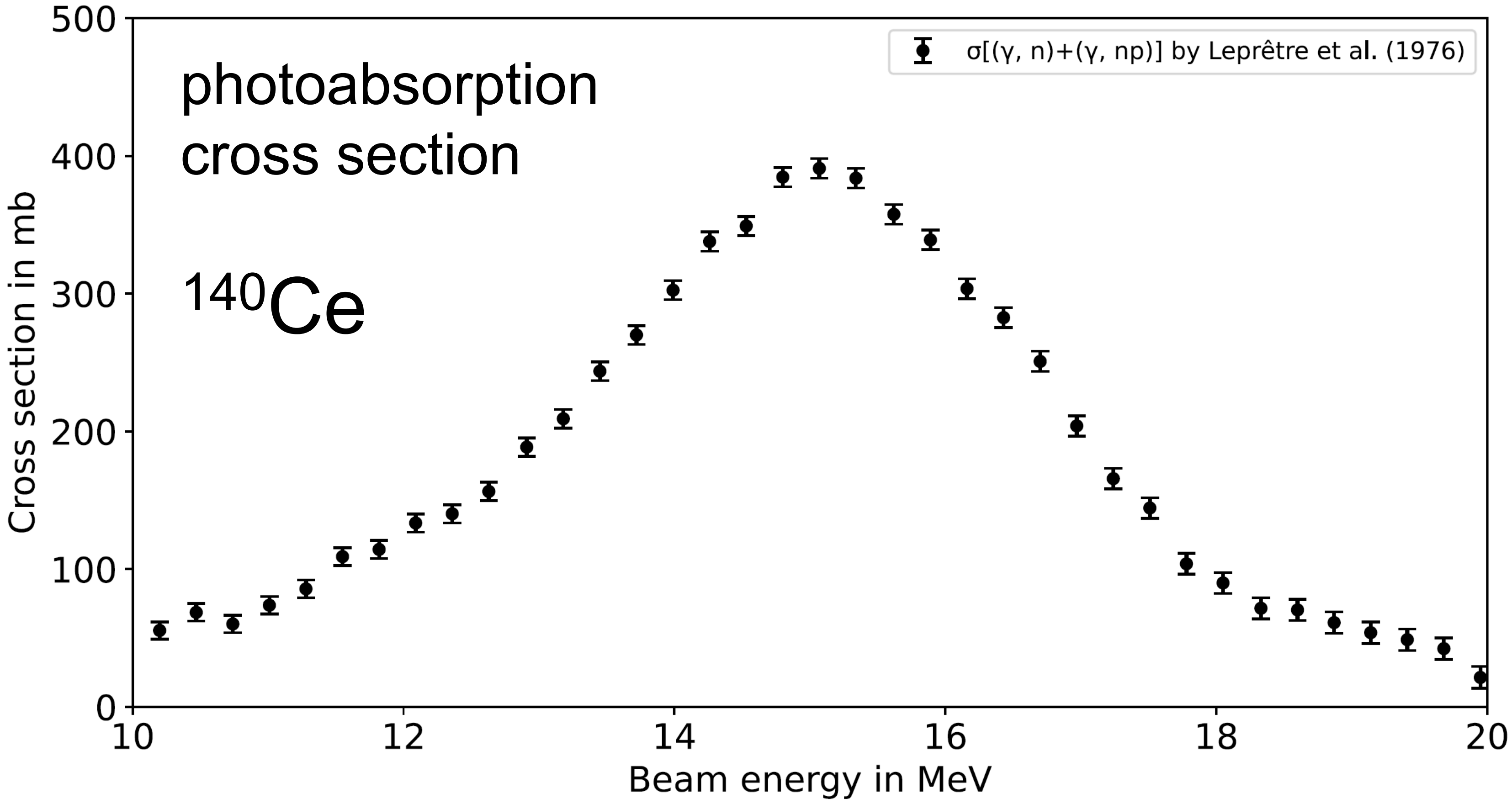
^{140}Ce GDR Lepretre et al, 1976

$$\int \sigma_{\mathrm{abs}}(E)dE = 3\pi^2 \lambda\!\!\!^{-2} \Gamma^{\lambda}_{\gamma 0}$$



EM excitation width:

$$\Gamma_{\gamma 0} = 55\ \mathrm{keV}$$

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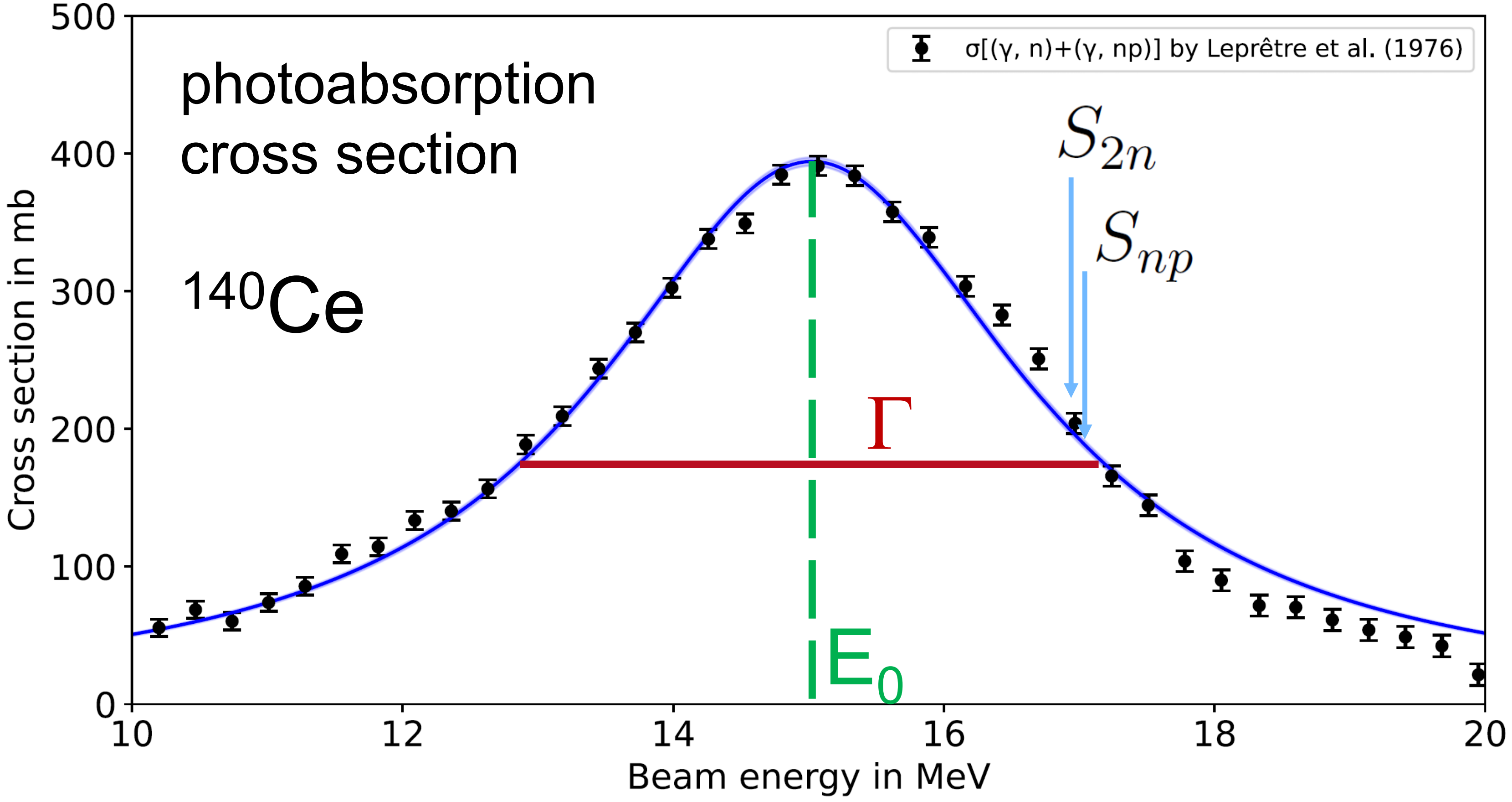
SLO and typical parameter values

^{140}Ce GDR Lepretre et al, 1976



$$\int \sigma_{\text{abs}}(E)dE = 3\pi^2\lambda\!\!\!^{-2}\Gamma^{\lambda}_{\gamma 0}$$

EM excitation width:

$$\Gamma_{\gamma 0} = 55 \text{ keV}$$

Standard Lorentzian (SLO) parametrization

$$\sigma_{abs}(E) = \frac{\sigma_0 E^2 \Gamma^2}{(E^2 - E_0^2)^2 + E^2\Gamma^2}$$

E_0 = 15.0 MeV
Γ = 4.7 MeV
σ_0 = 0.38 b

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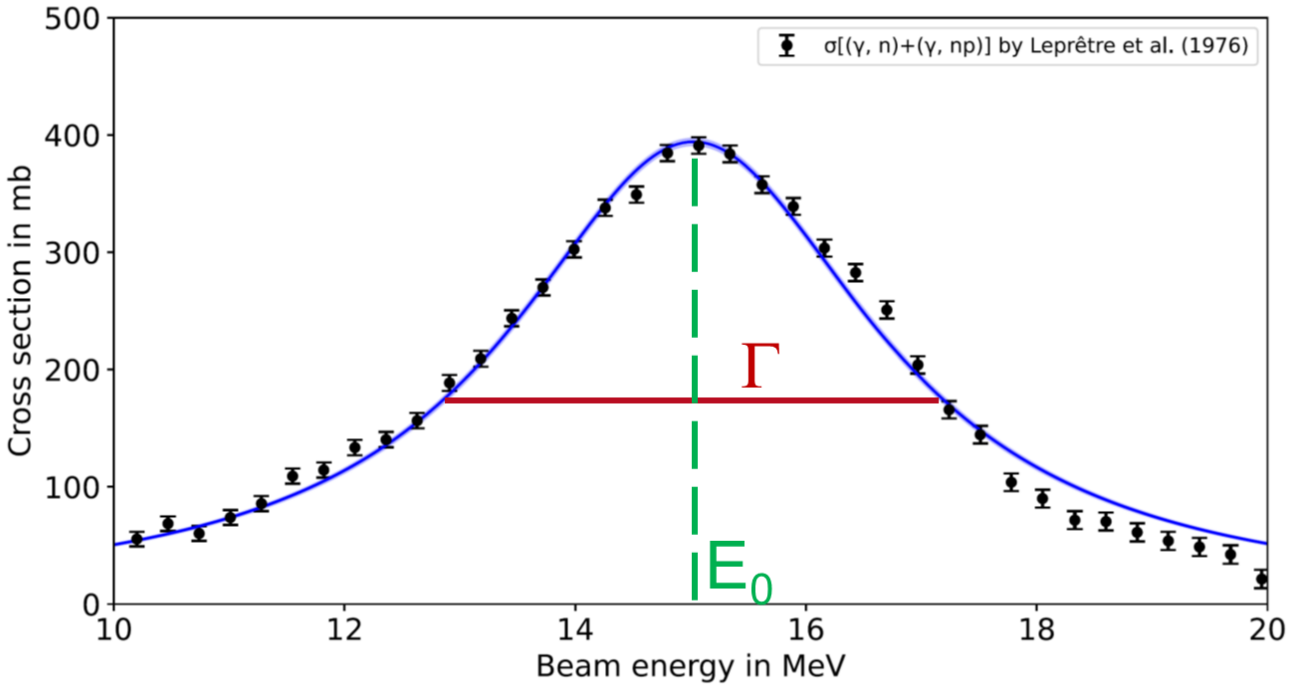
What is the meaning of the GDR **width**?



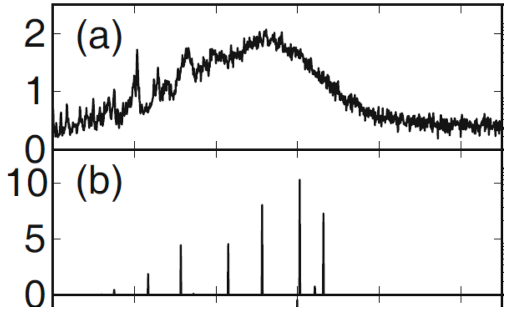
$$|\mathrm{GDR}\rangle = \hat{F}^{\dagger}_{\mathrm{ext}}|0^+_1\rangle$$
$$= \sum \alpha_i |1^-_i\rangle$$

τ = 0.14 zs ?

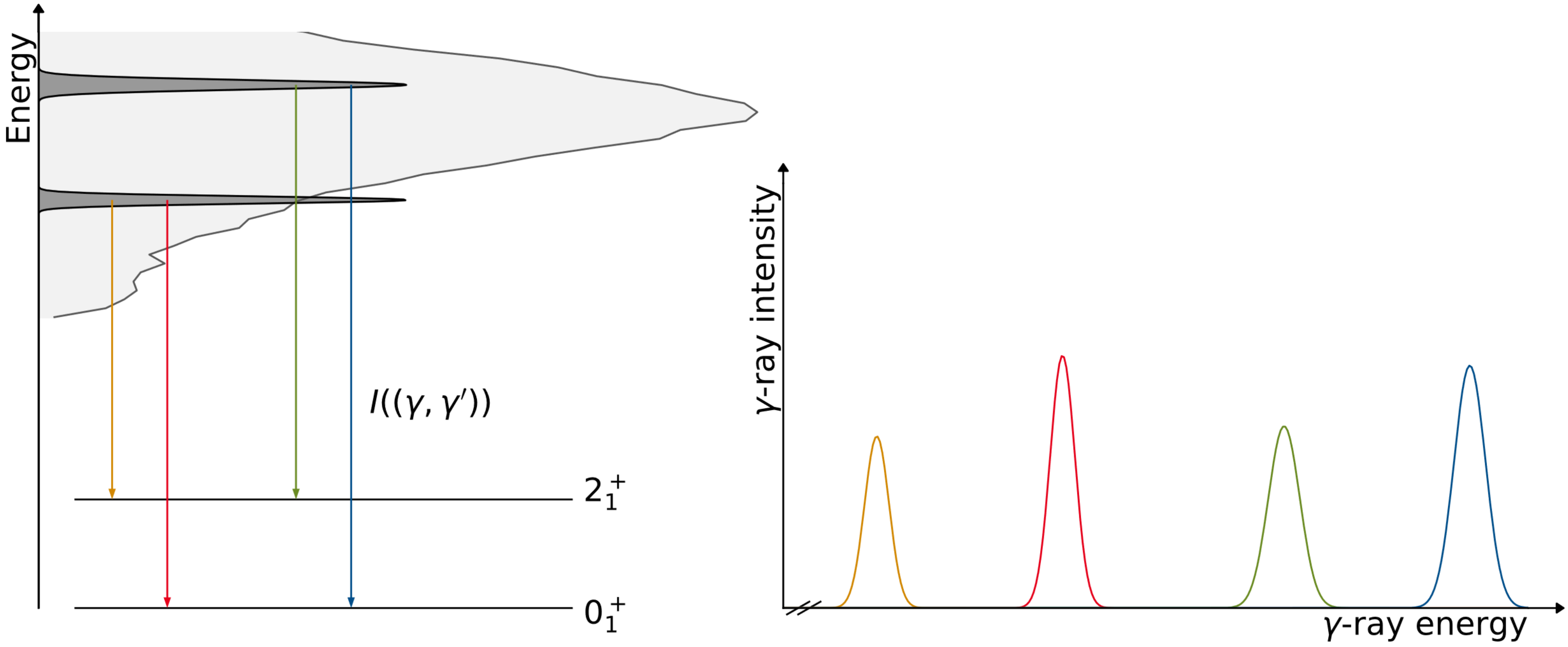
$$\Gamma = \frac{\hbar}{\tau}$$

⟷

Panoply of unresolved compound states



Measurement principle:
Photoexcite energy-slices of the GDR and detect the decay γ-rays



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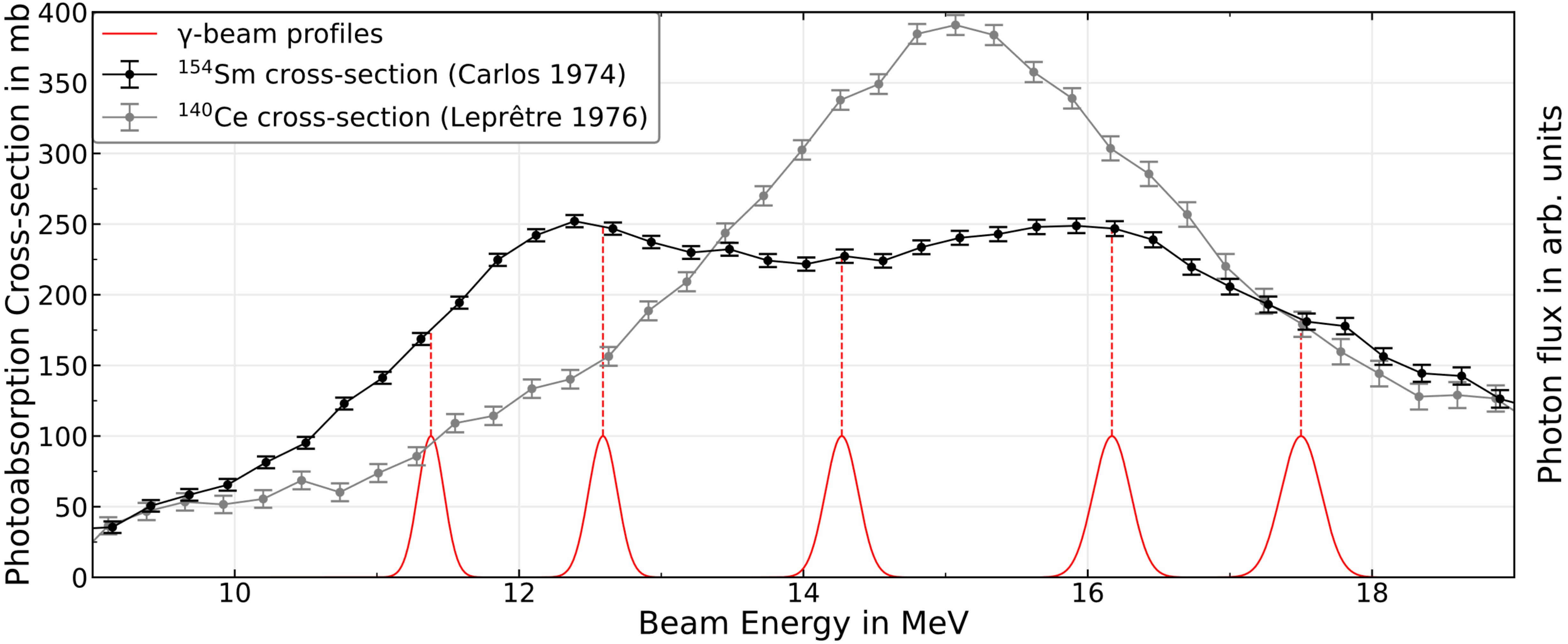
Measurement @ HIγS on ^{140}Ce and ^{154}Sm



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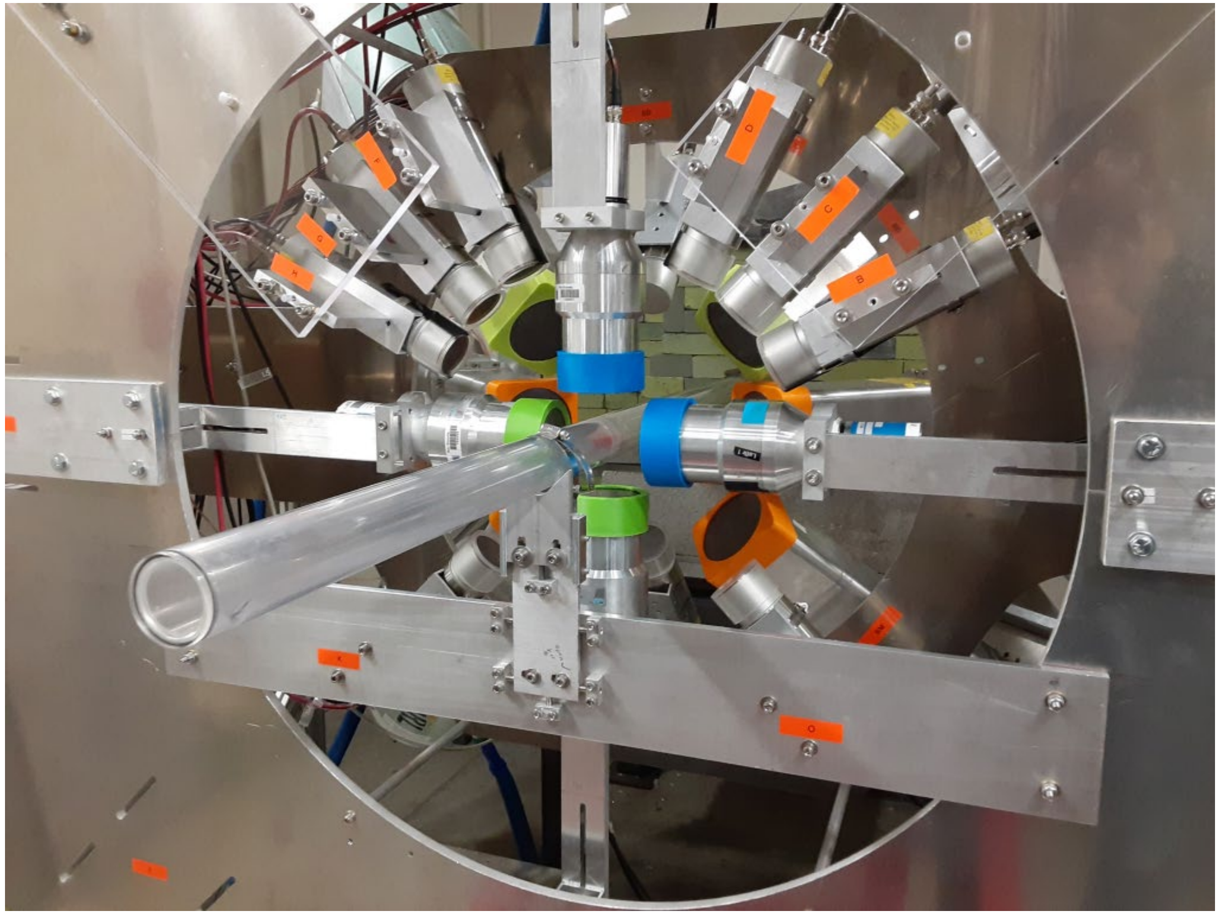
Our “photo camera”: γ^3 setup at HIγS

Johann Isaak

Volker Werner



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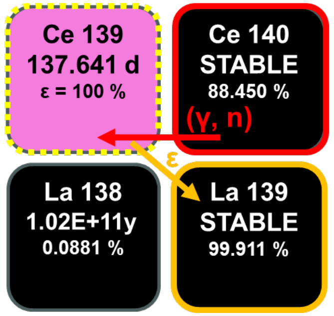
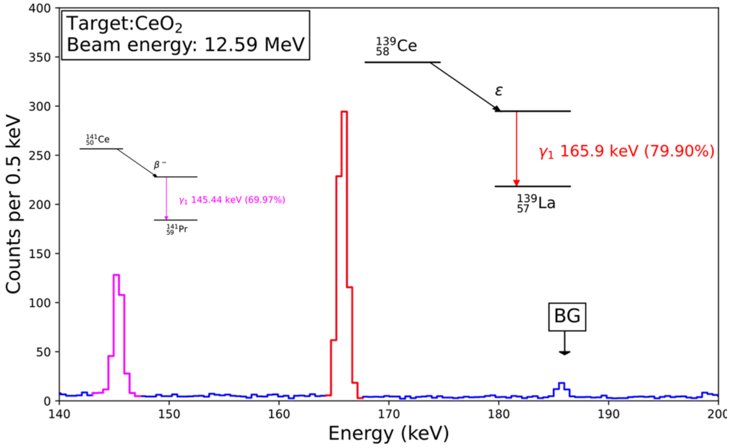
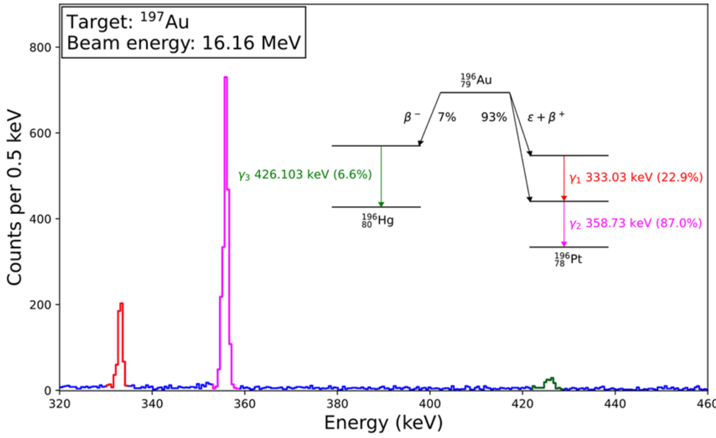
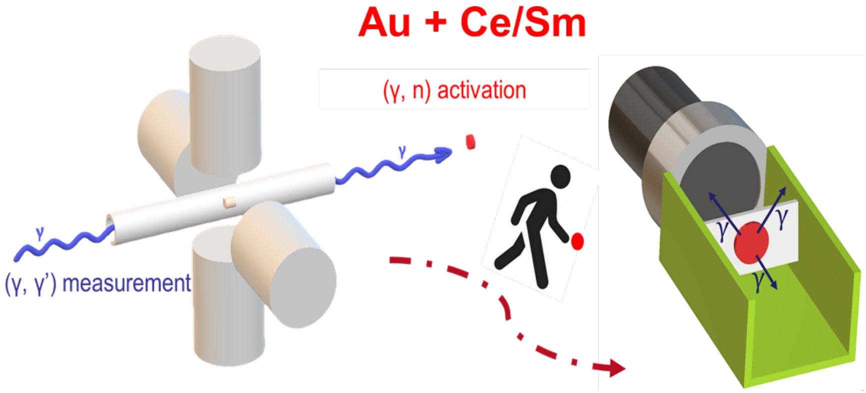
Photon flux calibration and verification of cross sections for ^{140}Ce and ^{154}Sm

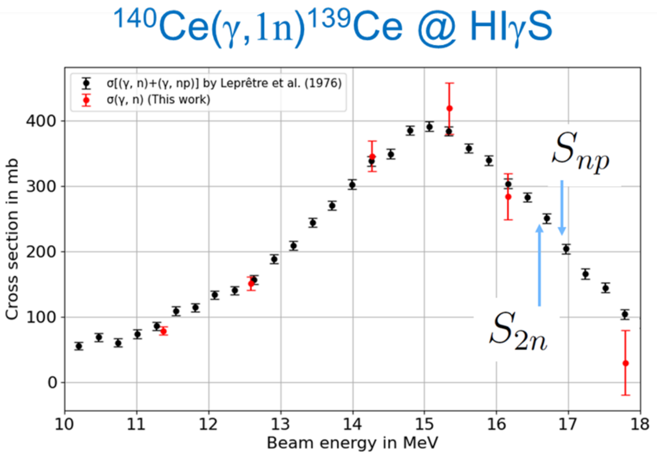


Kiriaki Prifti









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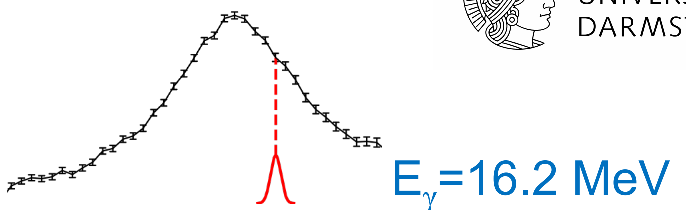
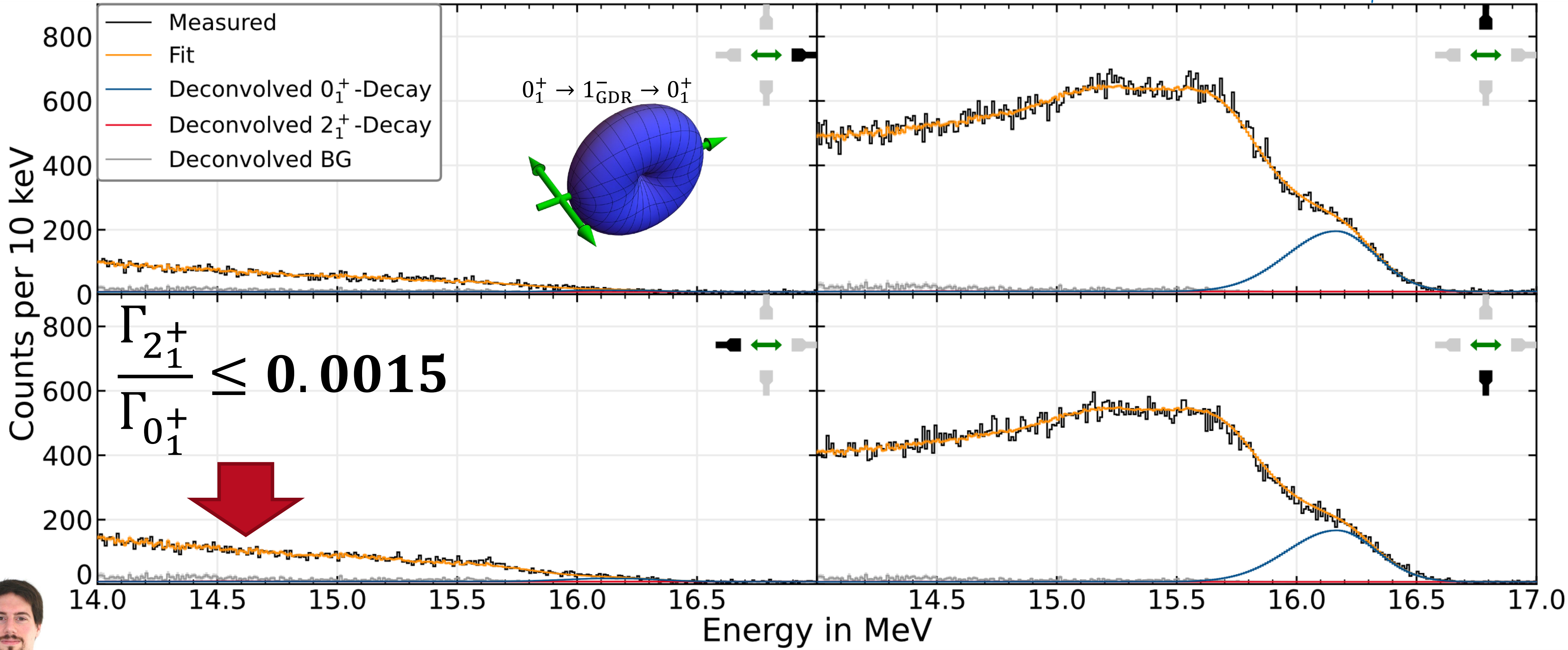
^{140}Ce(γ,γ')@16.2 MeV at HIγS





$$\frac{\Gamma_{2_1^+}}{\Gamma_{0_1^+}} \leq \mathbf{0.0015}$$

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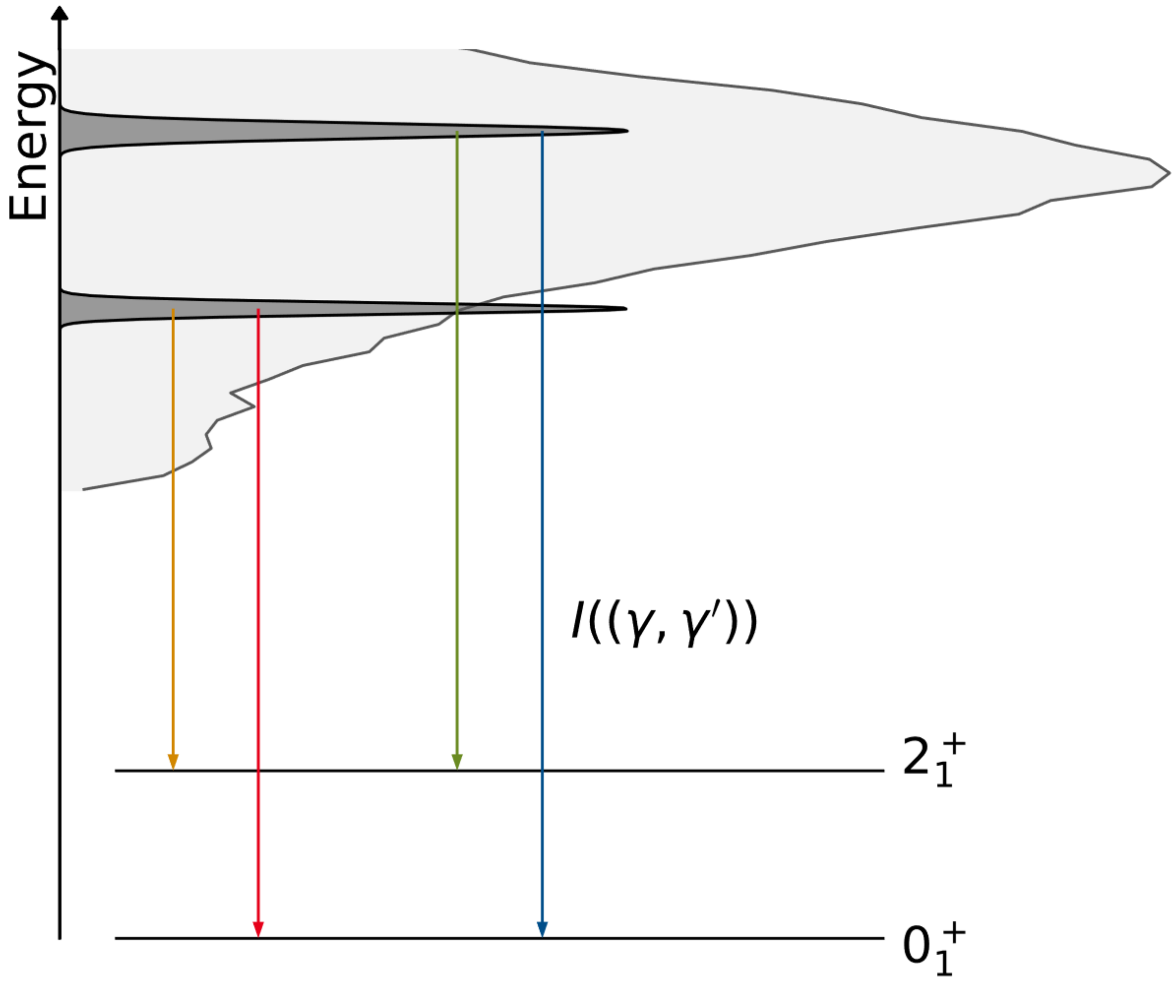

E_{beam} (MeV)	$I_{\gamma,2_1^+}/I_{\gamma,0_1^+}$
11.4	0.60(40)
12.6	0.0034(24)
14.3	0.0010(7)
15.4	0.0007(7)
16.2	0.0009(6)
17.8	0.0019(13)

^{140}Ce

relative cross sections

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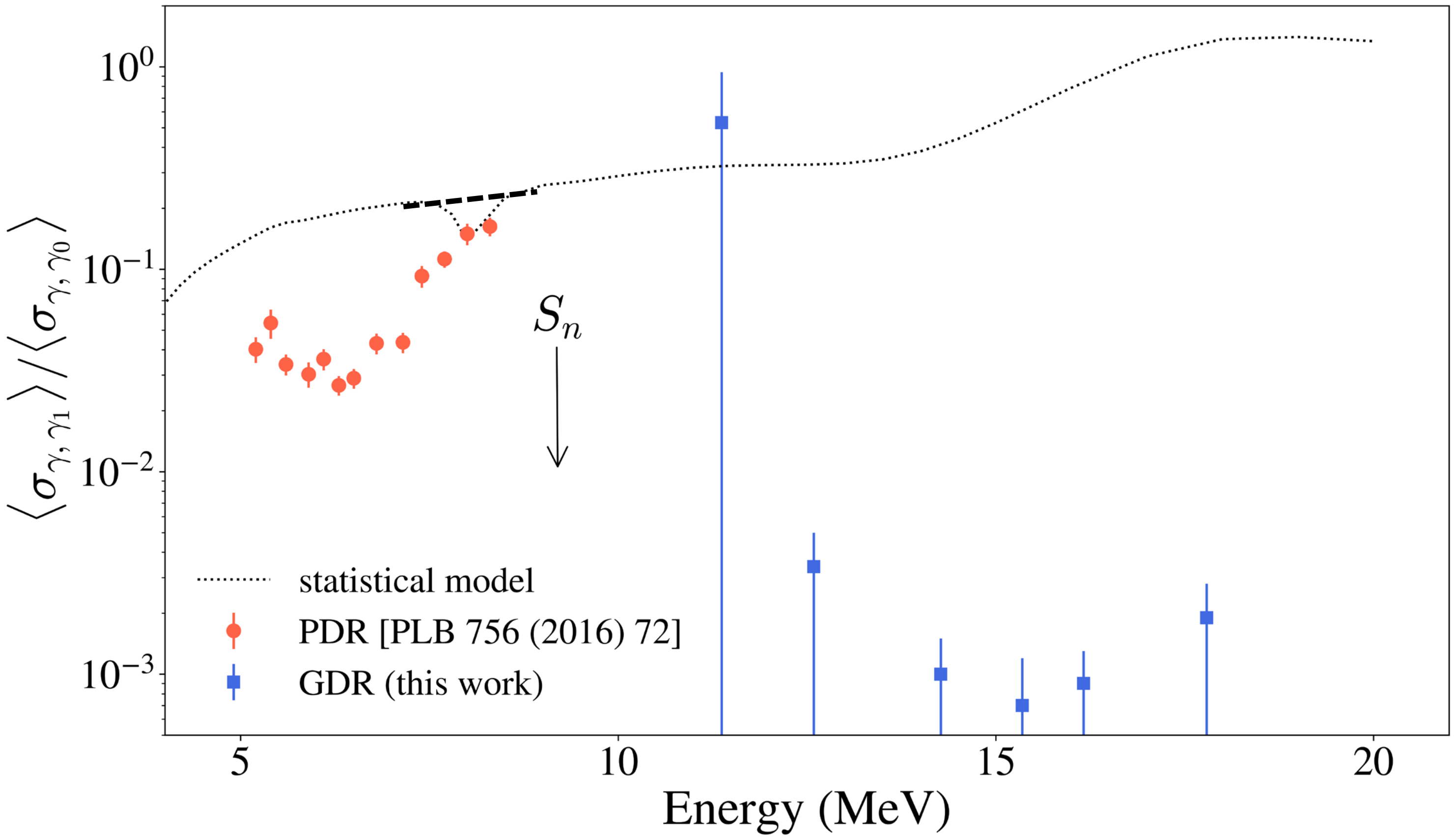
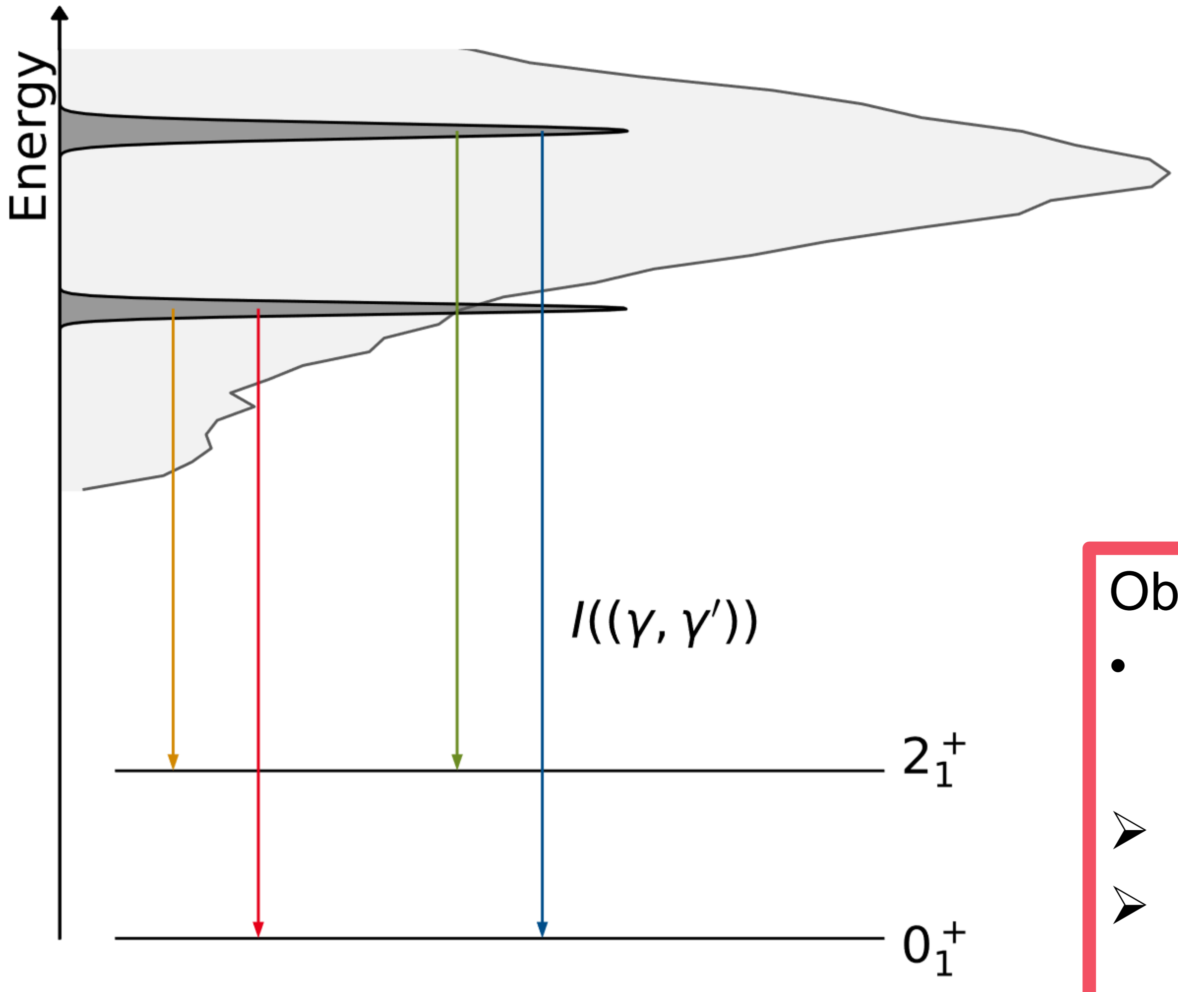
^{140}Ce

relative (γ,γ') cross sections for GDR decay into 2_1^+ state or ground state



GDR γ-decay into ground state is NOT statistical !



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^{140}Ce

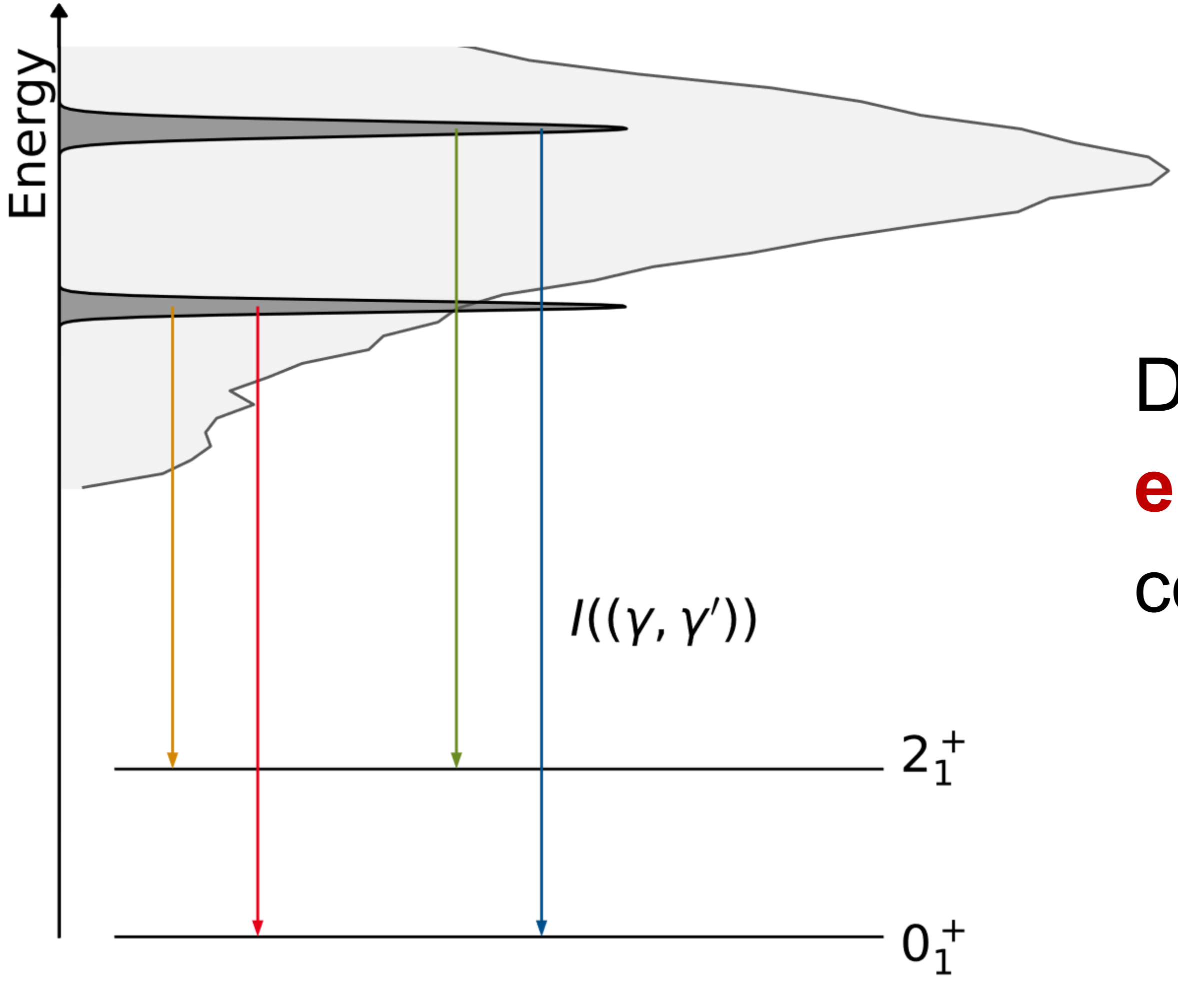
relative cross sections

Observation:

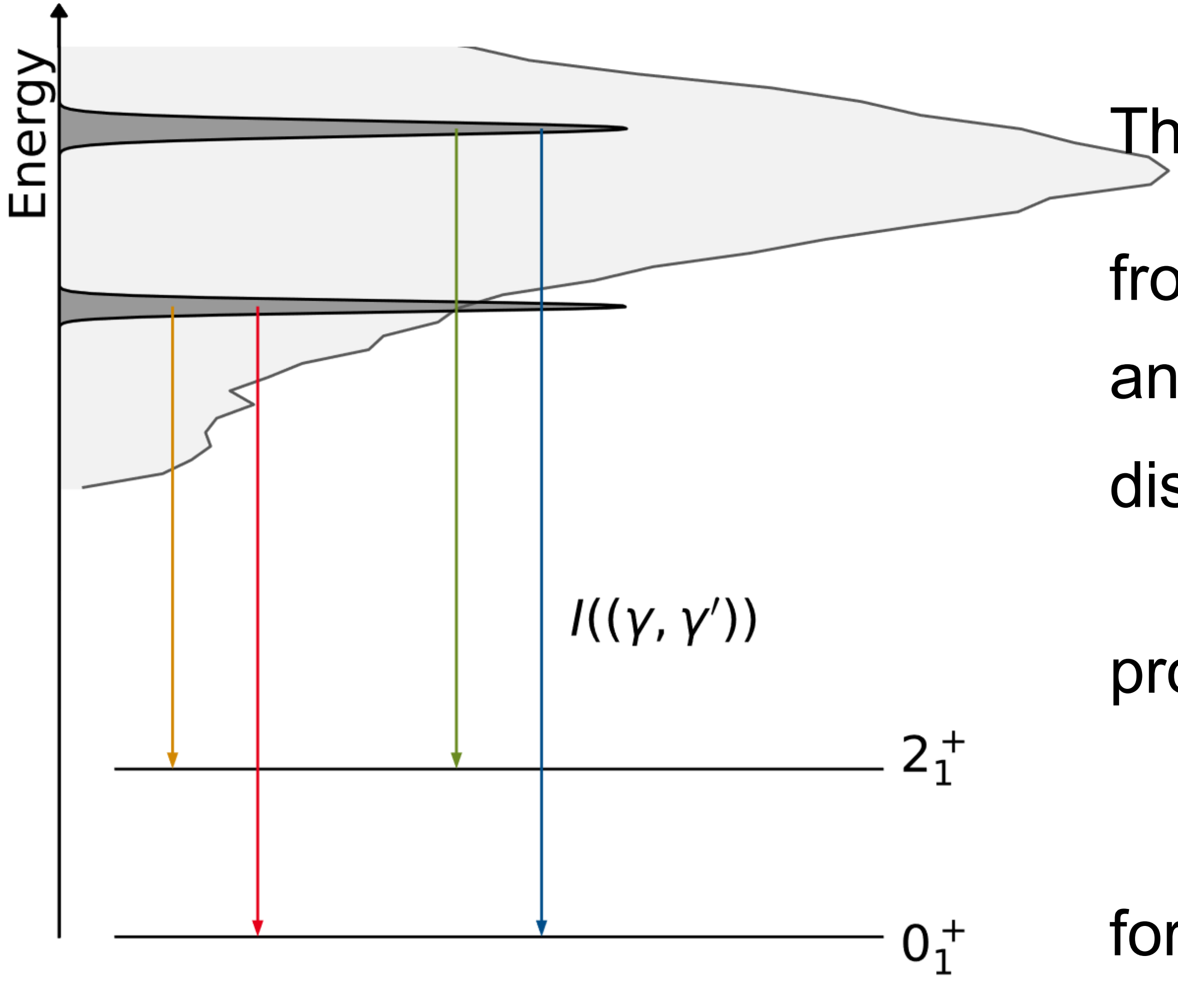
- γ-decay branches to 2^+_1 (or other excited states) are VERY small for **^{140}Ce**. **~10^{-3}**. At all energies.

➢ GDR decays to gs by γ due to collective operator.

➢ The γ–decay width of the GDR must be the EM width of the collective mode, i.e., $\Gamma_{\gamma 0}$ = 55 keV.



Do the **absolute cross sections** for **elastic photon scattering** confirm notion of single coherent mode?



Elastic scattering cross section

$$\sigma_{\gamma,\gamma_0'}(E) = \frac{8\pi}{3}|f_T + f_{\mathrm{NRF}_0}(E)|^2$$

Thomson: f_T known, constant, and real

from optical theorem $$Im f_{\mathrm{NRF}_0}(E) = \frac{E}{4\pi\hbar c}\sigma_{\mathrm{abs}}(E)$$

and

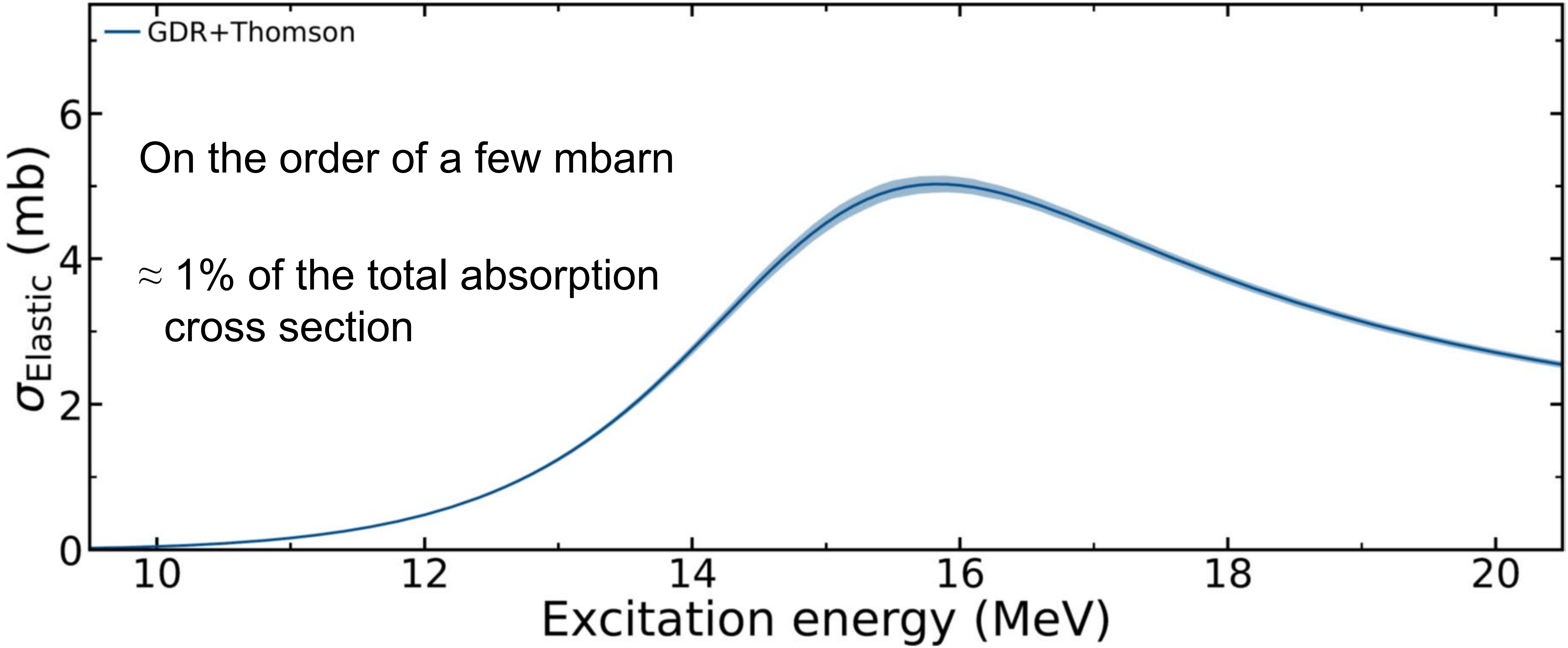
dispersion relation $$Re f_{\mathrm{NRF}_0}(E) = \frac{E^2}{2\pi^2\hbar c}\mathcal{P}\int_0^\infty \frac{\sigma_{abs}(\epsilon)}{\epsilon^2 - E^2}d\epsilon$$

providing

$$Re f_{\mathrm{NRF}_0}(E) = \frac{\sigma_0 E^2\Gamma}{4\pi\hbar c}\frac{E^2 - E_0^2}{(E^2 - E_0^2)^2 + E^2\Gamma^2}$$

for SLO parametrization and constant damping

GDR’s elastic photon scattering cross section: consequence from SLO



On the order of a few mbarn

$\approx$ 1% of the total absorption cross section

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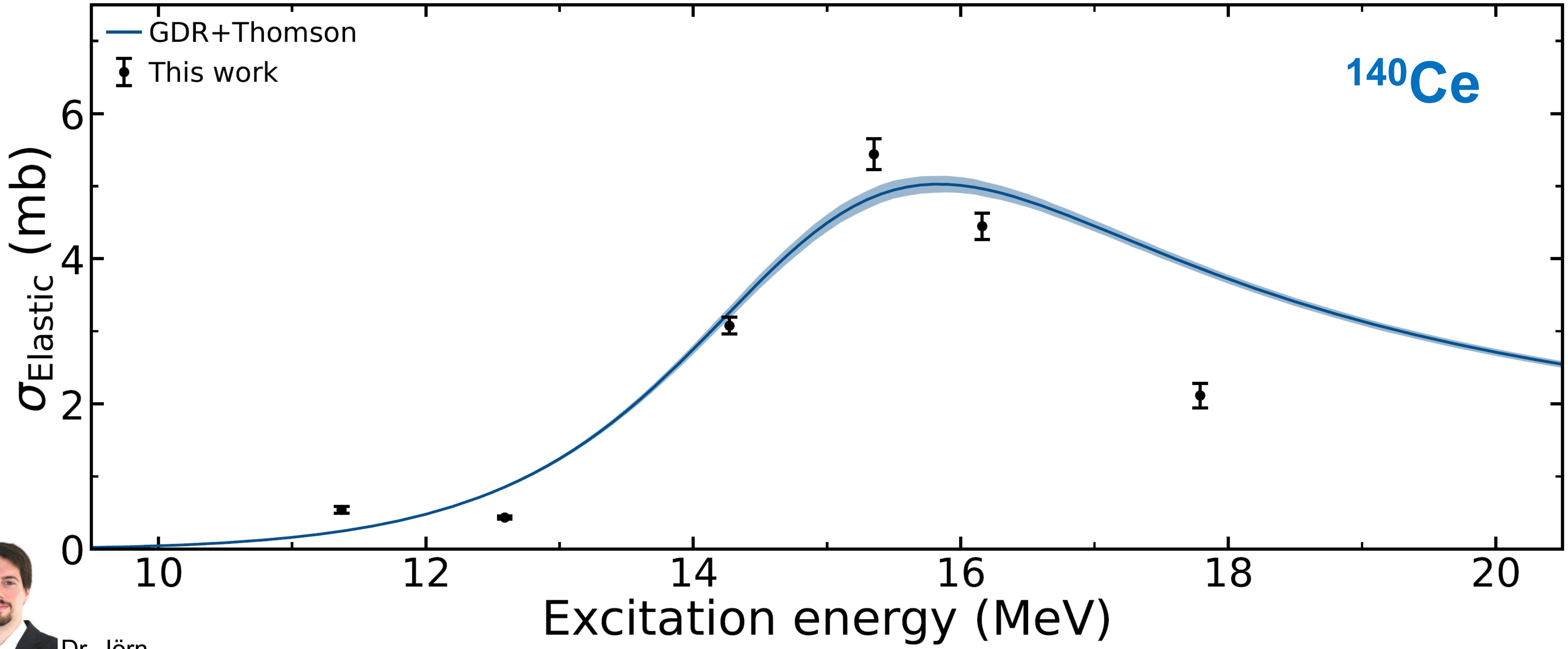
GDR's elastic photon scattering cross section: first compared to data



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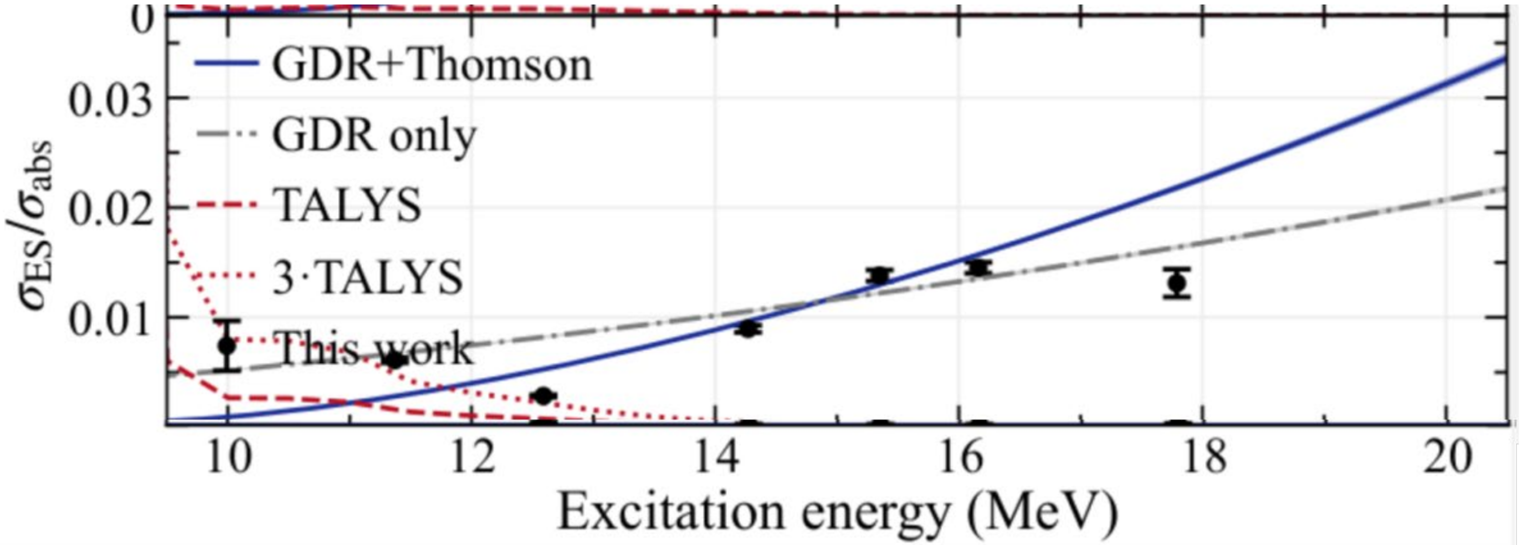
What is the energy dependence of the $(\gamma,\gamma_0')/(\gamma,n)$ branching ratio?

Neglecting the (small) Thomson term in SLO parametrization yields

$$\sigma_{\gamma,\gamma_0'}(E) = \left(\frac{\lambda_0}{\lambda}\right)^2 \frac{\Gamma_{\gamma_0}}{\Gamma}\sigma_{abs}(E) \quad \sim E^2 \; \sigma_{abs}(E)$$



^{140}Ce

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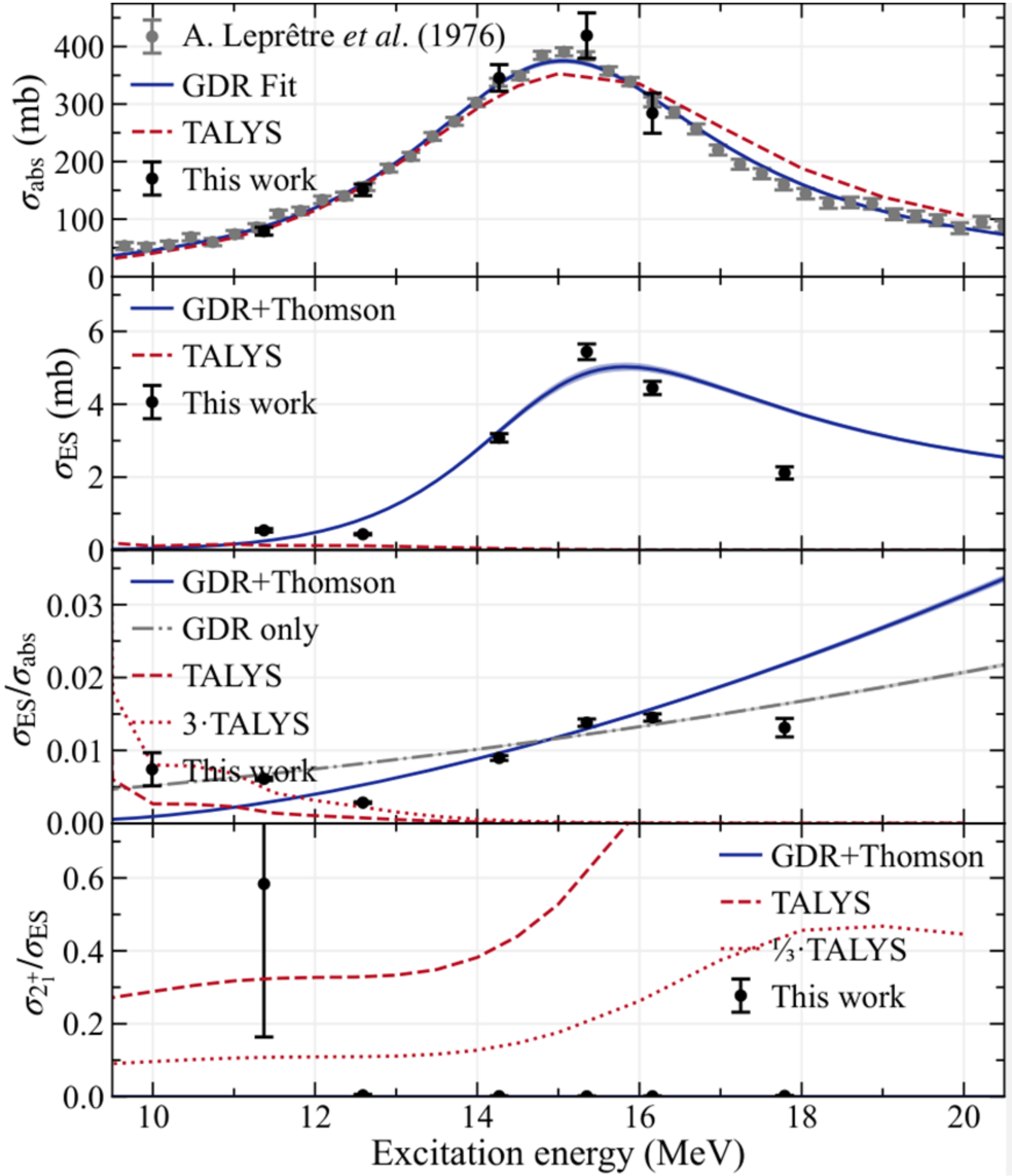
Observations: **^{140}Ce**

- GDR decays by γ collectively. (coherent 1p1h)
- Width for γ–decay of GDR is EM-width of this collective state. Γ_γ = 55 keV.
- Decay leading to particle emission is ~90 times faster. $\Rightarrow \Gamma$ = 4.7 MeV.

➢ Implying Γ IS the decay probability of this collective GDR state. q.m.-dephasing into chaotic compound

➢ The GDR "dephases" within 0.14 zs. ~ half of oscillation period $T=1/\nu = h/E$

➢ Statistical γ-decay from final compound state is much smaller.



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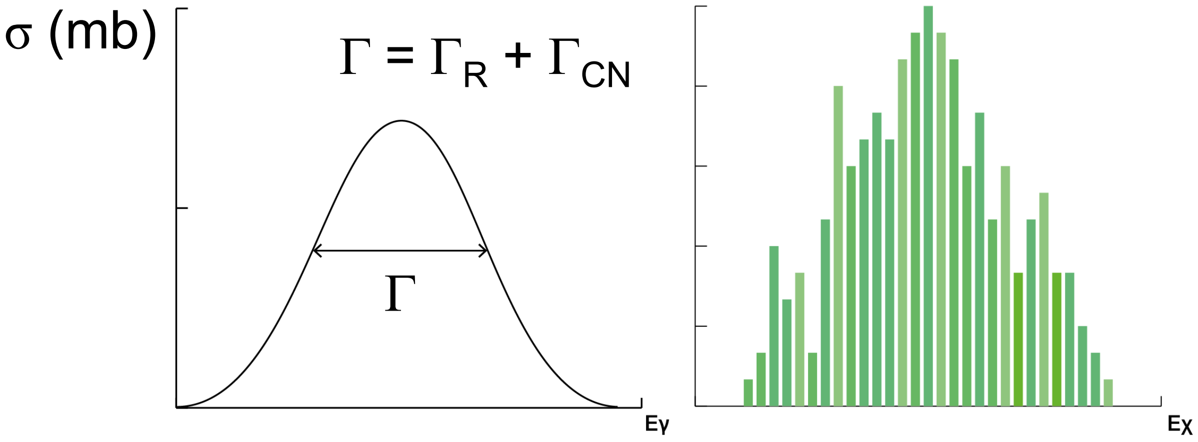
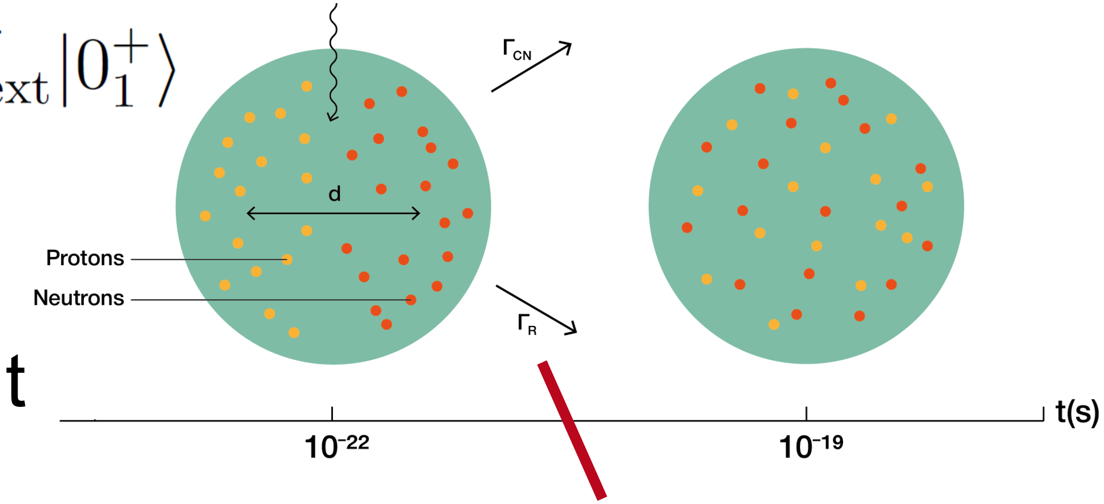


$$|\mathrm{GDR}\rangle = \hat{\mathrm{F}}^{\dagger}_{\mathrm{ext}}|0^+_1\rangle$$



ordered coherent motion

99% formation of compound nucleus (chaotic)

with subsequent statistical decay

~1% collective γ-decay to gs

CONCLUSIONS

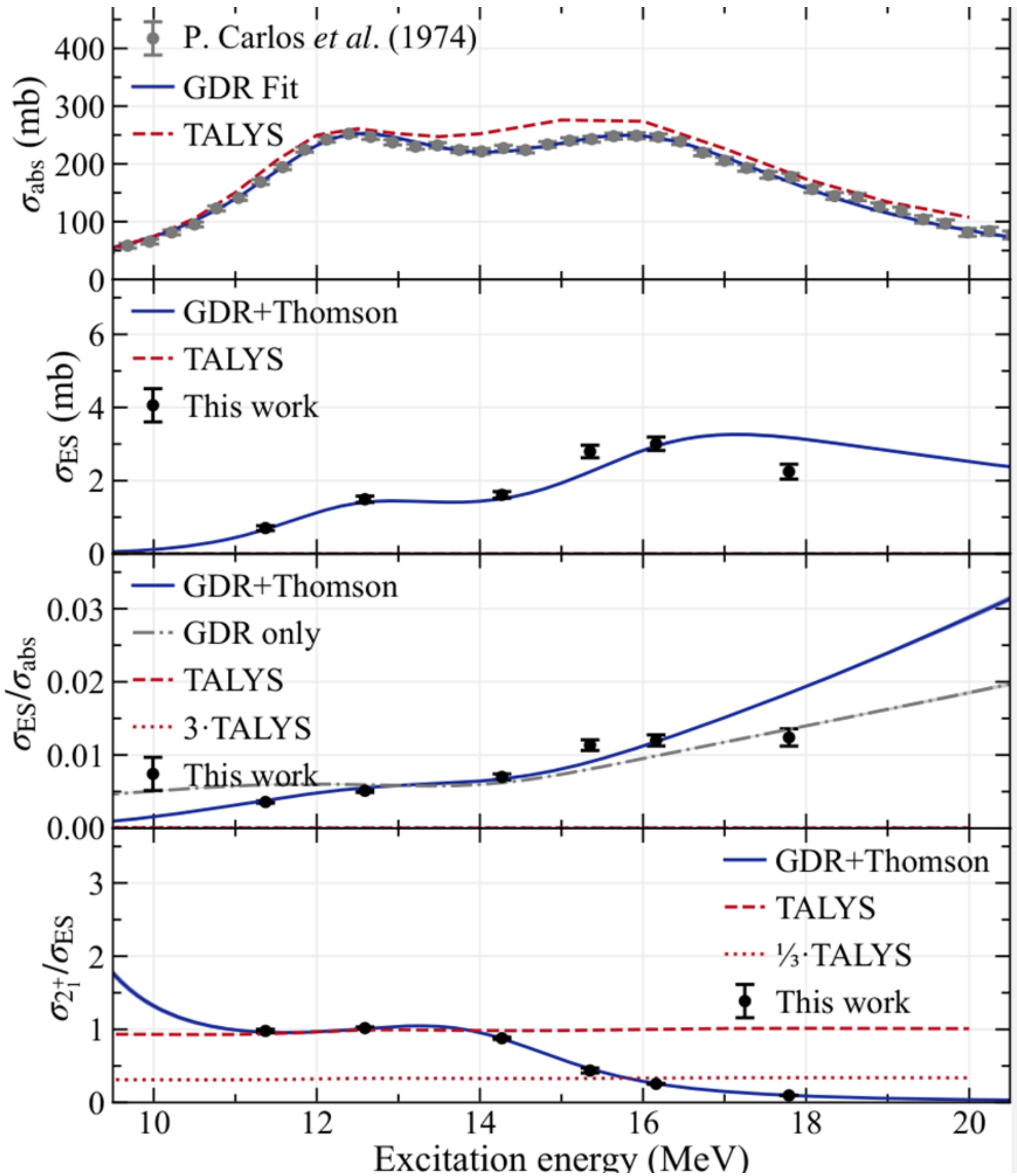
Similar observations on the deformed nucleus ^{154}**Sm**:

- GDR decays by γ collectively to gs, and to the 2^+_1, too.
- Evolution of γ-branching ratio with energy is due to interferences of 3 SLOs about 3 axes

Identical conclusions as for ^{140}Ce

- ➢ γ-decay from compound is small.
- ➢ Width of $\sigma_{abs}(E)$ is the sum of the decay probabilities of the collective modes (“dephasing”) about the 3 different axes.

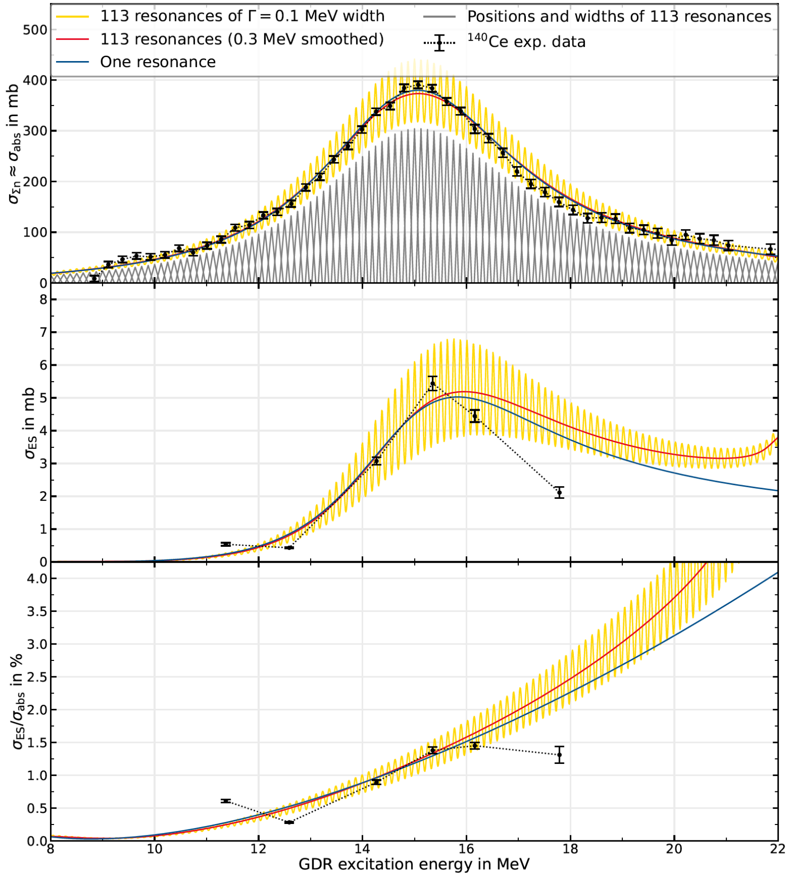
J.Kleemann, NP et al., PRL 134, 022503 (2025).



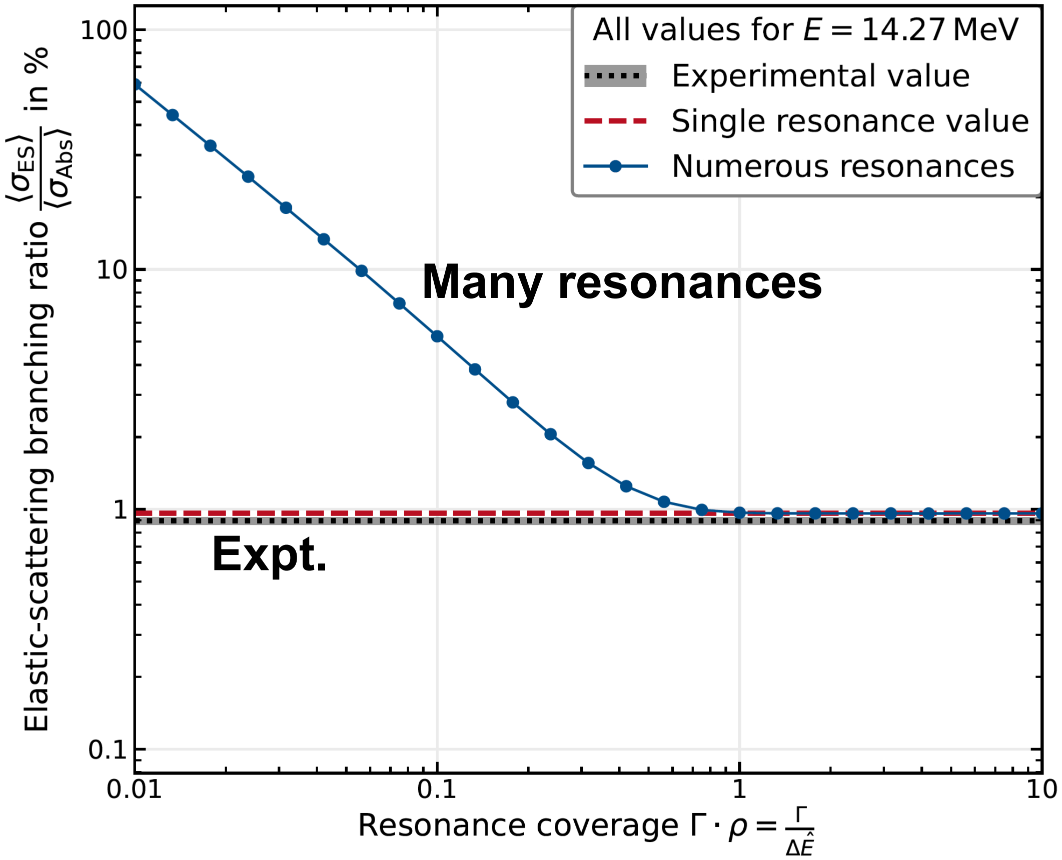
^{154}**Sm**

Can the data be consistent with zillions of isolated states?

- No! It only works when the individual 1^- states overlap and mix.



E.g., 113 equidistant SLOs



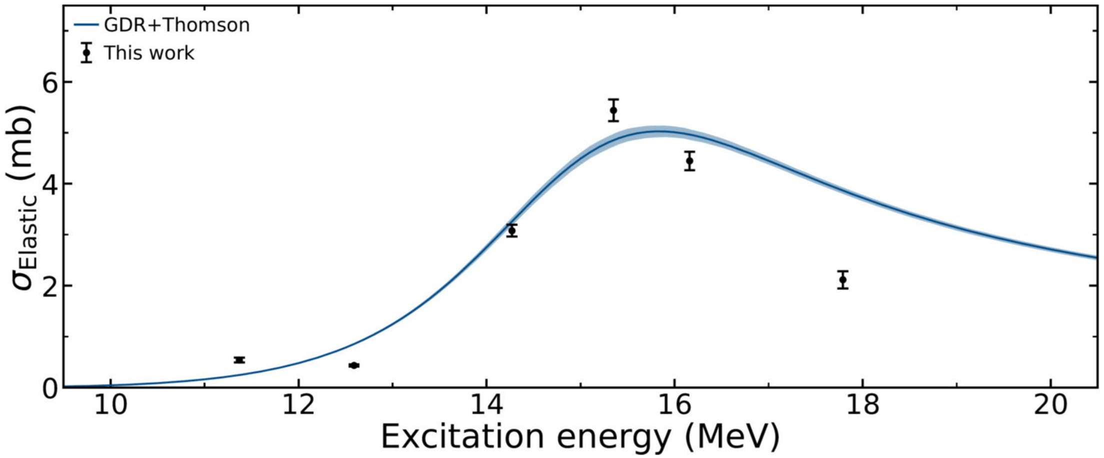
GDR modeled by few thousand equidistant equally-wide 1- states with widths Γ.

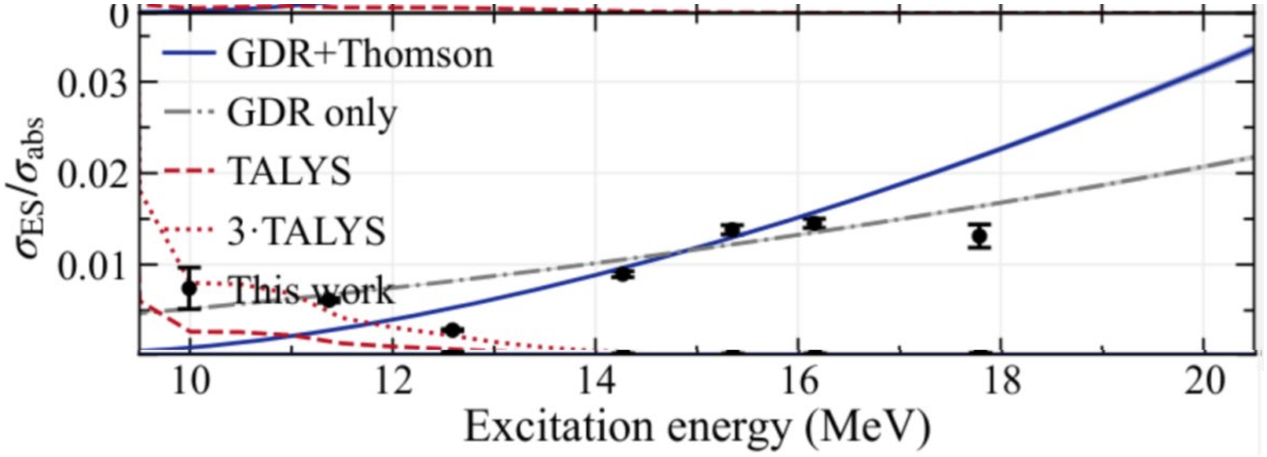
The elastic scattering data is recovered, only, if the spacing between the states is of the order of their widths or less.

The GDR is a single mode or a “coherent mixture of 1^- states”.

Observations:

- The γ-to-neutron–decay branching ratio of the GDR amounts to about 1%.
- It INCREASES with energy over the GDR.
- The γ–decay of the GDR is not statistical. It reflects the collective mode.
- The NRF cross section evolves over the GDR according to the collective mode.





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Observations:

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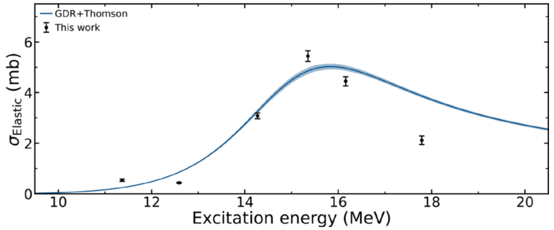

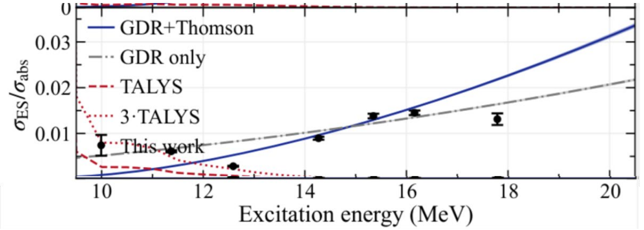

Conclusions:

- ➢ The GDR decays by γ with its collective EM-widths. $\Gamma_{\gamma 0}$ = 55 keV.
- ➢ Still, the GDR decays 90 times faster into chaotic compound states that decay statistically.
- ➢ With internal decay width Γ = 4.7 MeV, corresponding to internal decay time of τ = 0.14 zs.
- ➢ The GDR width IS its (internal!) decay width "decoherenization", timescale $\tau \approx$ 0.14 zs.

Conjecture:

- ➢ The GDR (of heavy nuclei) cannot show any finestructure ! Because it decays too fast.

Damping of the GDR = dephasing into 'chaotic' compound states

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- Addresses foreign female scientists who have received a bachelor degree or are close to receiving it

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- A stipend for 24 months is offered for master studies at the Physics Department at TU Darmstadt
- Scholarships$ start annually in October

$ 600 € per month stipend + at least 400 € per month bonification for work as student assistant

Technical University of Darmstadt, Master of Science in Physics

- TU Darmstadt is one of Germany's most international universities
- Duration: 4 Semesters
- Language: English
- The research activities of the department are grouped in three institutions, each of which comprises groups working in both experimental and theoretical fields

<table>
<tr><th>1st semester</th><th>2nd semester</th><th>3rd semester</th><th>4th semester</th></tr>
<tr><td>Seminar Theoretical Physics
(5 CP)</td><td>Seminar Experimental Physics
(5 CP)</td><td rowspan="4">Research Area:
Practical Introduction to Scientific Research
(30 CP)</td><td rowspan="4">Research Area:
Master Thesis
And Oral Presentation of Master Thesis
(27+3 CP)</td></tr>
<tr><td>Advanced Theoretical Physics:
Advanced Quantum Mechanics or Complex Dynamical Systems
(7 CP)</td><td></td></tr>
<tr><td colspan="2">Specialisation
(28 CP)
1 out of 3
- Nuclear Physics and Nuclear Astrophysics
- High energy Density in Matter
- or Individual Specialisation*</td></tr>
<tr><td colspan="2">Interdisciplinary Elective Area (15 CP)
- General Studies: Catalogue of All Modules of the Other Departments (not Physics) of TU Darmstadt (10-15 CP)
- Elective Area Physics (0-5 CP)</td></tr>
</table>

*Authorised Examination Plan necessary

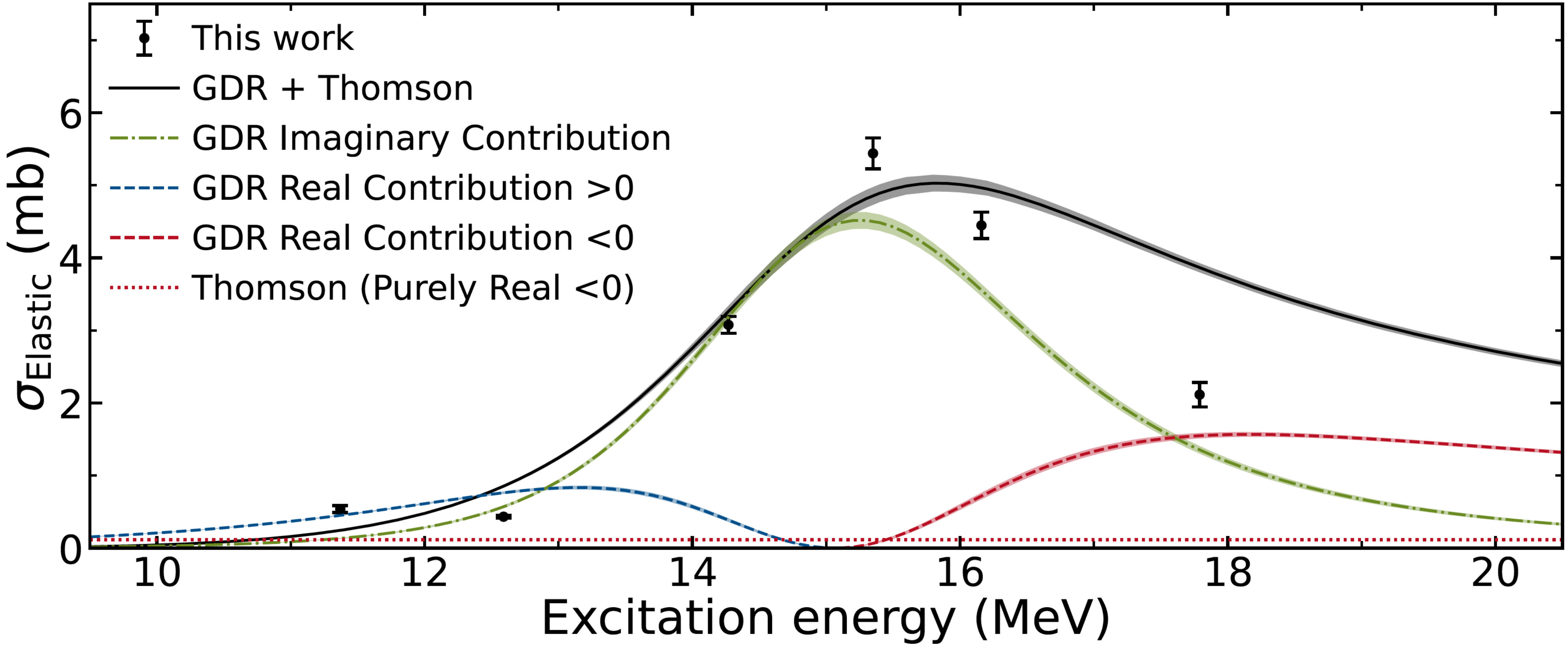
Spread the word!

Thank you very much!

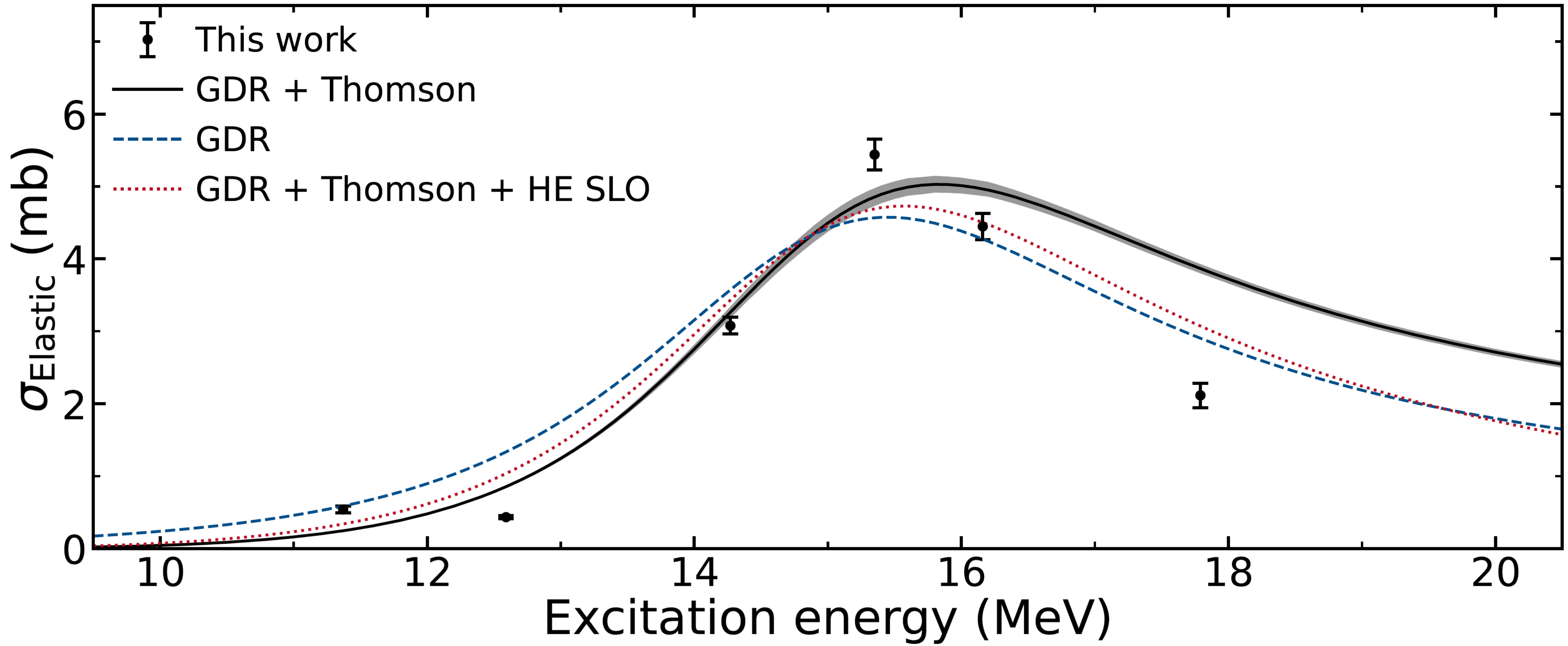
More information

More information

Elastic scattering on GDR: Imginary and real parts of squared amplitude for ^{140}Ce



Elastic scattering on GDR is sensitive to “high-energy photon absorption”: ^{140}Ce



High Intensity γ–Ray Source (HIgS)

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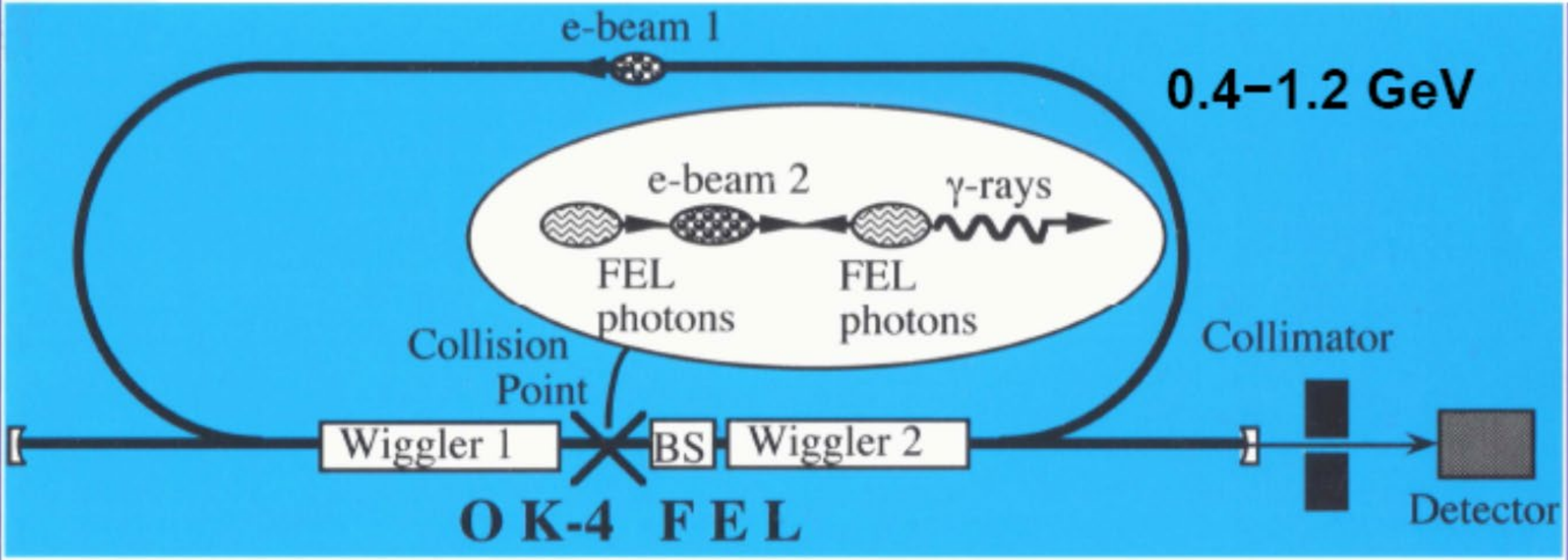
H.R.Weller, V.N.Litvinenko
Duke University, Durham, NC, U.S.A.

Compton Backscattering of Intra–cavity Laser Light



2 – 60 MeV 1.7 – 6.4 eV ~ 1000

$$E_\gamma = \frac{4\gamma^2 E_{ph}}{\left(1 + r + \gamma^2\theta^2\right)}; \quad r = \frac{4\gamma E_{ph}}{mc^2}; \quad E_{ph} = \frac{2\gamma^2 hc}{\lambda_w\left(1 + K_w^{\,2}/2\right)}; \quad \gamma = \frac{E_e}{mc^2};$$

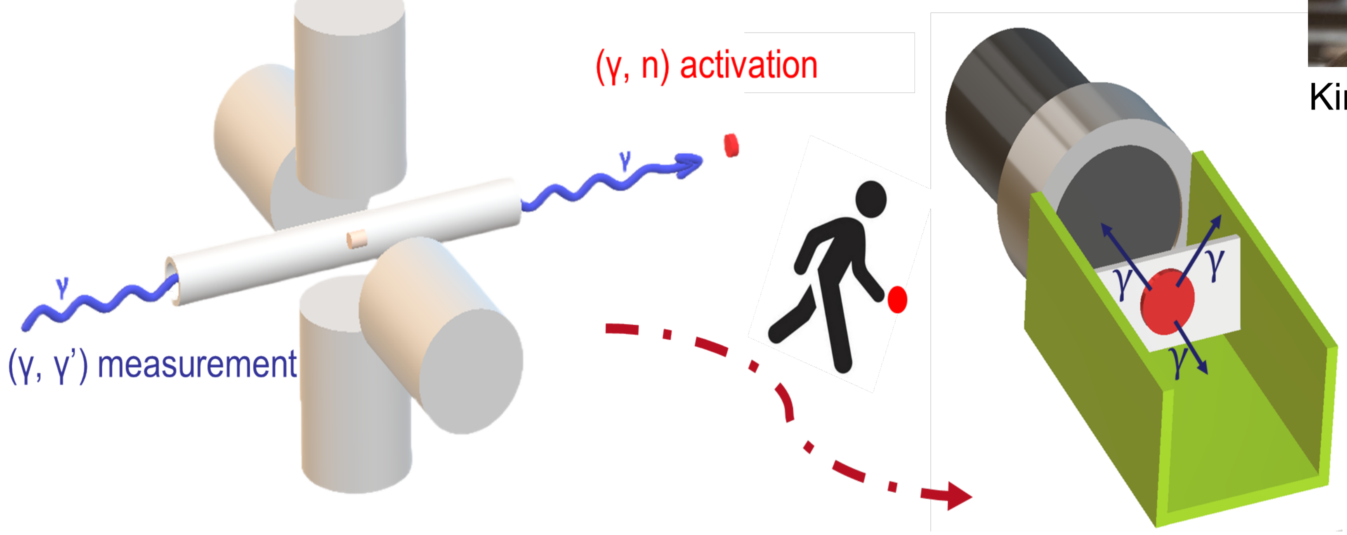
nearly monochromatic, tunable, completely polarized

historic transparency
V.Litvinenko, ~ 2000

at the time with
OK-4
from Novosibirsk

Photon fliux calibration and verification of cross sections for ^{140}Ce and ^{154}Sm

Au + Ce/Sm



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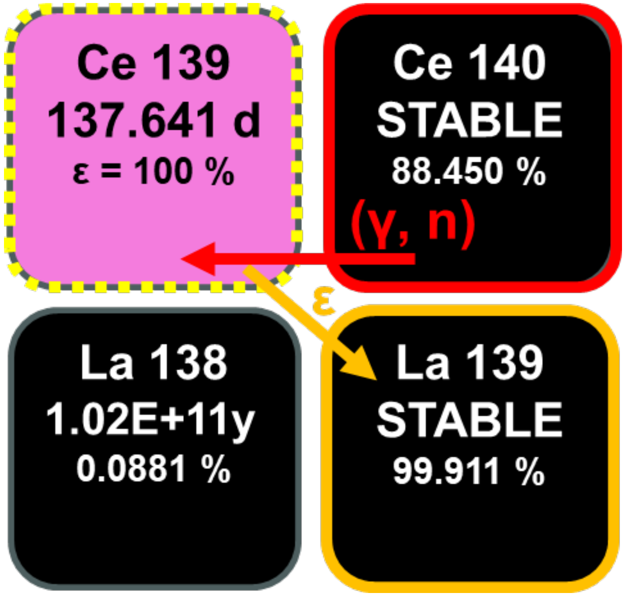

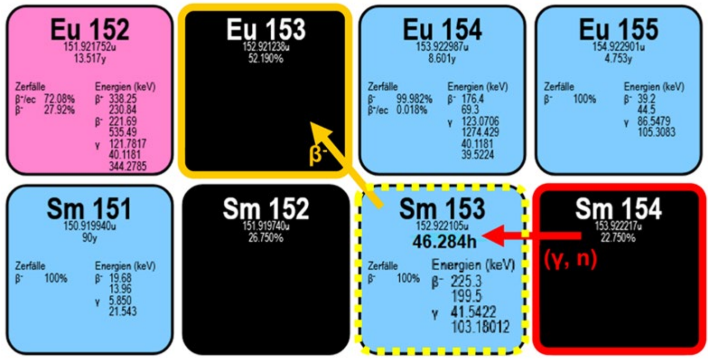

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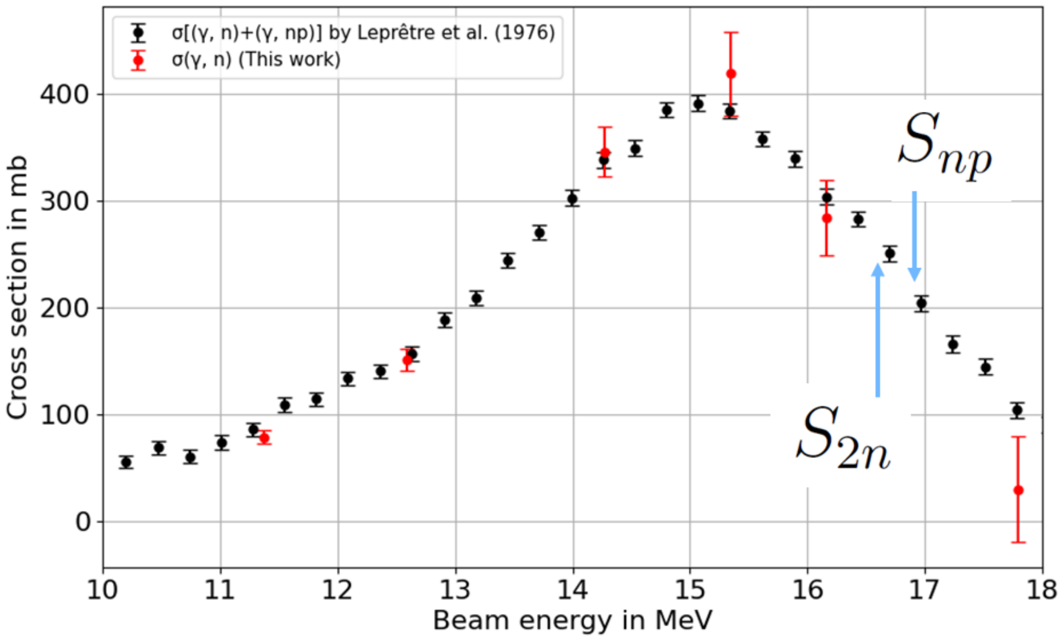
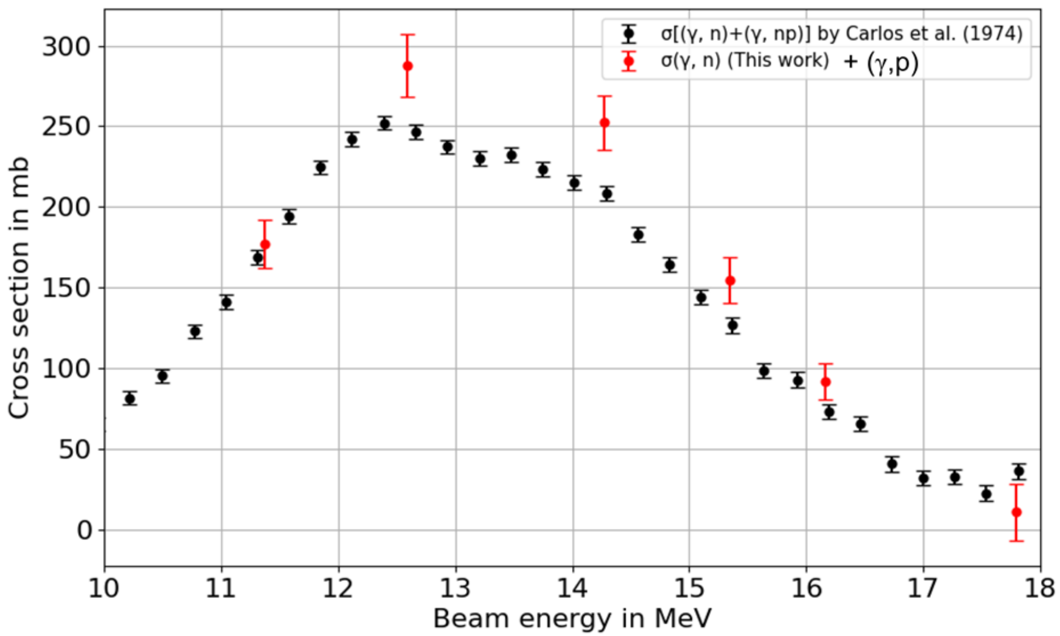
Photon fliux calibration and verification of cross sections for ^{140}Ce and ^{154}Sm

$^{140}Ce(\gamma,1n)^{139}Ce$ @ HIγS



$^{154}Sm(\gamma,1n)^{153}Sm$ @ HIγS



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Consistency check: our photon flux calibration is accurate

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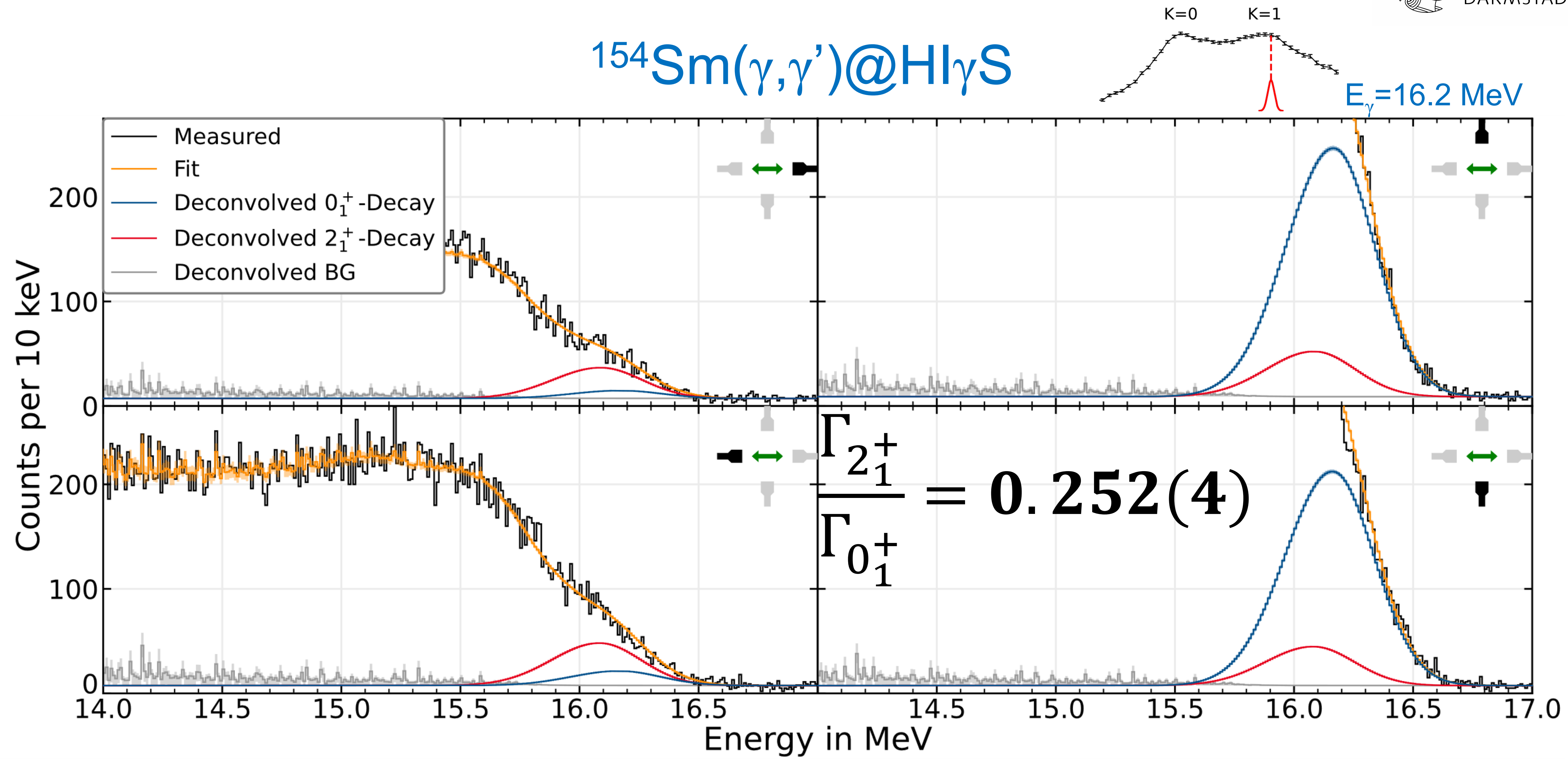
^{154}Sm(γ,γ')@HIγS



$$\frac{\Gamma_{2_1^+}}{\Gamma_{0_1^+}} = 0.252(4)$$

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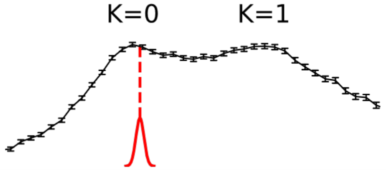
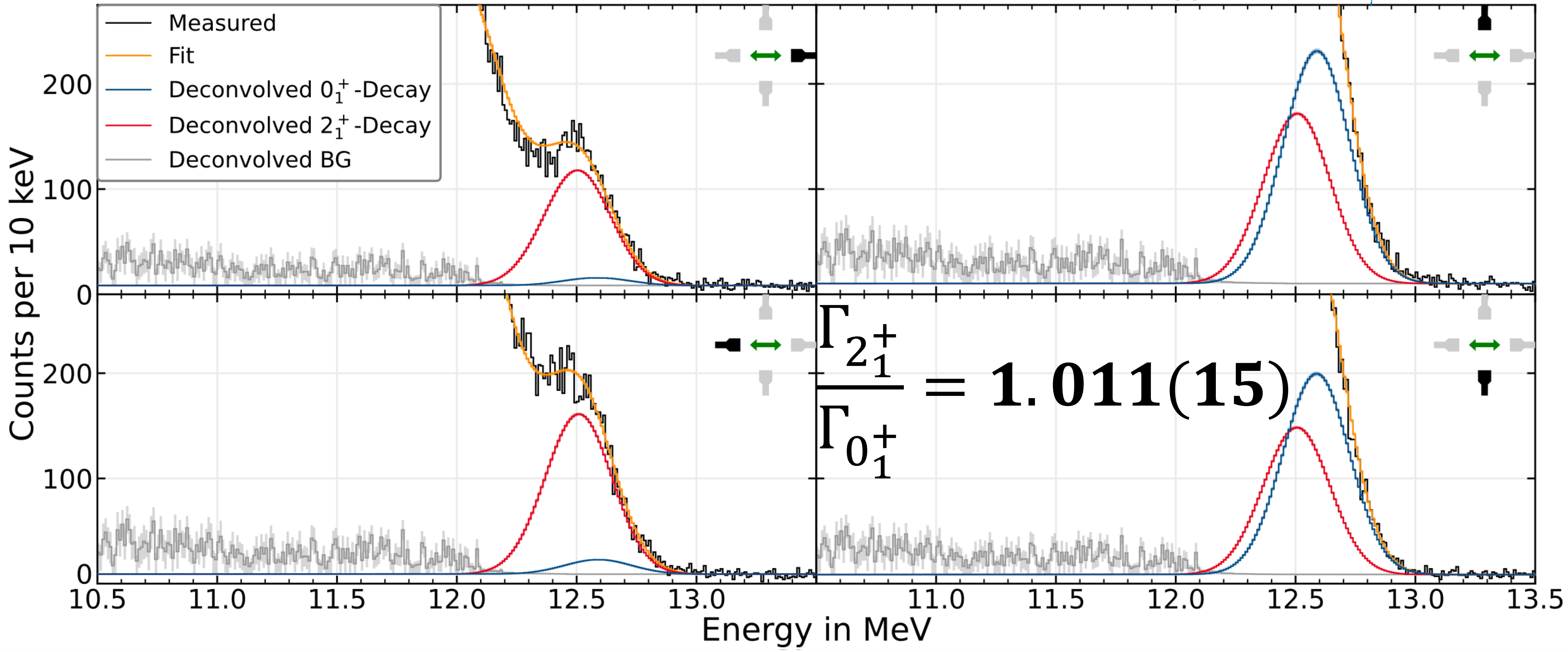
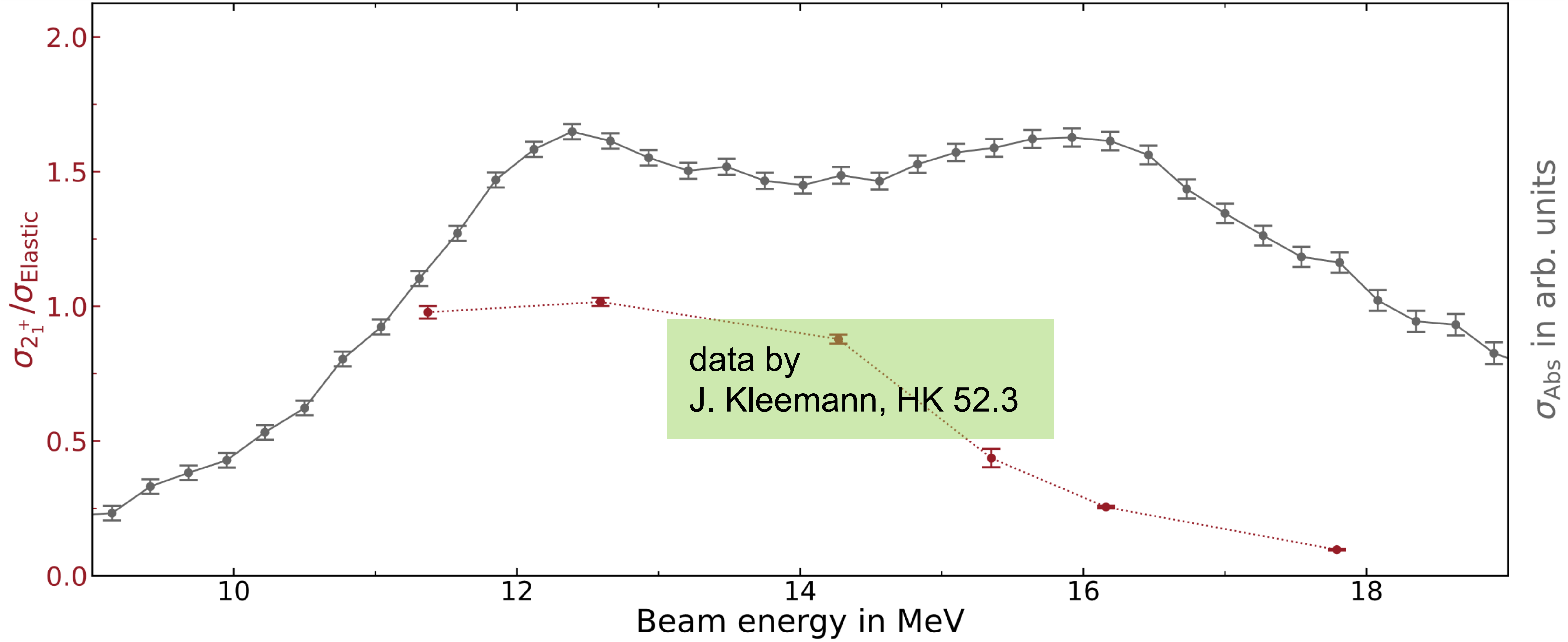
^{154}Sm(γ,γ')@HIγS



E_γ=12.6 MeV



$$\frac{\Gamma_{2_1^+}}{\Gamma_{0_1^+}} = \mathbf{1.011(15)}$$


$\sigma_{2_1^+}/\sigma_{\mathrm{Elastic}}$
σ_{Abs} in arb. units
Beam energy in MeV
0.0
0.5
1.0
1.5
2.0
10
12
14
16
18
data by
J. Kleemann, HK 52.3

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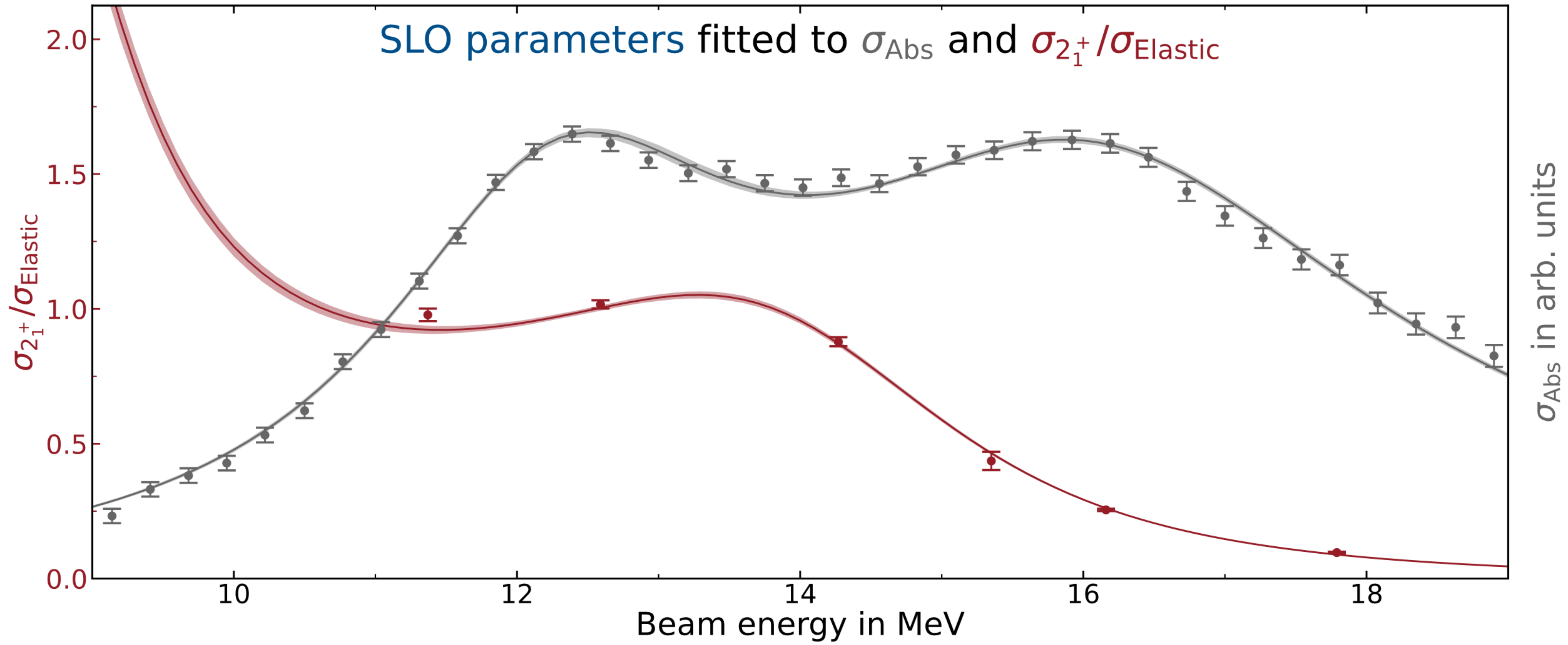
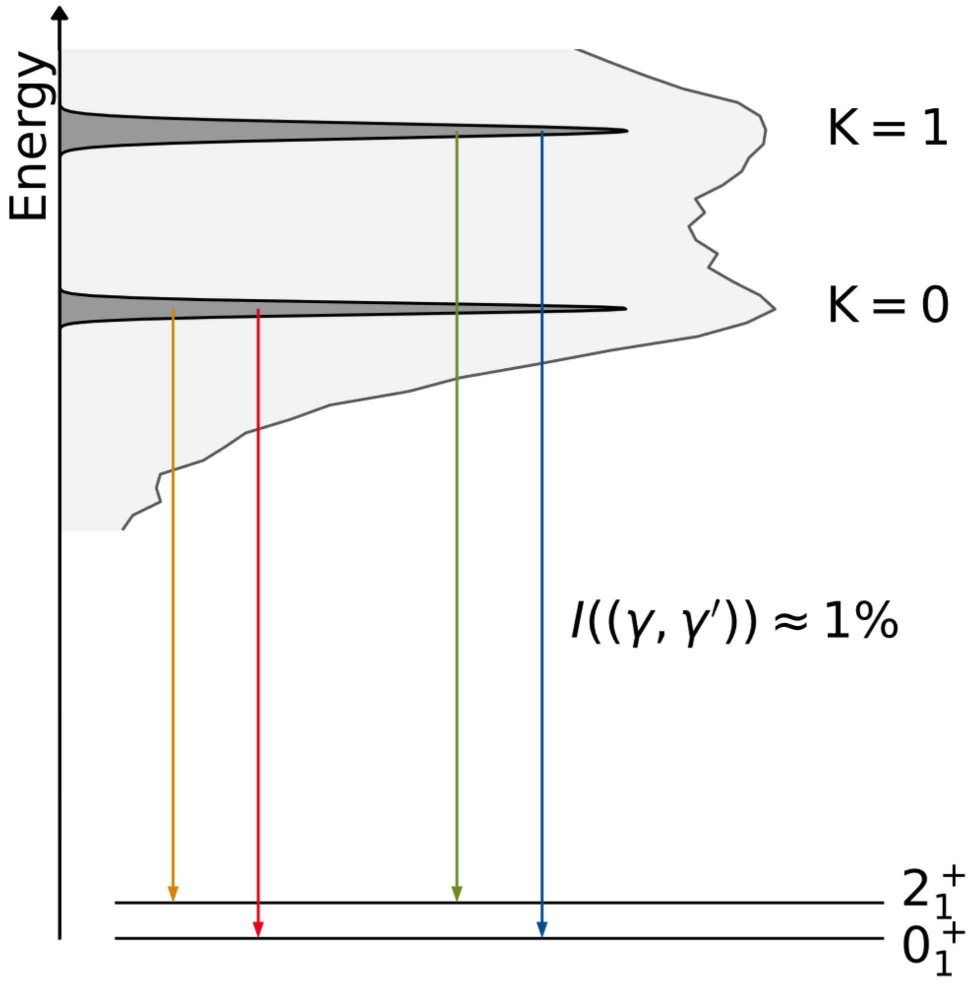
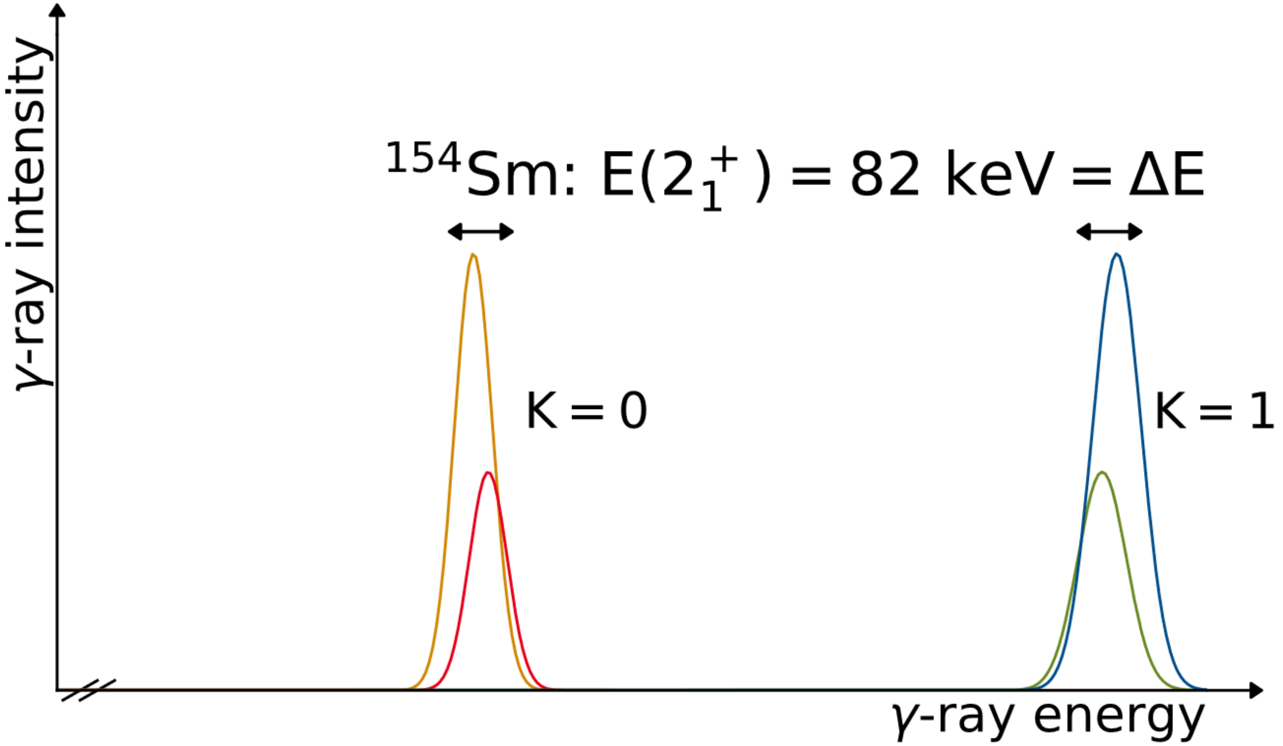
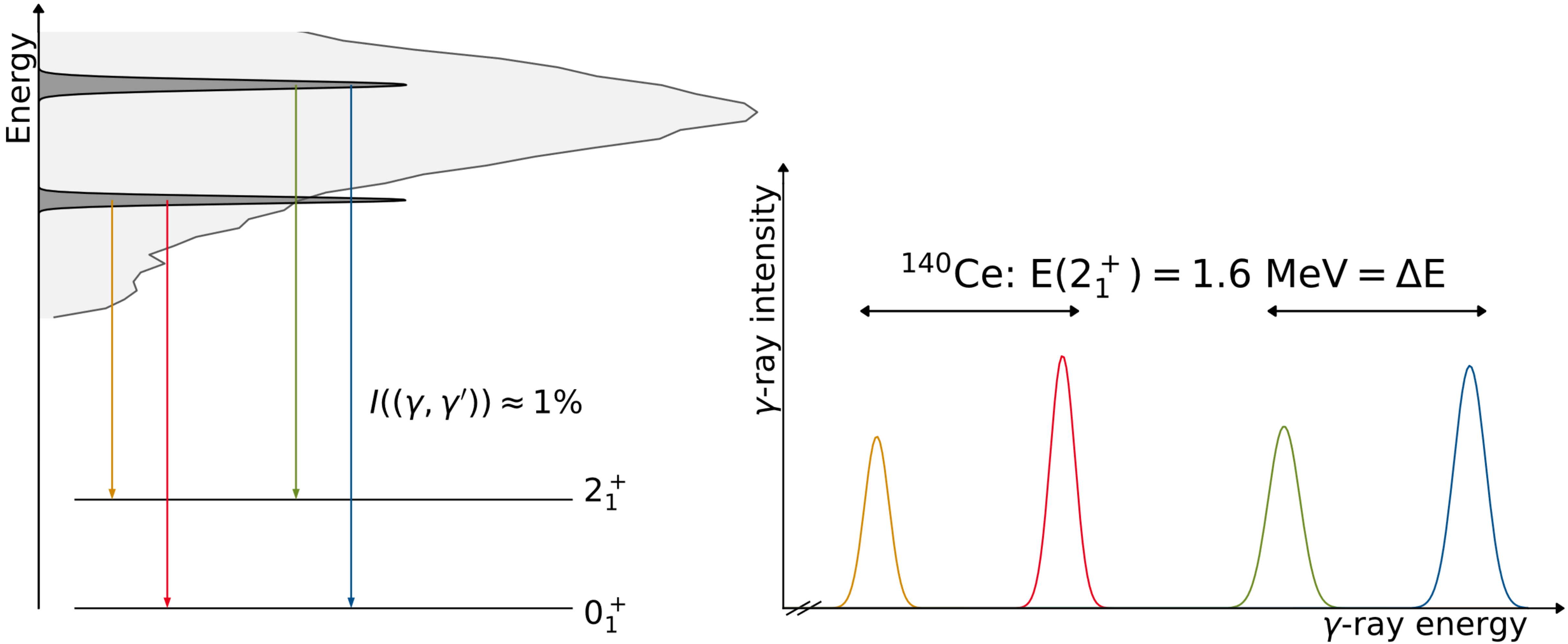



Energy
K = 1
K = 0
I((γ, γ′)) ≈ 1%
2_1^+
0_1^+


γ-ray intensity
^{154}Sm: E(2_1^+) = 82 keV = ΔE
K = 0
K = 1
γ-ray energy


Energy
$I((\gamma, \gamma')) \approx 1\%$
2_1^+
0_1^+
^{140}Ce: $E(2_1^+) = 1.6$ MeV $= \Delta E$
γ-ray intensity
γ-ray energy

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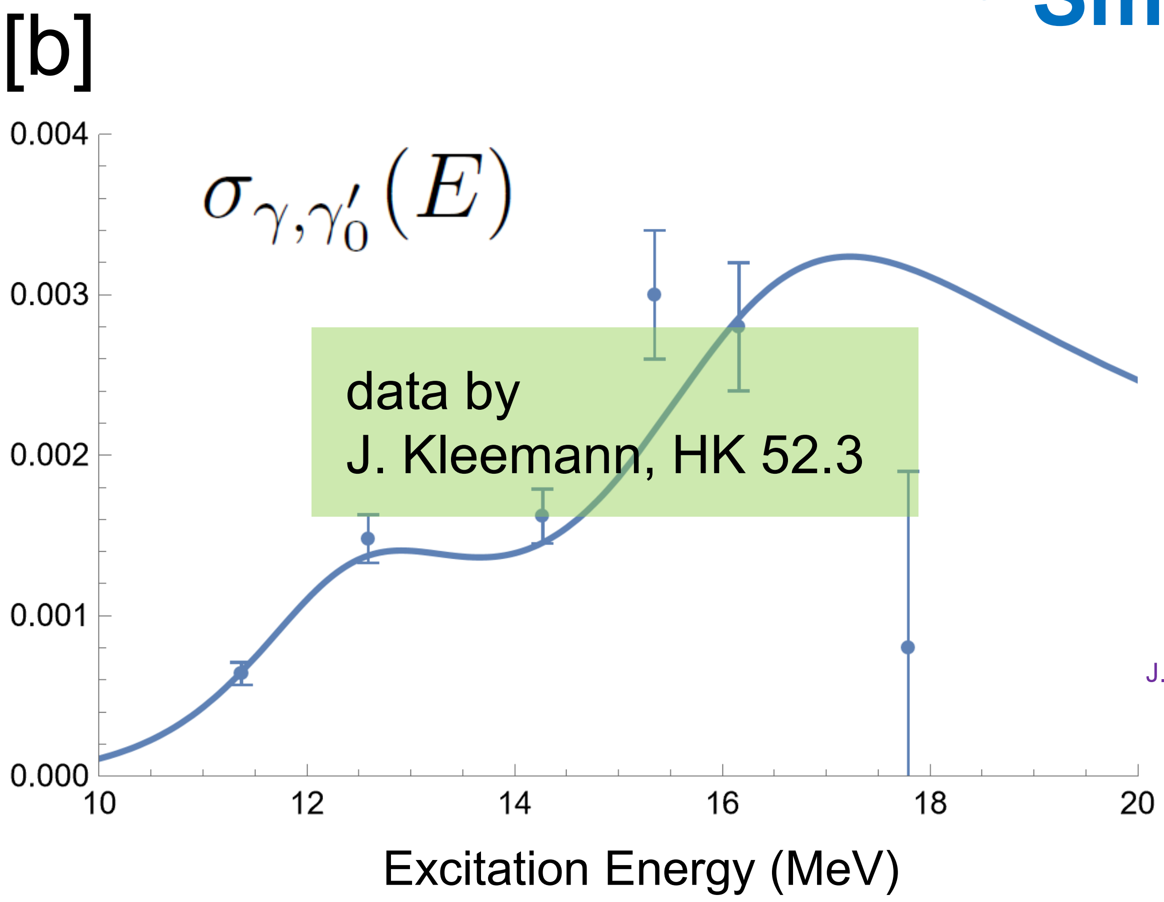
$^{154}Sm(\gamma,\gamma_0')$

Absolute NRF cross section of GDR obtained from dispersion relation



J. Kleemann et al., to be subm. for publication

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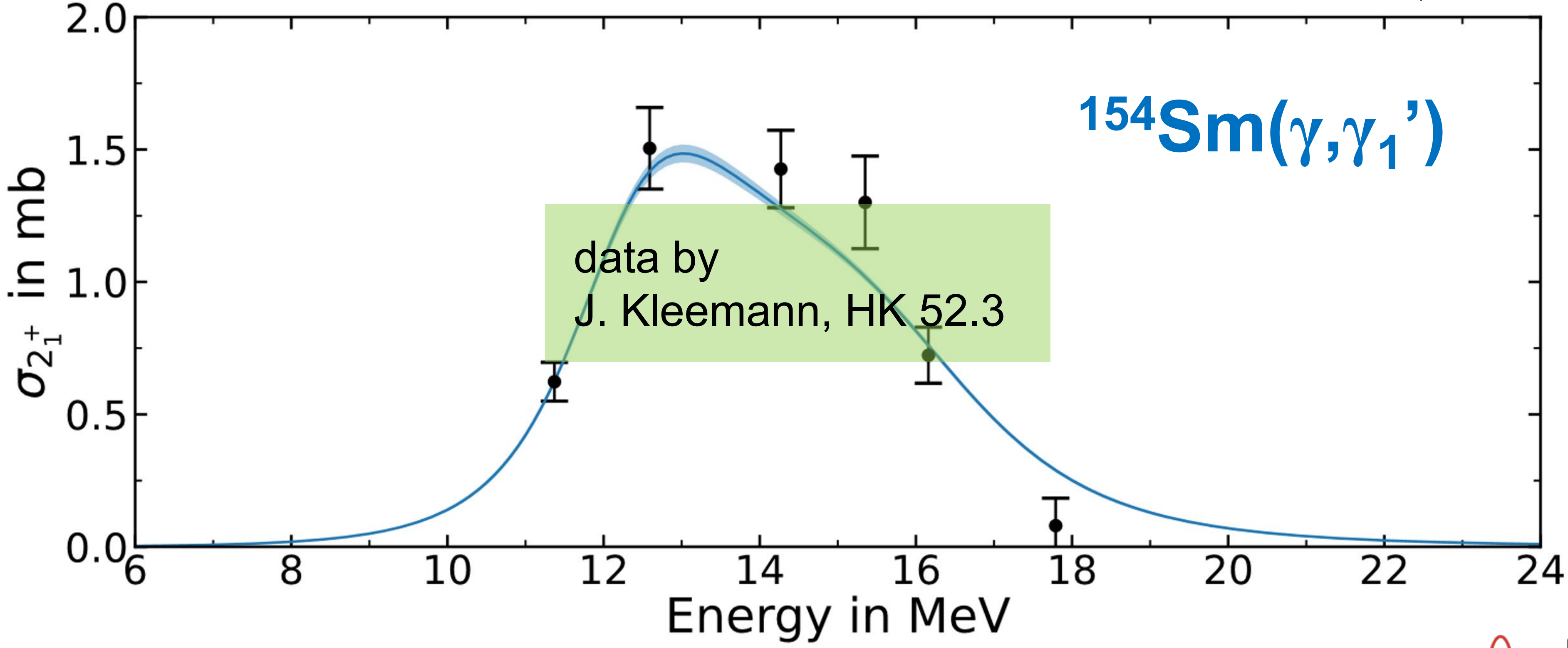

Nuclear Photonics