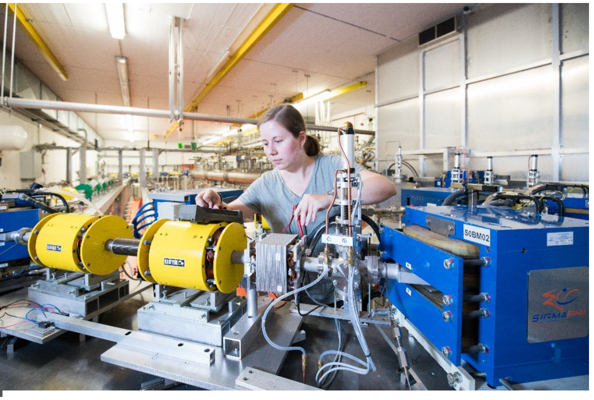
Nuclear Photonics

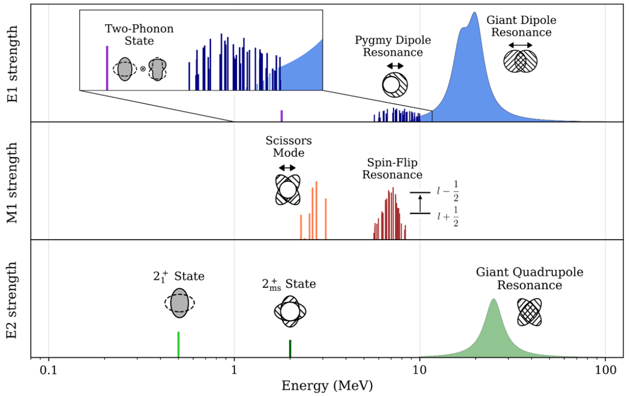
TECHNISCHE UNIVERSITÄT DARMSTADT

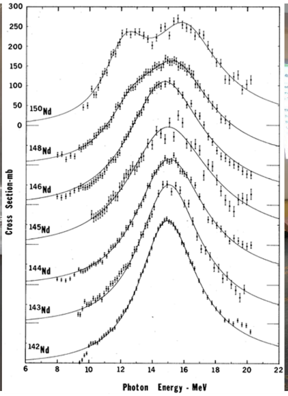
PHOTONUCLEAR REACTIONS

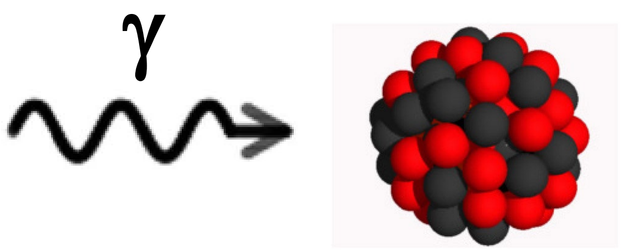
Status and Perspectives

Professor Dr. Norbert Pietralla (TU Darmstadt)









What happens ?

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1937: **Atomumwandlungen durch γ-Strahlen.**

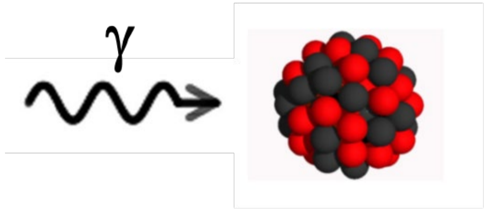
Von **W. Bothe** und **W. Gentner** in Heidelberg.

Z. Phys. ***106*** *(1937) 236*

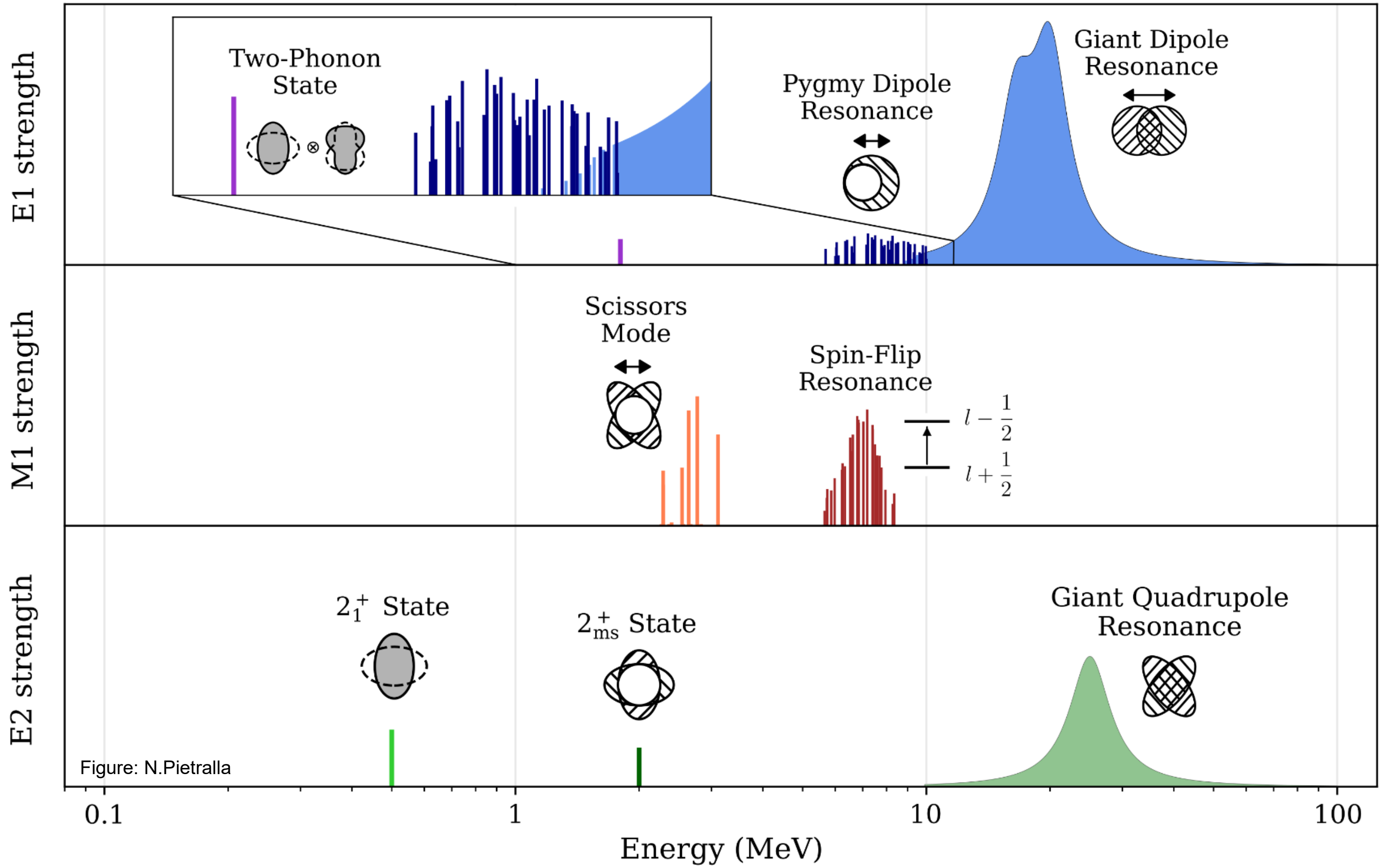
6. Diskussion.

Die beschriebenen Versuche zeigen, daß bei gewissen Elementen der Prozeß (γ, n) verhältnismäßig leicht beobachtbar ist.

... Vielleicht spielen hierbei Resonanzverhältnisse eine entscheidende Rolle, ...



What happens ?



atomic | nuclear | hadronic

PHOTONUCLEAR PHENOMENA

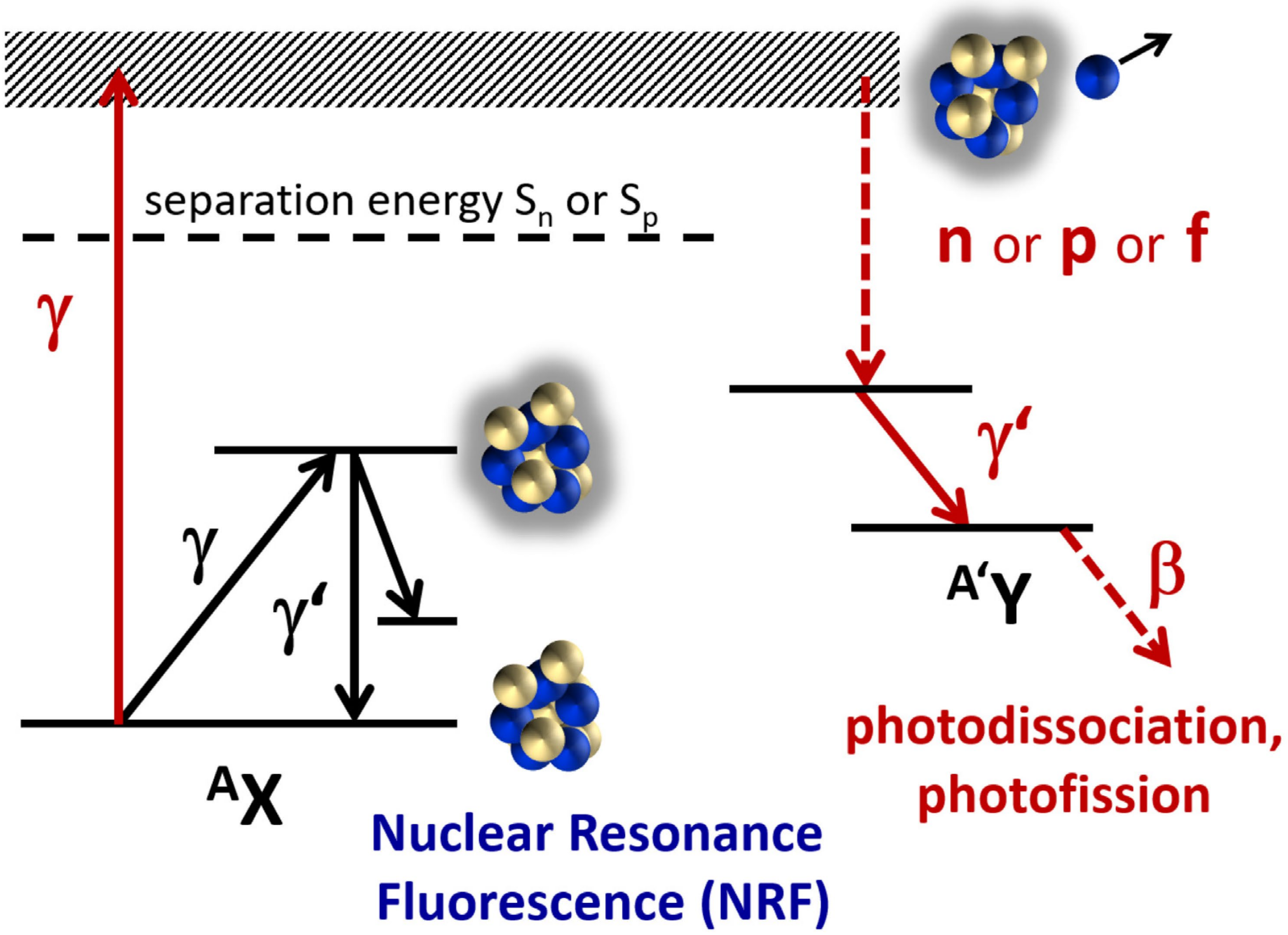
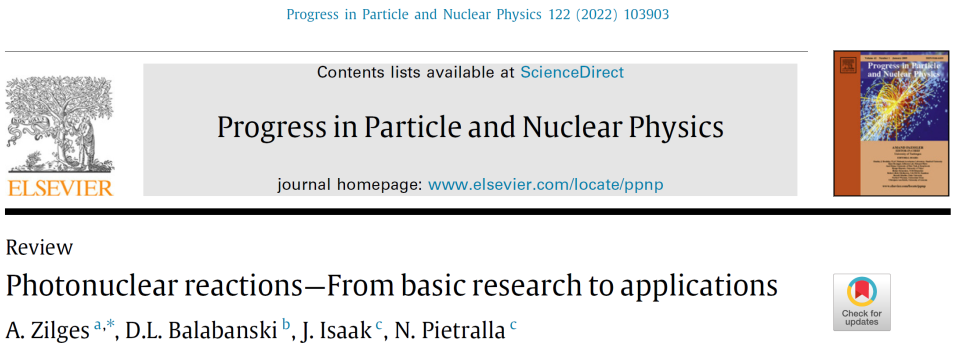


Figure from:


Progress in Particle and Nuclear Physics 122 (2022) 103903

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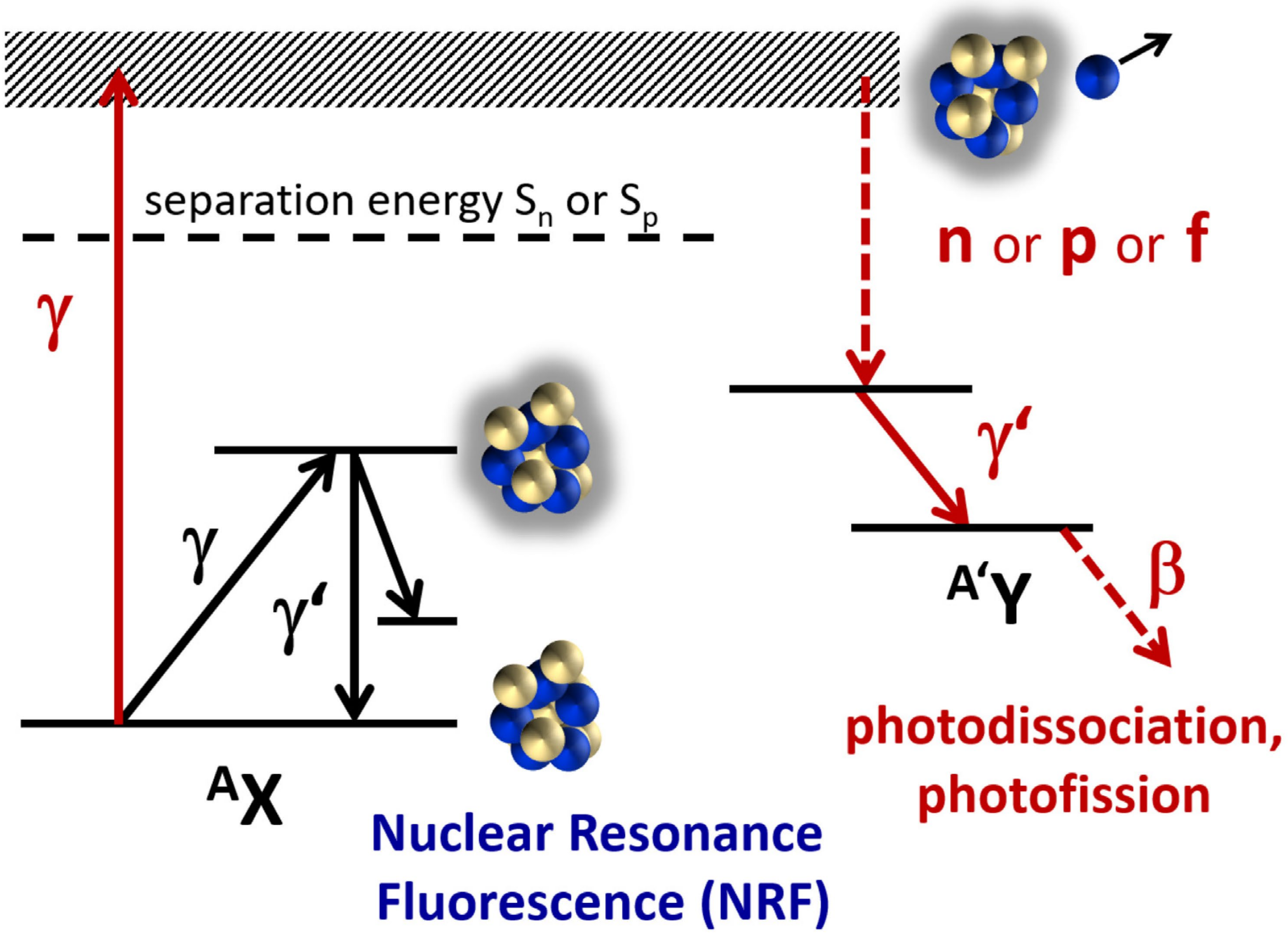
journal homepage: www.elsevier.com/locate/ppnp

Review

Photonuclear reactions—From basic research to applications

A. Zilges [a,*], D.L. Balabanski [b], J. Isaak [c], N. Pietralla [c]



In memoriam:
Prof. Dr. Ulli Kneißl
† 4.1.2023

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OUTLINE

1 **Status**: Recent Examples on Contemporary Topics of Nuclear Structure Physics

A) E2: Quadrupole collectivity of Sn isotopes (**NRF relative to calibration standard**)

B) M1: Evidence for 2-body currents (**generation of a standard: Relative Self-Absorption**)

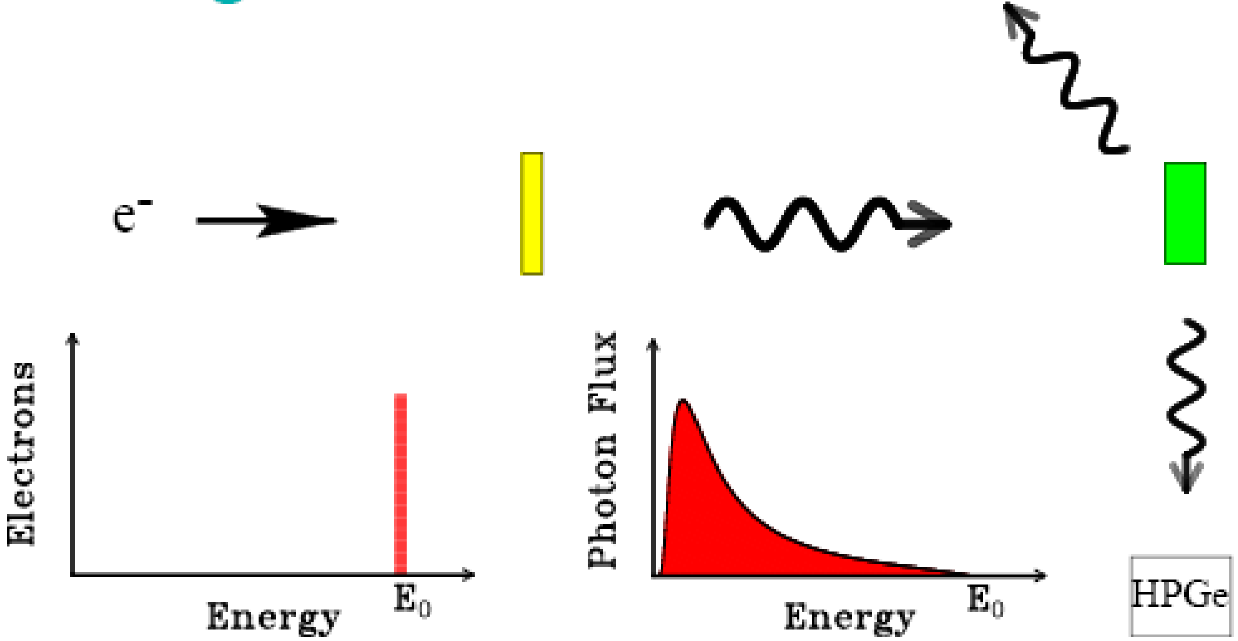
C) E1: γ-decay of the Giant Dipole Resonance (**NRF beyond particle separation threshold**)

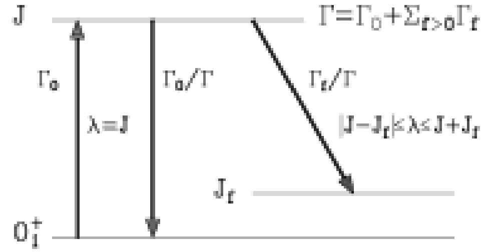
2 **Perspectives**: Accelerator Technology towards a 4^{th}-generation γ–ray Source (**ERL-LCB**)

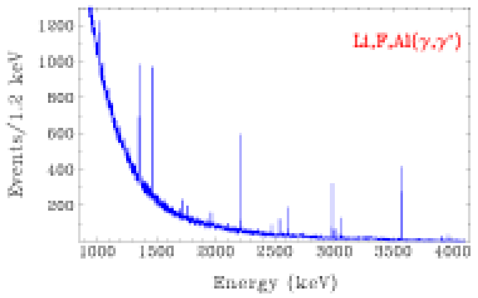
3 **Perspectives**: International Research Training of next-generation Scientists

Photon Scattering
(Nuclear Resonance Fluorescence)

high energy resolution
spin selective: ΔJ=1,2
strength selective



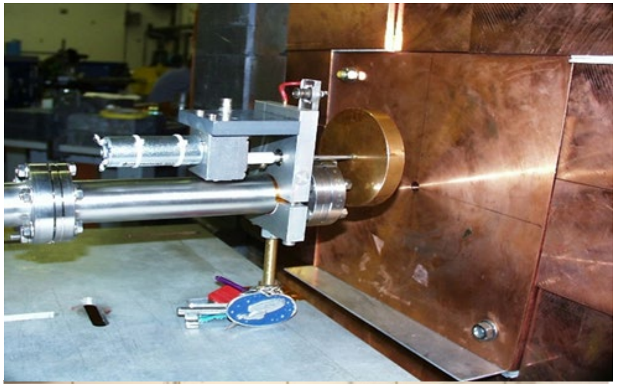


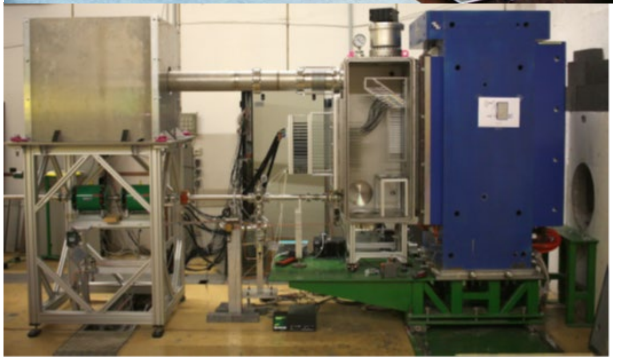


Observables

- Excitation Energy E_r
- Spin J
- Parity π
- Decay Energies E_γ
- Partial Widths Γ_i/Γ_0
- K-quantum numbers
- Level Width Γ (eV)
- Lifetime τ (ps – as)
- Multipole Mixing δ
- Decay Strengths $B(\pi\lambda)$

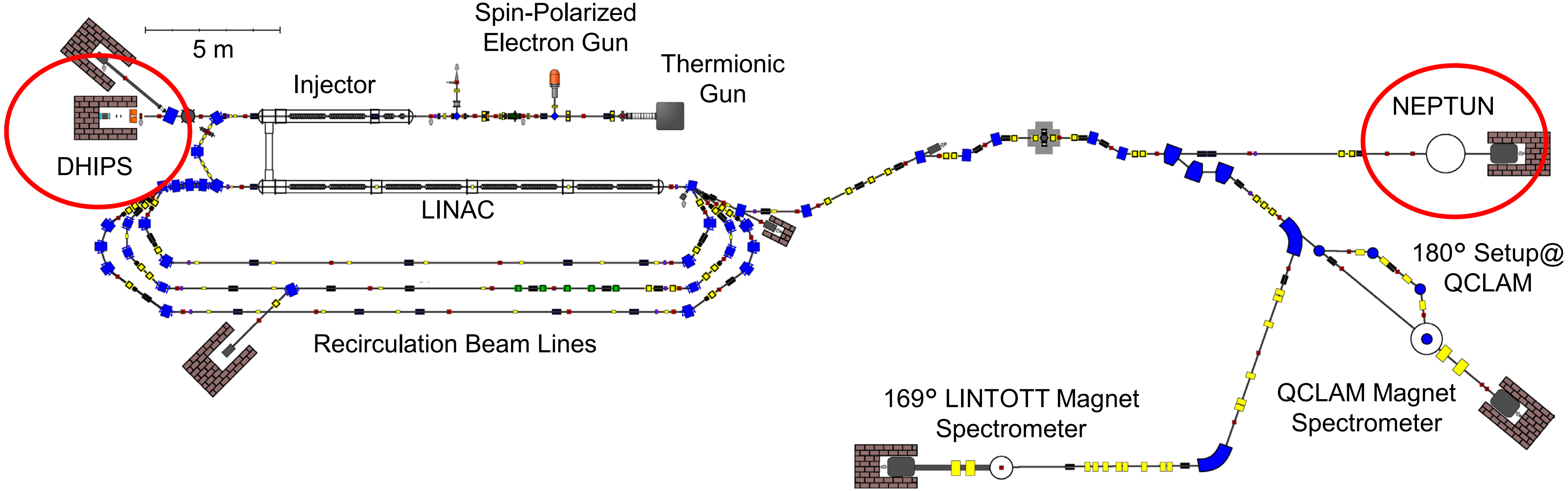
PHOTONUCLEAR REACTION SITES @ S-DALINAC





Superconducting Darmstadt Linear Accelerator (S-DALINAC)

$E_{e,max}$ = 130 MeV

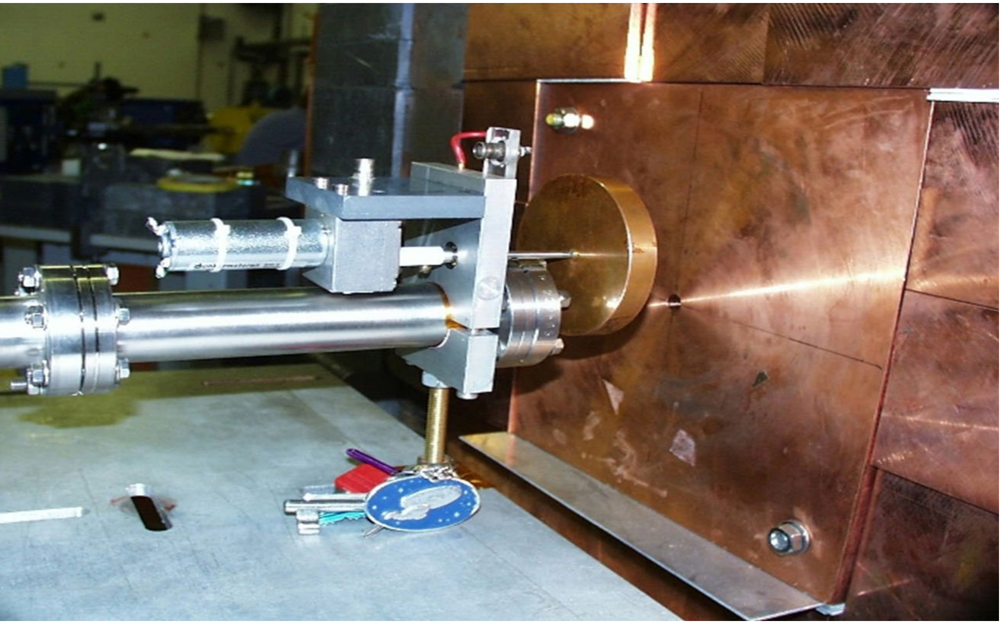


@ 2 bremsstrahlungs-sites:

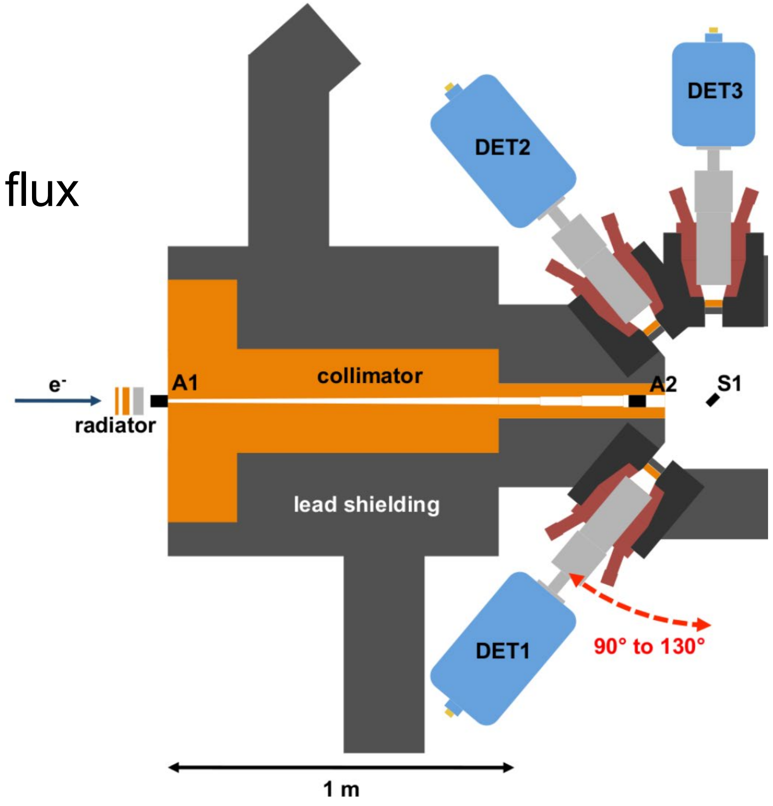
- Darmstadt High-Intensity Photon Set-up (DHIPS) 2 – 10 MeV, 10^3 γ/(s eV cm^2)
- Photon-tagger spectrometer NEPTUN 5 – 60 MeV, 1 MHz tagging rate

Darmstadt High-Intensity Photon Setup (DHIPS)

K. Sonnabend et al., NIM **A640** (2011)



- Bremsstrahlung-photon flux $\sim 10^3\ s^{-1}eV^{-1}cm^{-2}$
- γ-ray detection by three High-Purity Germanium (HPGe) detectors



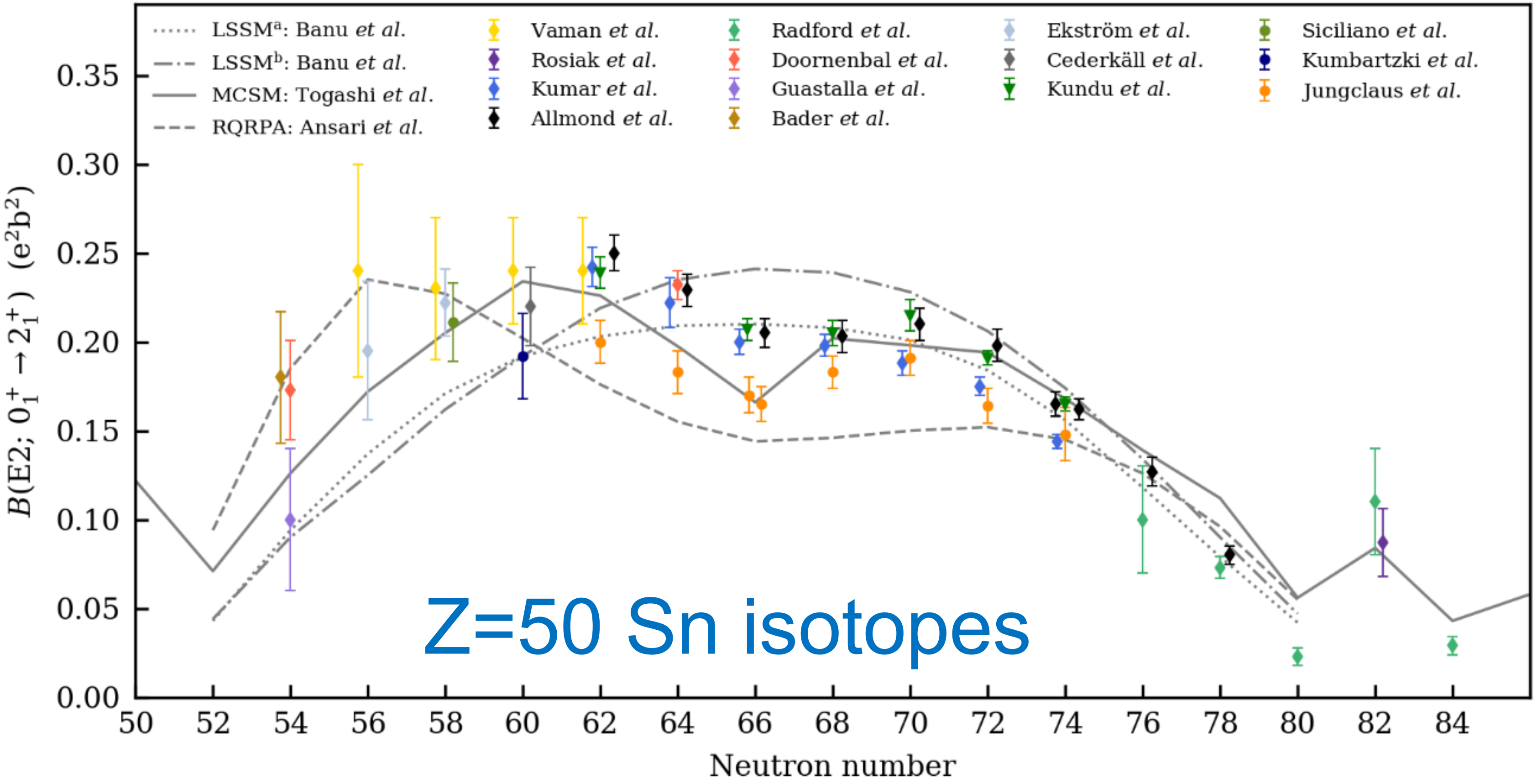
C. Romig, Doctoral Thesis, TU Darmstadt (2015)

Example I:

Precision Measurement of E2 Transition Strengths in Sn Isotopes

NRF relative to a Strength-Standard

EXAMPLE I: STRUCTURE OF Z=50 CLOSED-SHELL SN ISOTOPES



^{112}Sn(γ,γ')@DHIPS

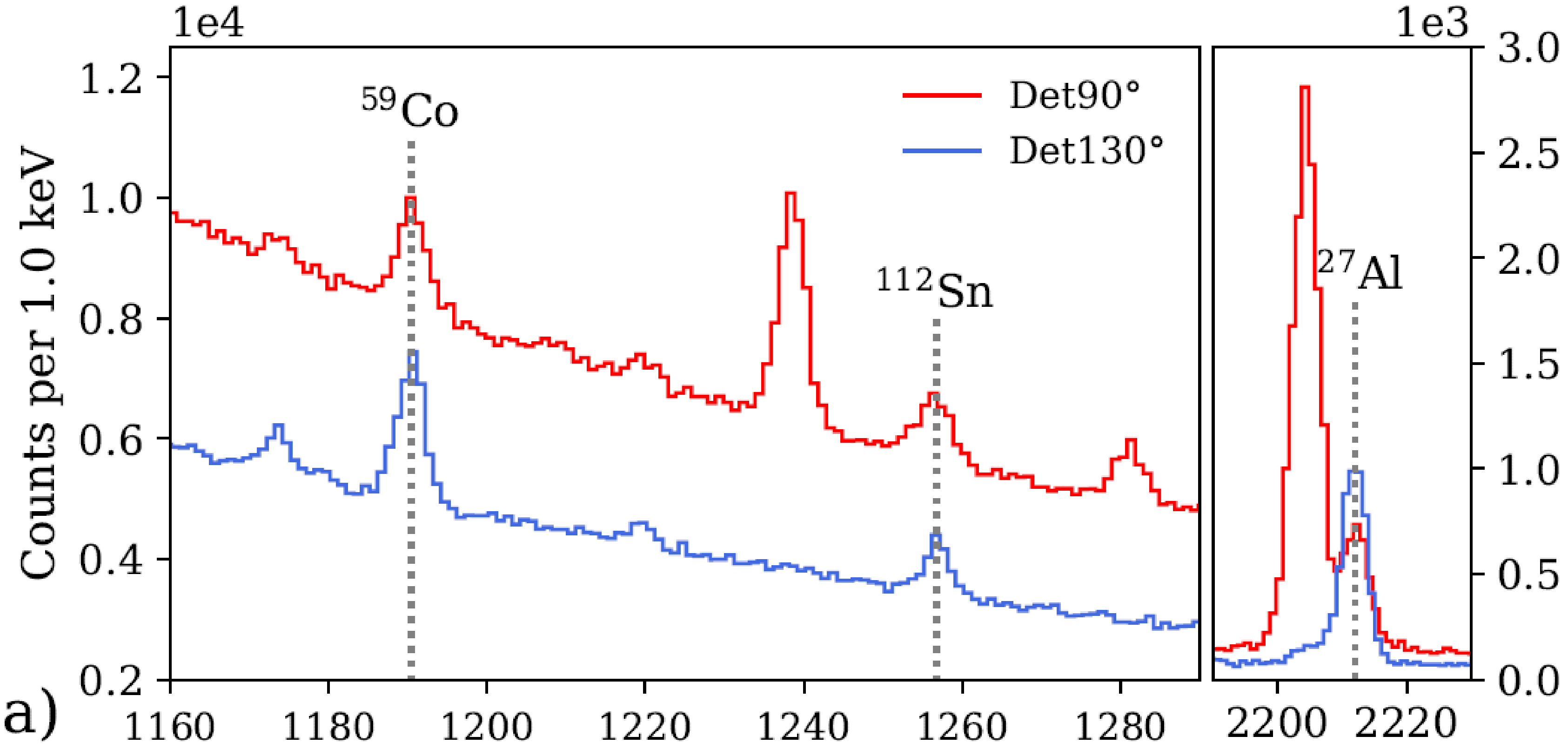
- Nuclear Resonance Fluorescence of ^{112}Sn
- relative to photon flux calibration standards ^{27}Al and ^{59}Co

➢ NRF cross section

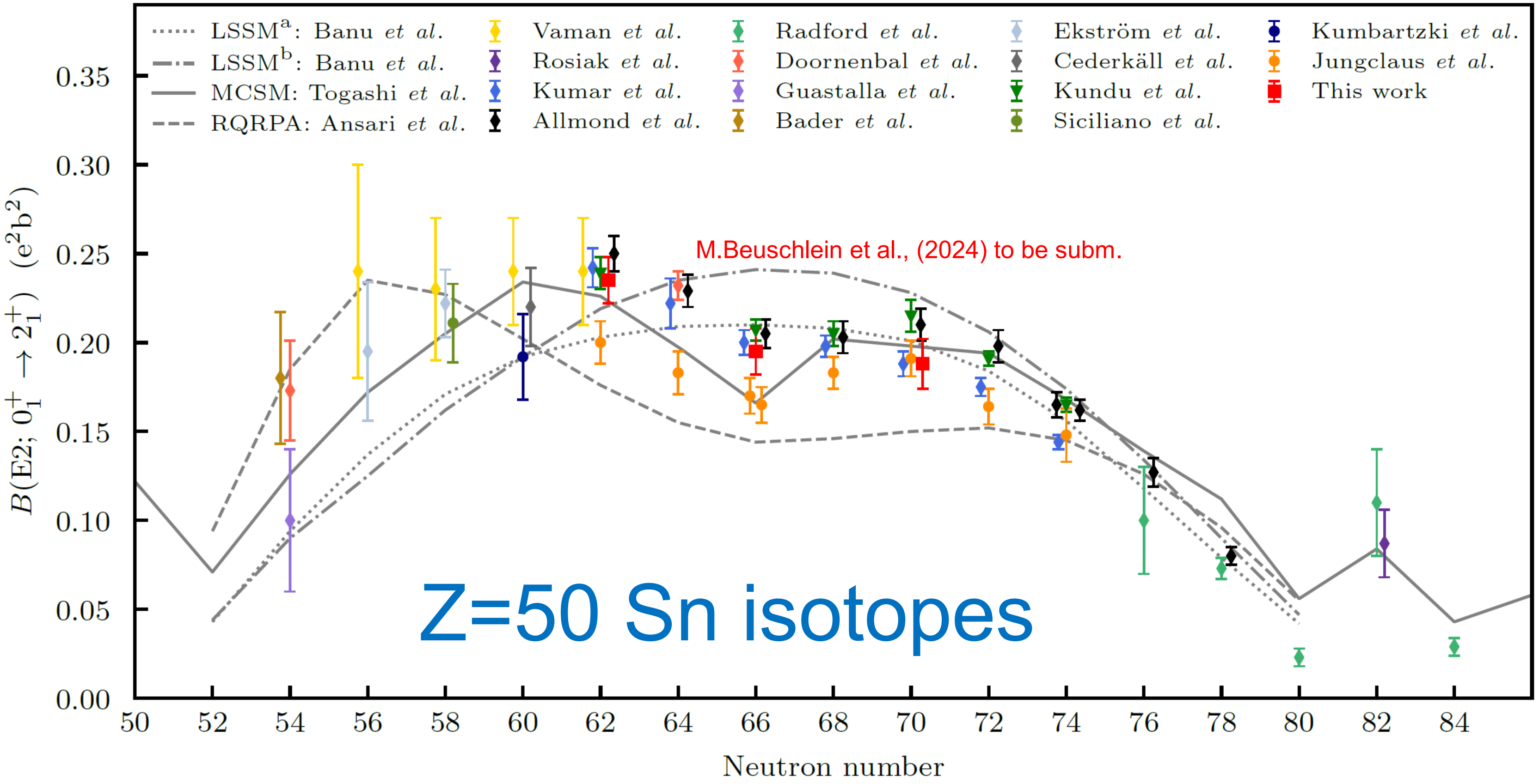
➢ Level width

➢ Electromagnetic excitation strength

➢ $B(E2)_{up} = 0.234(23)\ e^2b^2$



M.Beuschlein et al., (2024) subm. for publication



decisive, model-independent information from photonuclear reactions

Nuclear Photonics

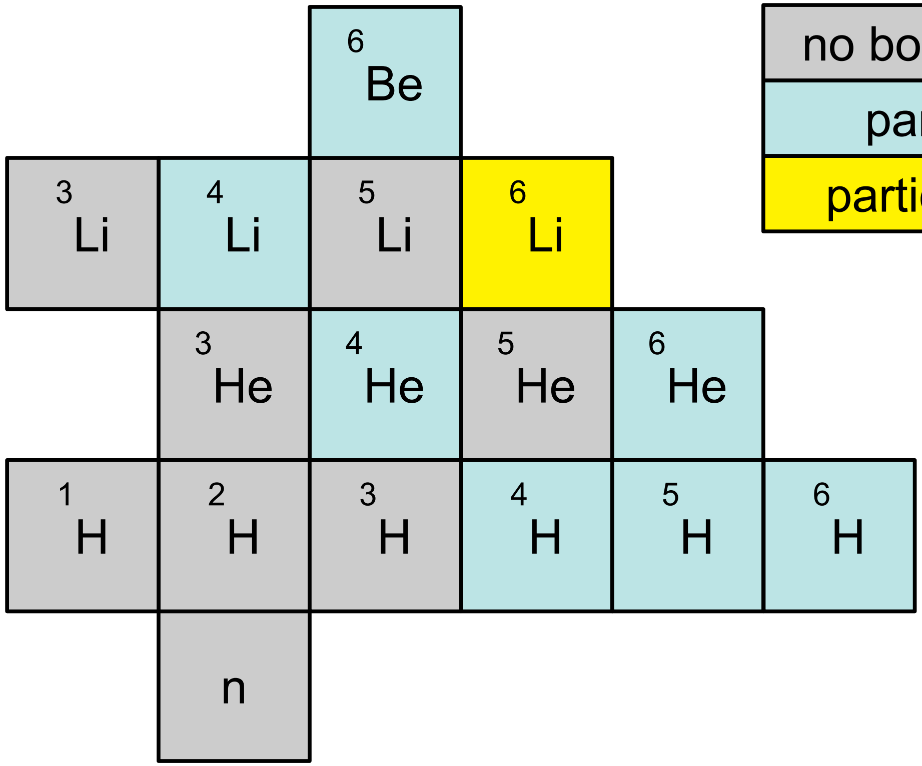
M. Beuschlein, HK 53.5

Example II:

Calibration of a Strength-Standard: Absolute Precision Measurement of Level Widths

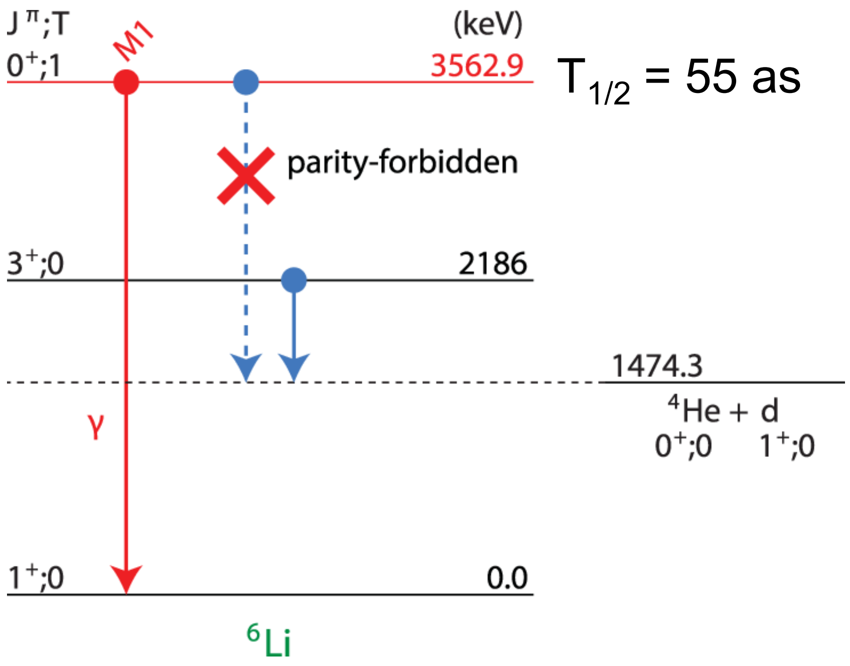
Evidence for 2-Body Currents in M1 transition in ^{6}Li

Predominant decay modes of excited states of known A ≤ 6 nuclei



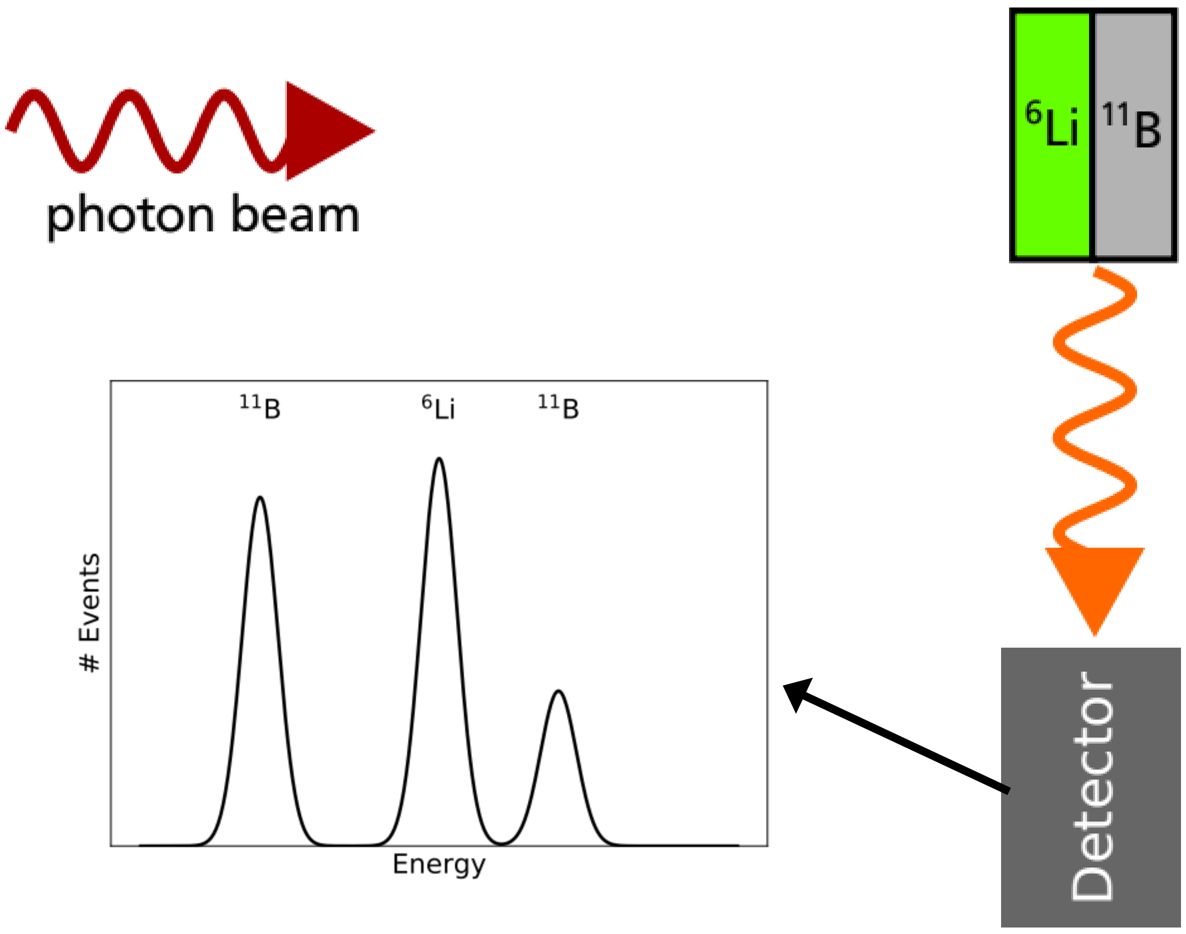
no bound excited state
particle emission
particle + γ emission

- ^{6}Li(3.562 MeV) is lightest system decaying via EM
- B(M1; $0^{+} \rightarrow 1^{+}$) one of strongest M1
- Ideal testing ground for ab-initio theory



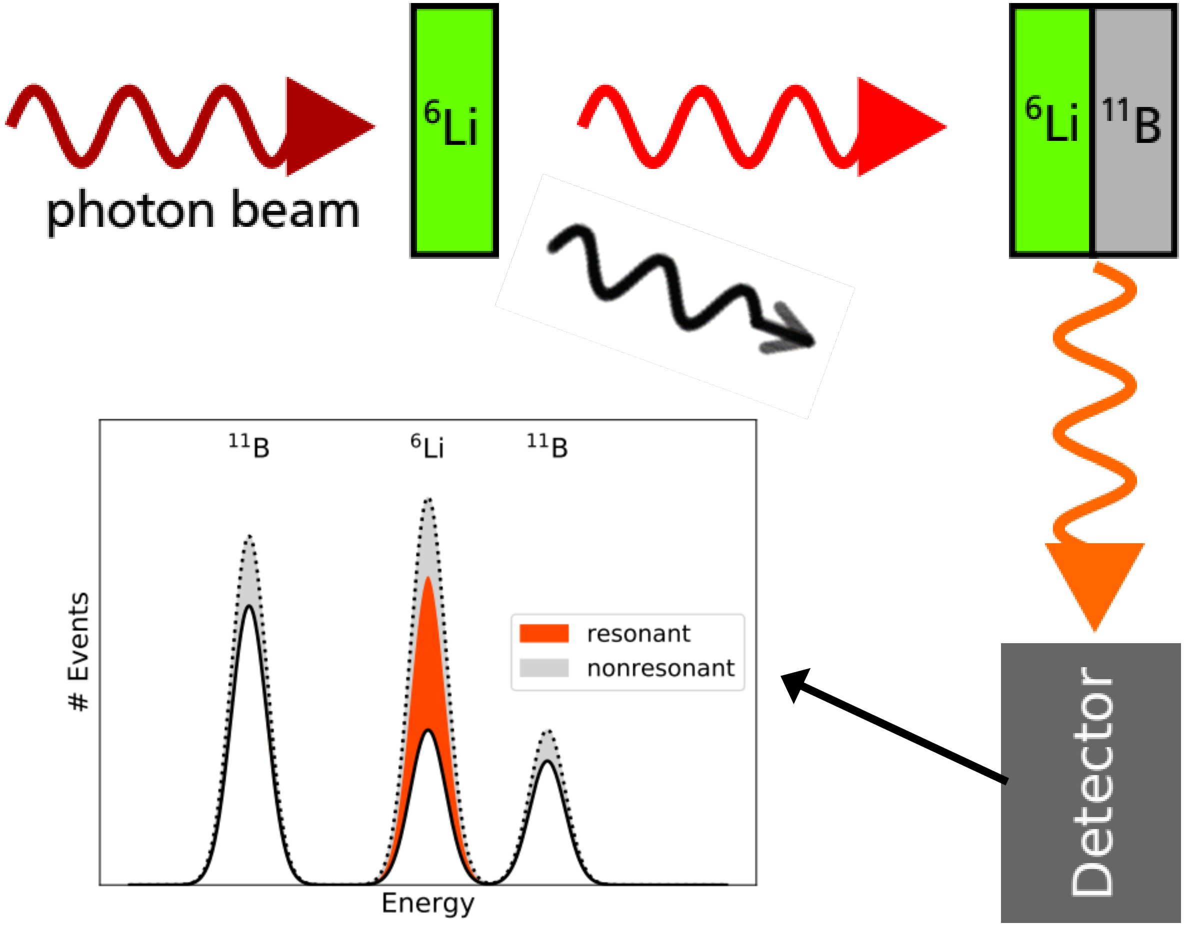
Decay data from: https://www.nndc.bnl.gov/ (03/25/2019)

1. Step: Nuclear Resonance Fluorescence relative to Monitor



F.R. Metzger, Prog. Nucl. Phys. **7** (1959)

2. Step: Strength of Absorption Lines



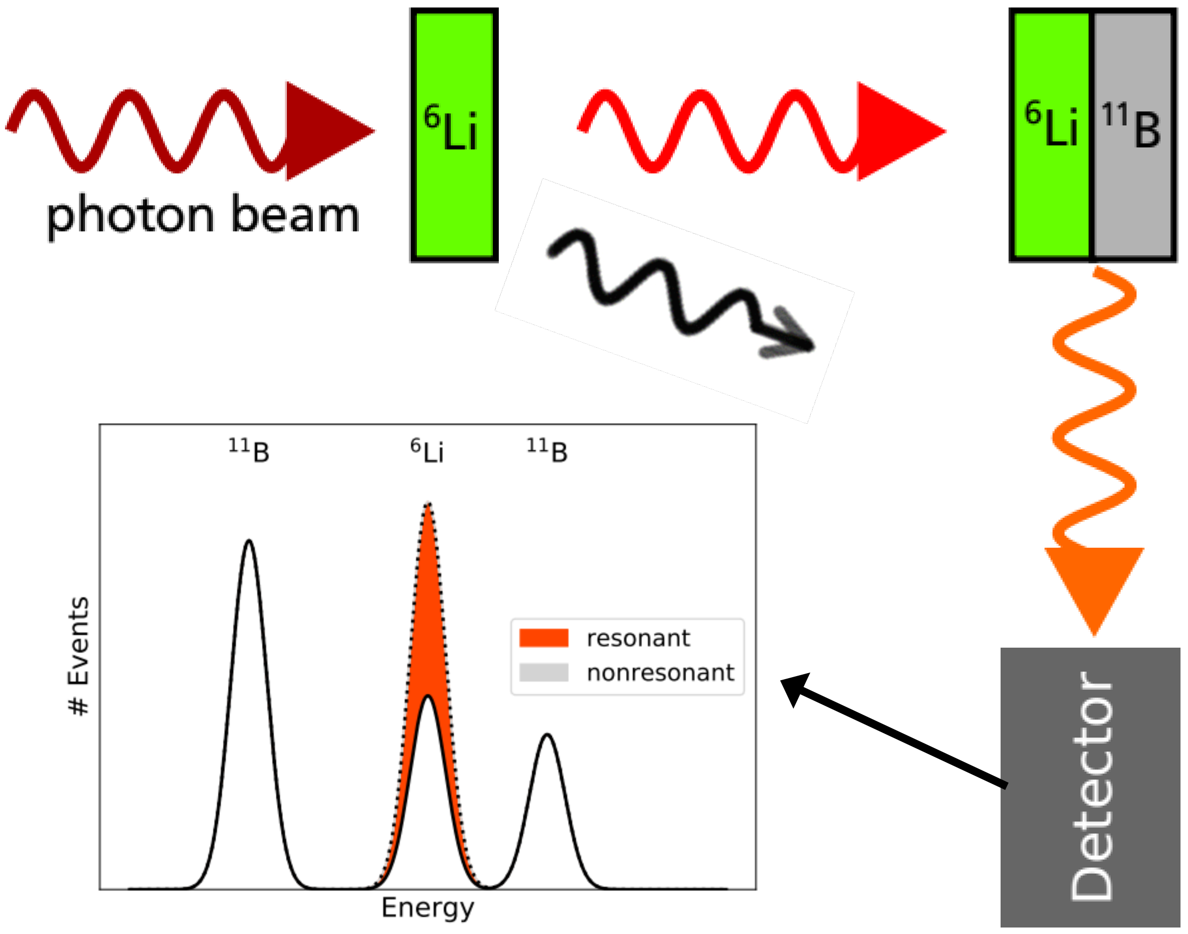
- Relative self-absorption (RSA) based on NRF

  N. Pietralla *et al.*, Phys. Rev. C 51, 1021 (1995).

  C. Romig *et al.*, Phys. Lett. B **744** 369 (2015).

- Reduction of count rate depends on level width and atomic absorption

Relative Self-Absorption (RSA)



- Relative self-absorption (RSA) based on NRF

N. Pietralla *et al.*, Phys. Rev. C 51, 1021 (1995).

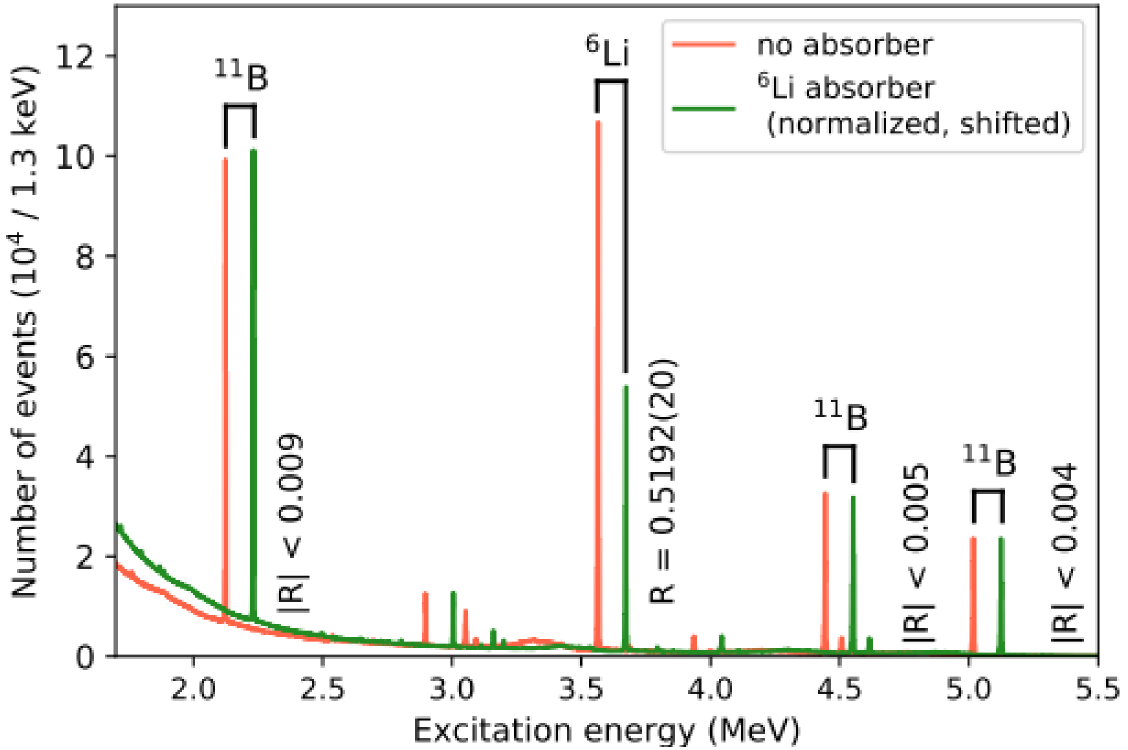
C. Romig *et al.*, Phys. Lett. B **744** 369 (2015).

- Reduction of count rate depends on level width
- and atomic absorption

$$R\left(\Gamma_{0^+\rightarrow 1^+}\right) = \frac{N_{NRF} - N_{RSA}}{N_{NRF}}$$

- ‘Monitor target’ to correct for atomic absorption

Self-Absorption γ–ray Spectrum of ^{6}Li



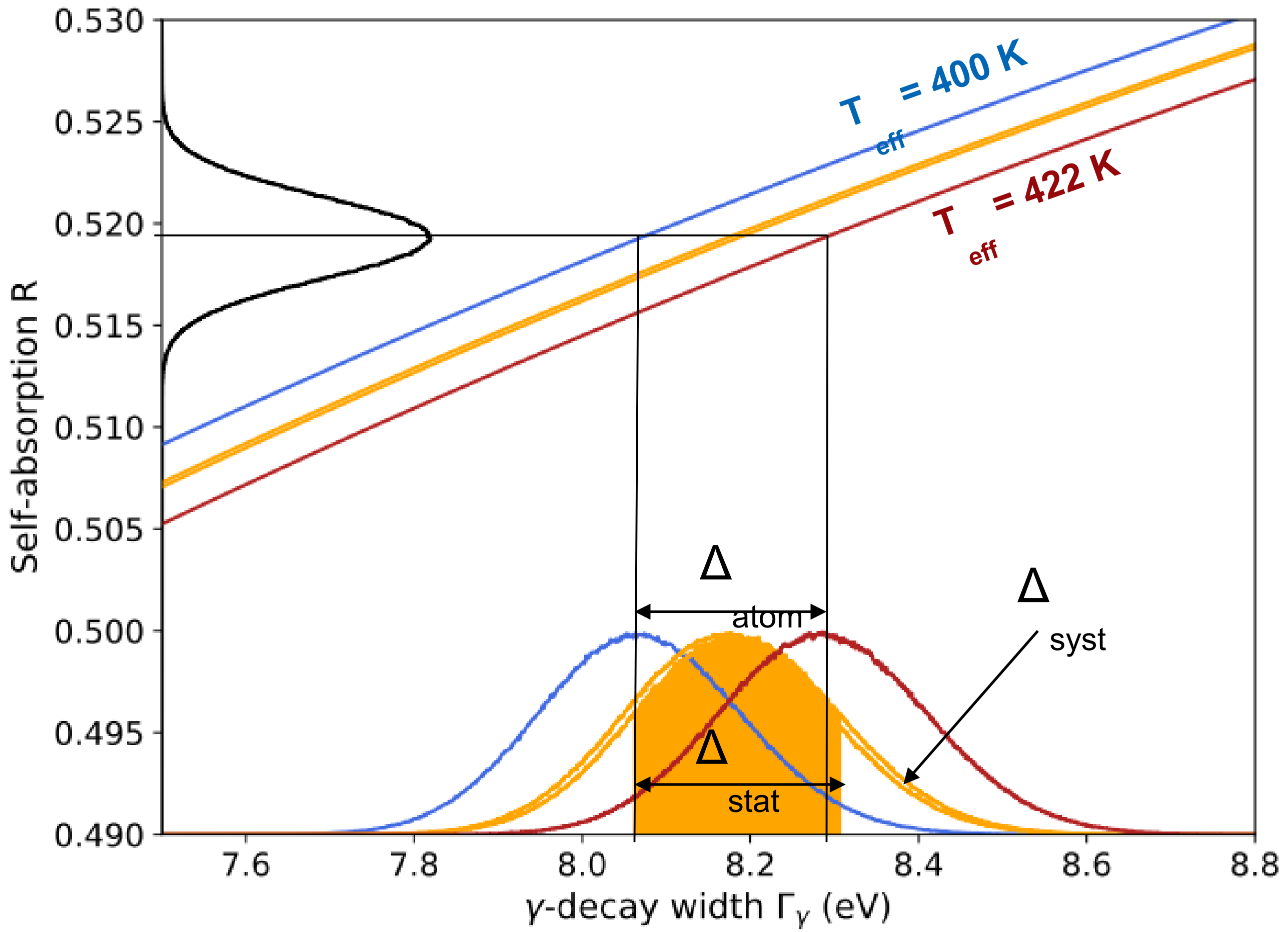
- Normalization of atomic scattering to ^{11}B monitor target

- Measuring times:
- 122h (NRF)
- 189h (RSA)

$$R\left(\Gamma_{0^+\rightarrow 1^+}\right) = \frac{N_{NRF} - N_{RSA}}{N_{NRF}} = 0.5192(20)$$

→ Relative statistical **uncertainty of 0.4%**!

Uncertainty Budget, $1\sigma(T_{1/2})$ = 1 attosecond



B(M1) = 15.61

Δ_{stat} statistics

+0.23 – 0.21

Δ_{atom} atomic theory

+0.19 – 0.21

Δ_{syst} target dimensions

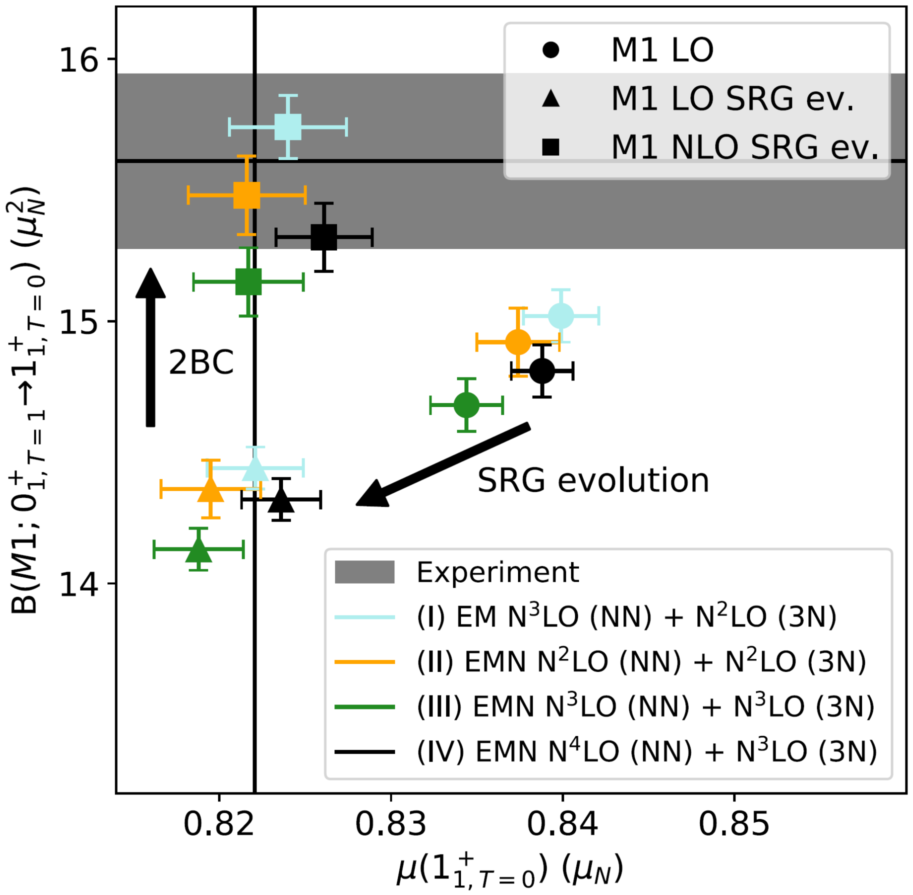
+-0.04

Δ_{num} numerical evaluation

+- << 0.01

= 15.61 +- 0.33
(100% +- 2.1%)

Evidence for necessity of 2BC in modelling of M1 transitions

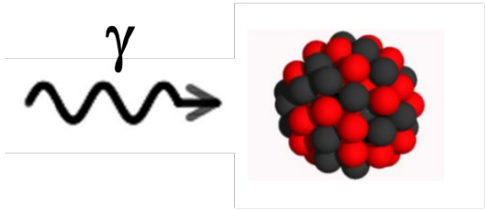


- χEFT calculations of $B(M1;1^+ \to 0^+)$ and $\mu(1^+)$ in the no-core shell model
- SRG-evolved chiral NN+3N interactions up to N4LO+N3LO
  D.R. Entem, R. Machleidt, Y. Nosyk, PRC **96** (2017)
- Evolved M1 operator at NLO

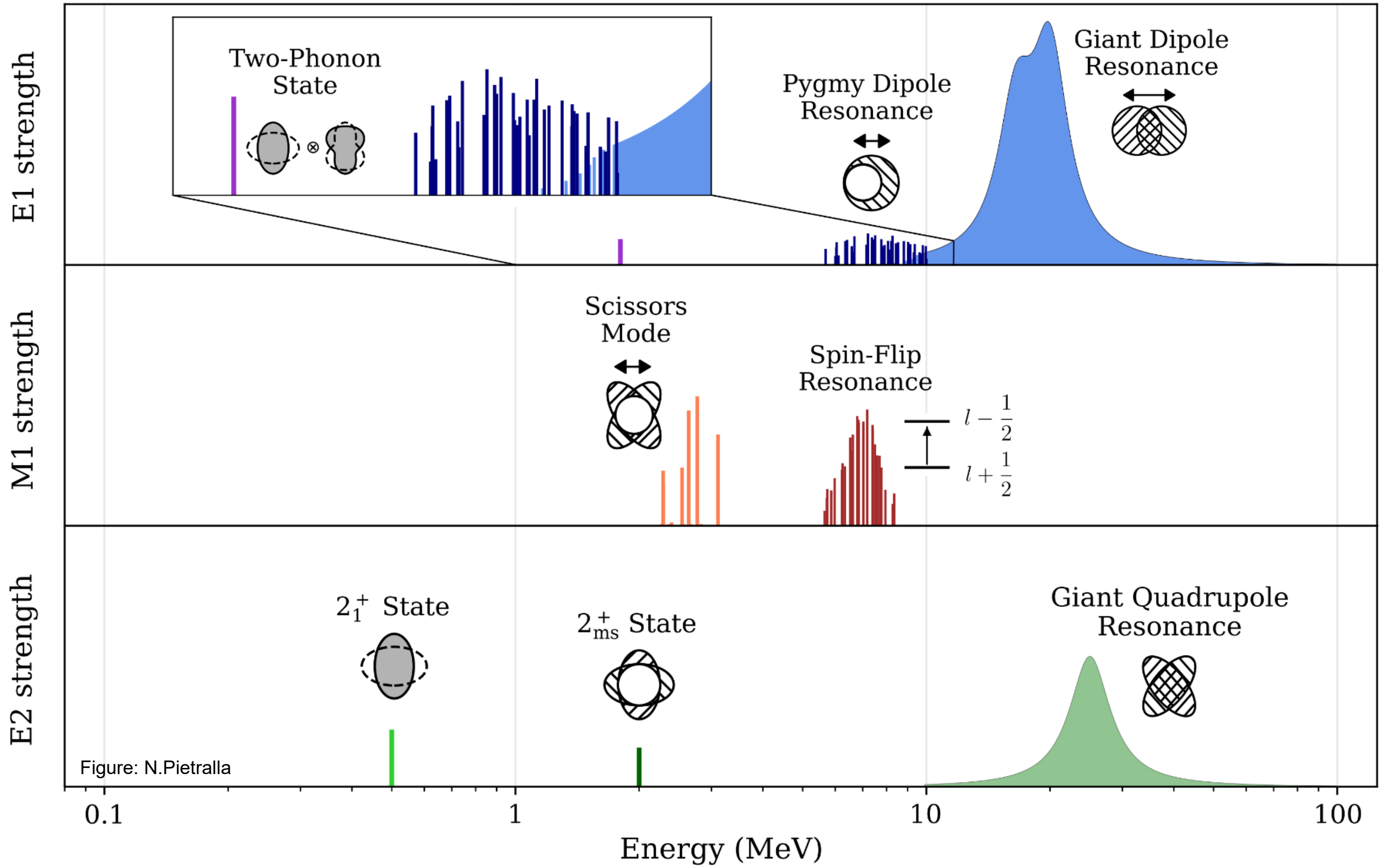
→ Complete chiral calculation of these observables

U.Friman-Gayer et al.
Role of Chiral Two-Body Currents in ^{6}Li Magnetic Properties in Light of a New Precision Measurement with the Relative Self-Absorption Technique
Phys. Rev. Lett. **126**, 102501 (2021)

High experimental precision crucial to test state-of-the-art theory!



What happens ?



atomic | nuclear | hadronic

Example III:

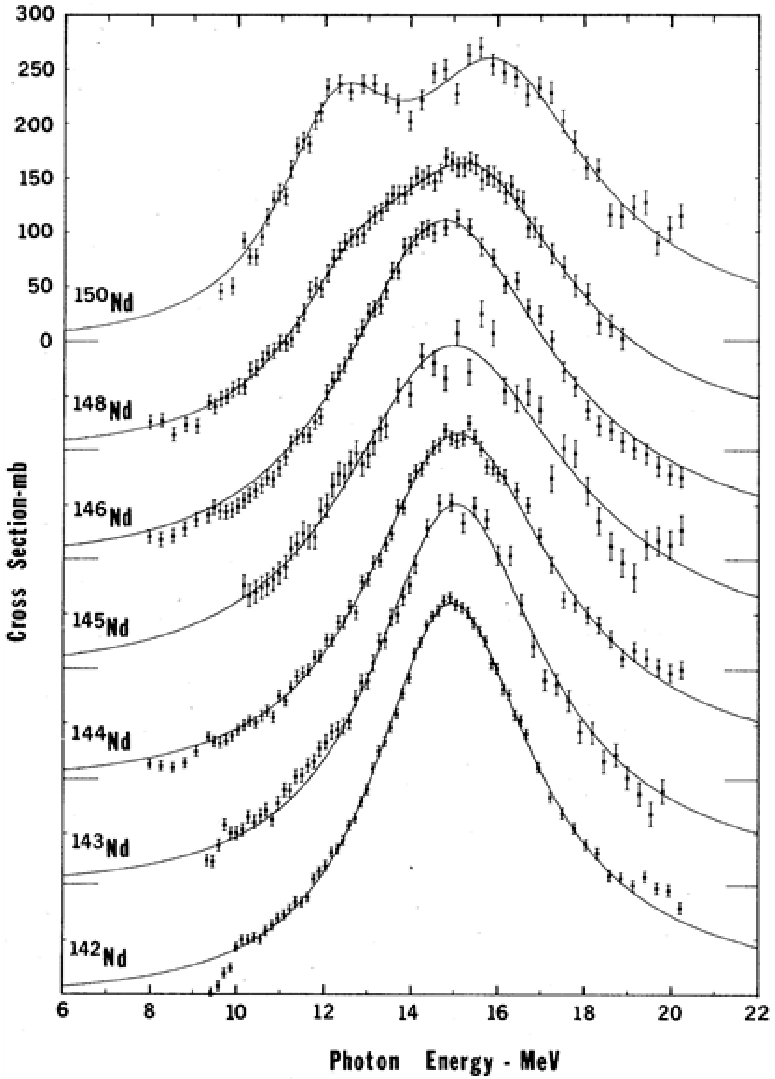
γ-ray Decay of the Giant Dipole Resonance

- **GDR evolves as a function of nuclear deformation**
- GDR decays predominantly by neutron emission
- Data on γ/n–branching ratio very scarce
- Complete data on Raman scattering

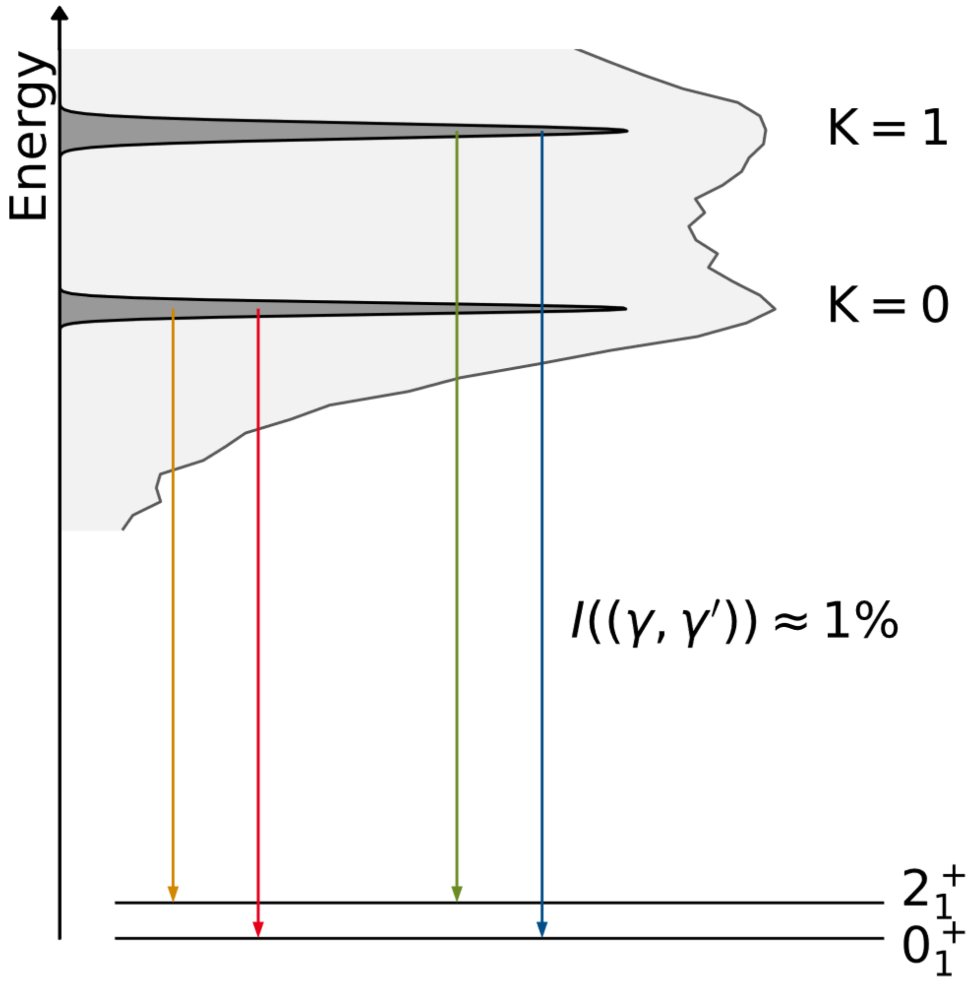
$$0_1^+ \rightarrow 1_{\mathrm{GDR}}^- \rightarrow 2_1^+$$

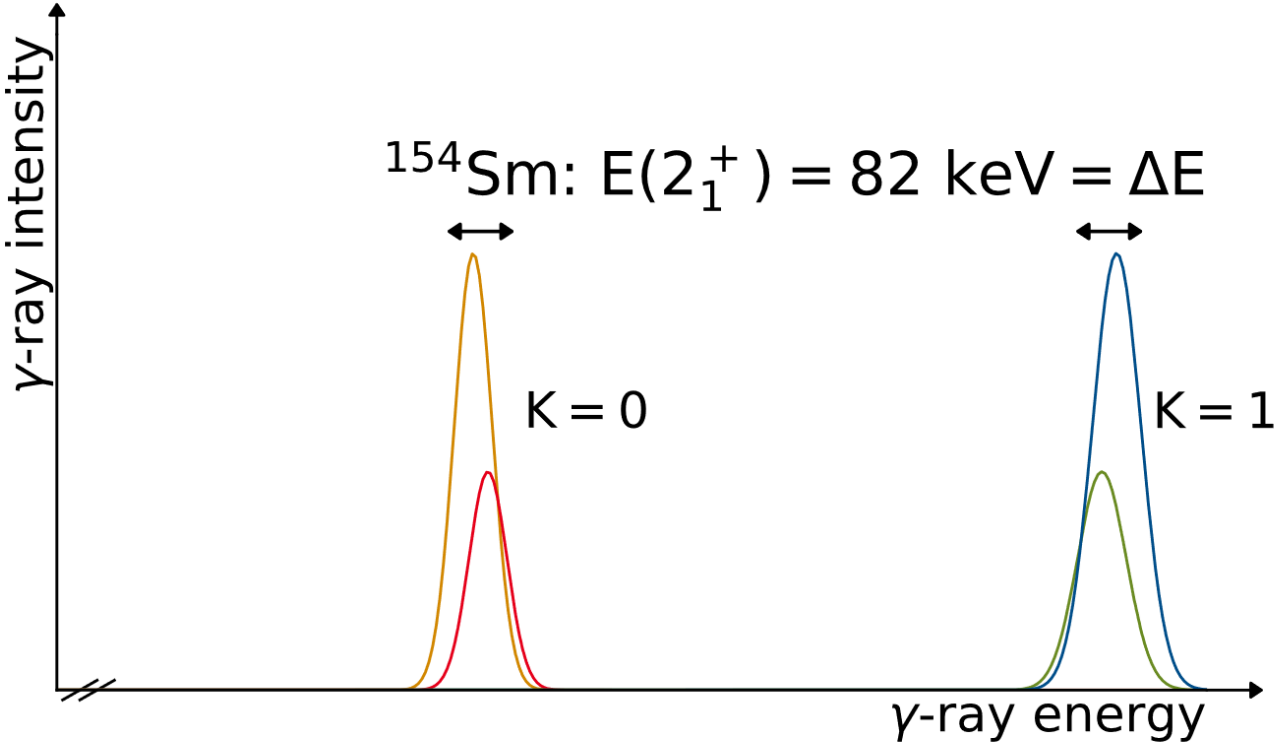
absent for deformed nuclei

- **How do they develop as a function of excitation energy over the resonance?**



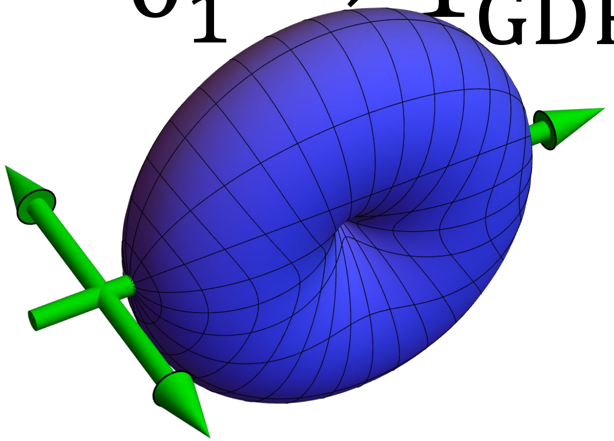
B. L. Berman and S. C. Fultz, Rev. Mod. Phys. **47**, 713 (1975)


Energy
K = 1
K = 0
$I((\gamma,\gamma')) \approx 1\%$
2_1^+
0_1^+

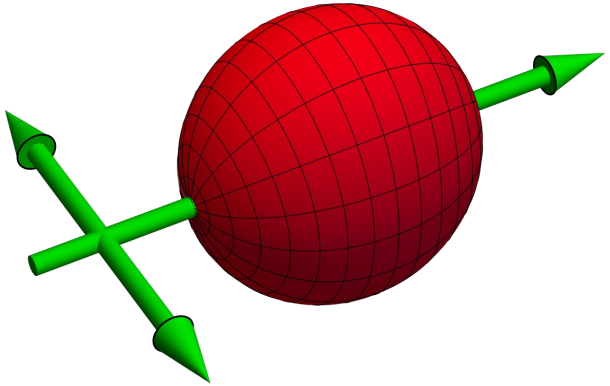

γ-ray intensity
^{154}Sm: $E(2_1^+) = 82$ keV = ΔE
K = 0
K = 1
γ-ray energy

EXCITING THE GDR USING A LINEARLY POLARIZED BEAM

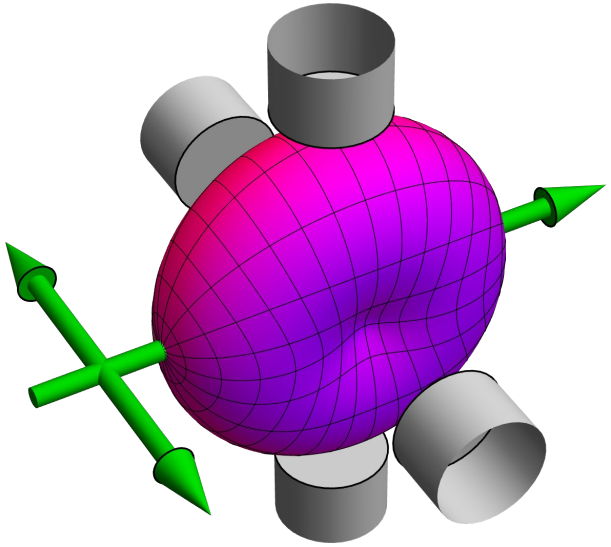
$$0_1^+ \rightarrow 1^-_{\mathrm{GDR}} \rightarrow 0_1^+ \qquad 0_1^+ \rightarrow 1^-_{\mathrm{GDR}} \rightarrow 2_1^+$$



$$+\frac{\Gamma_{2_1^+}}{\Gamma_{0_1^+}} \times$$



$$=$$



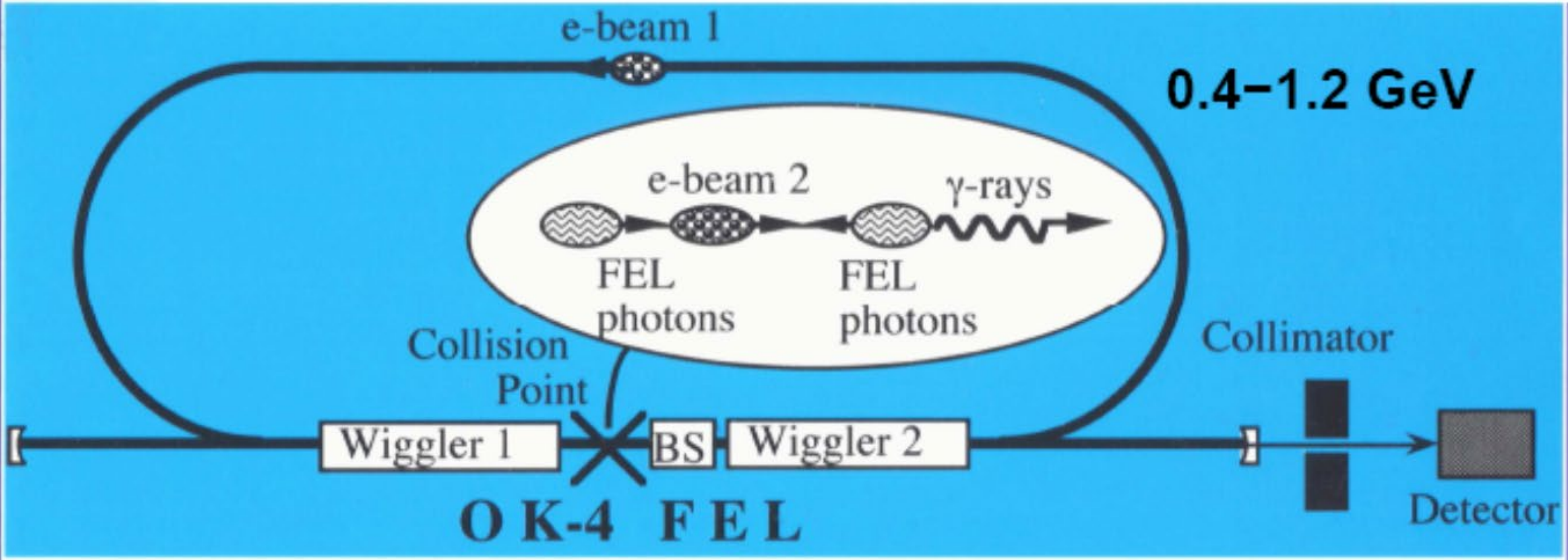
$$\left(\frac{\Gamma_{2_1^+}}{\Gamma_{0_1^+}}\right)$$

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

High Intensity γ−Ray Source (HIgS)

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

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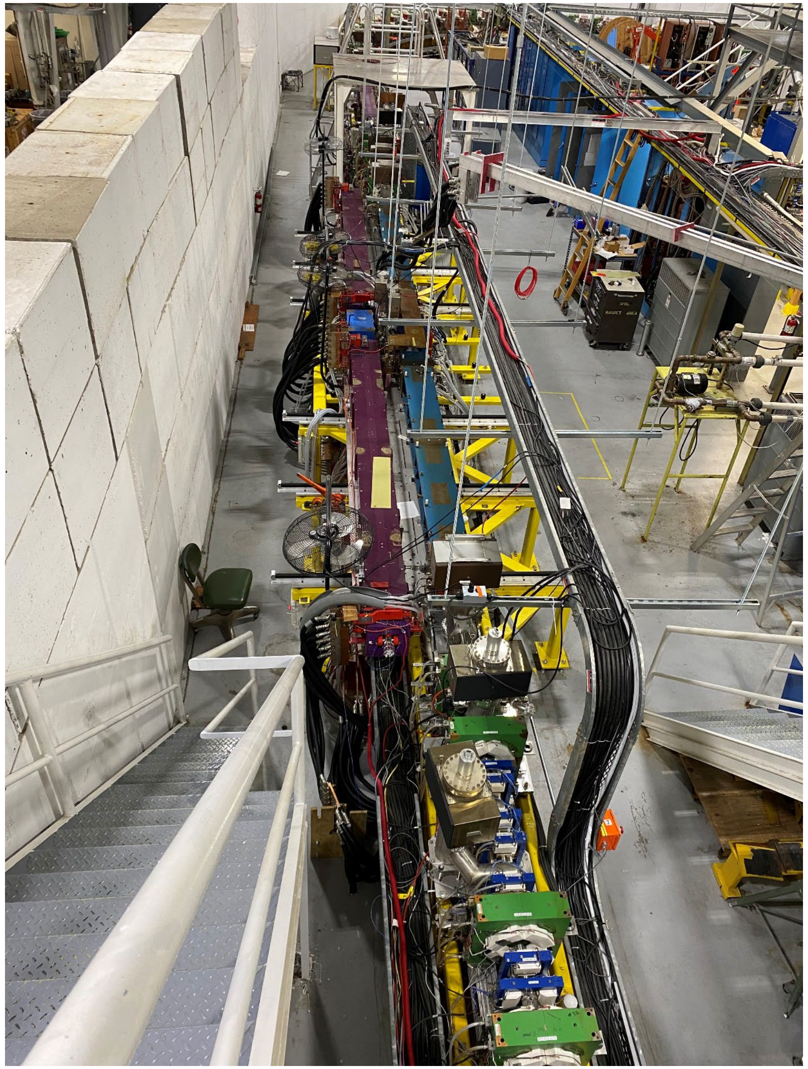
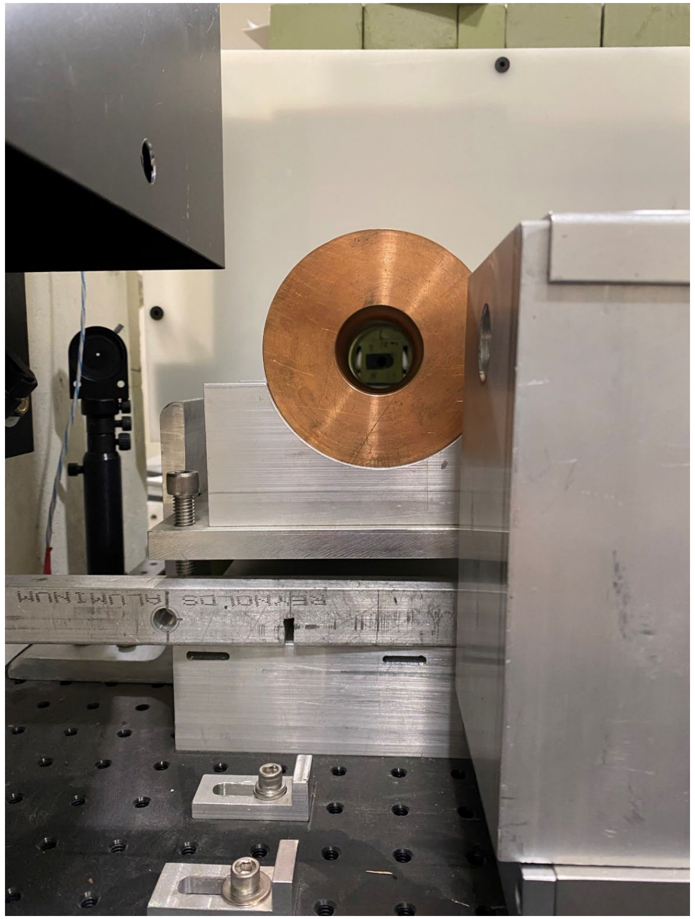


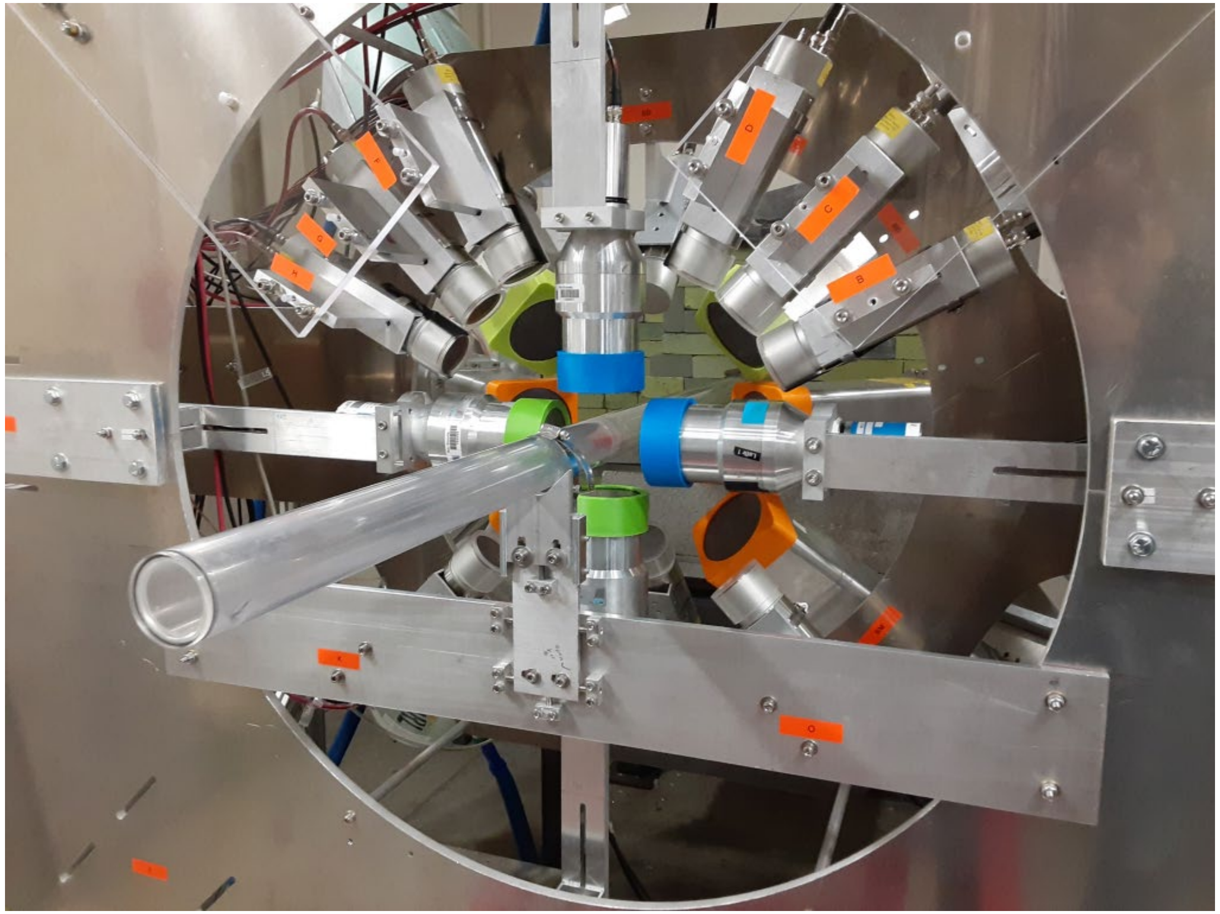
photos from Sept. 2023

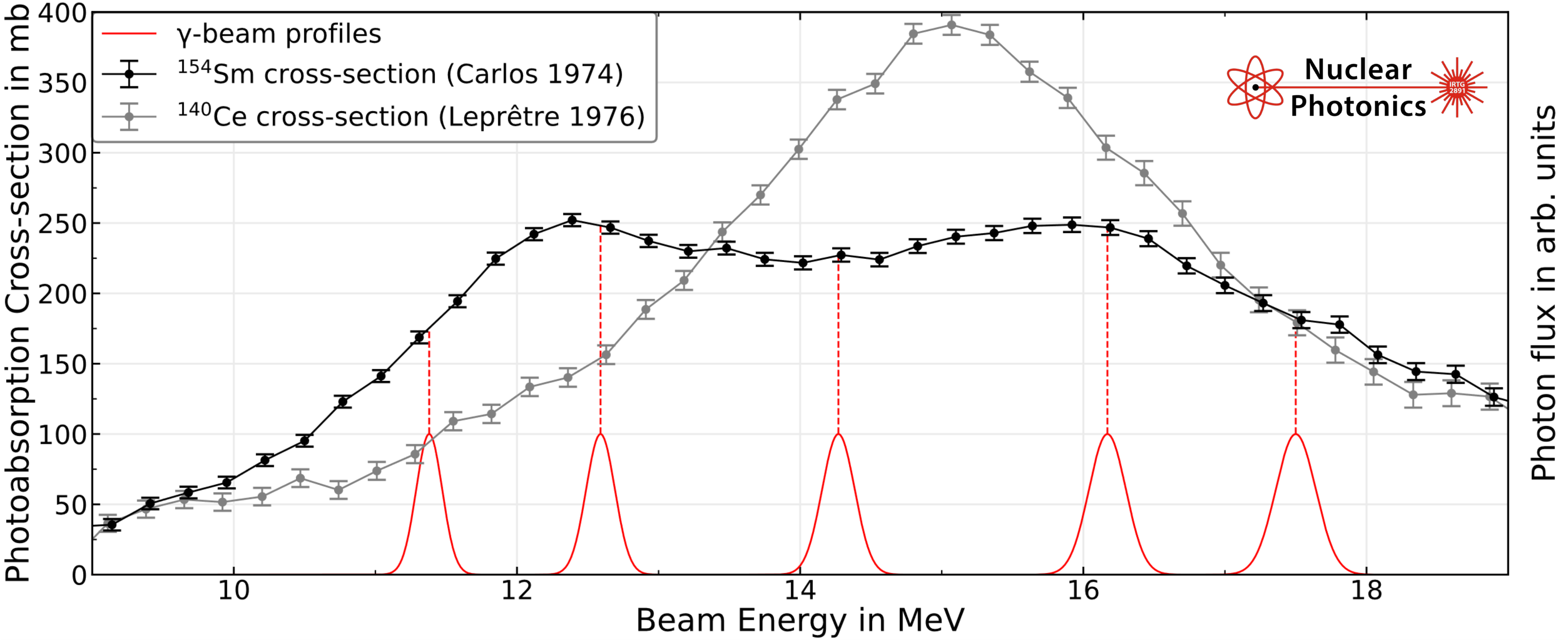
OK-5: this is a lamp!



collimators

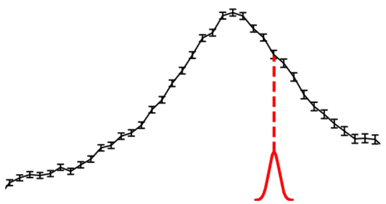
GAMMA-CUBE: LABR-CLOVER-SETUP AT HIGS



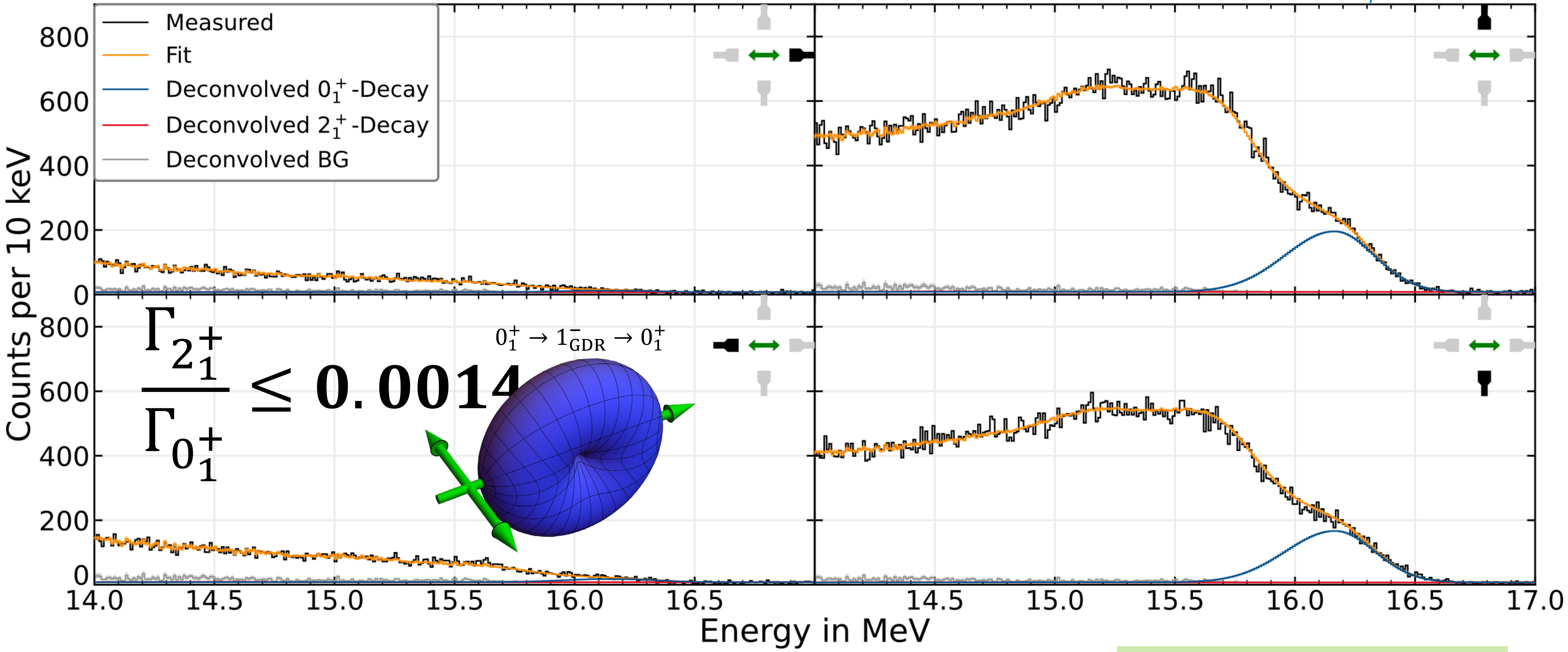


γ-beam profiles
154Sm cross-section (Carlos 1974)
140Ce cross-section (Leprêtre 1976)
Nuclear Photonics
Photoabsorption Cross-section in mb
Photon flux in arb. units
Beam Energy in MeV
0
50
100
150
200
250
300
350
400
10
12
14
16
18

^{140}Ce(γ,γ')@HIγS



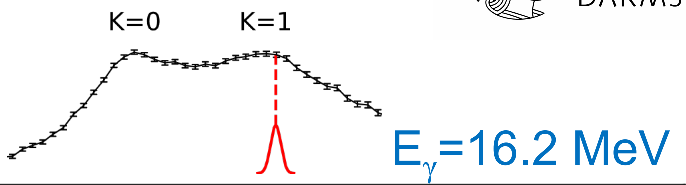
E_{γ}=16.2 MeV

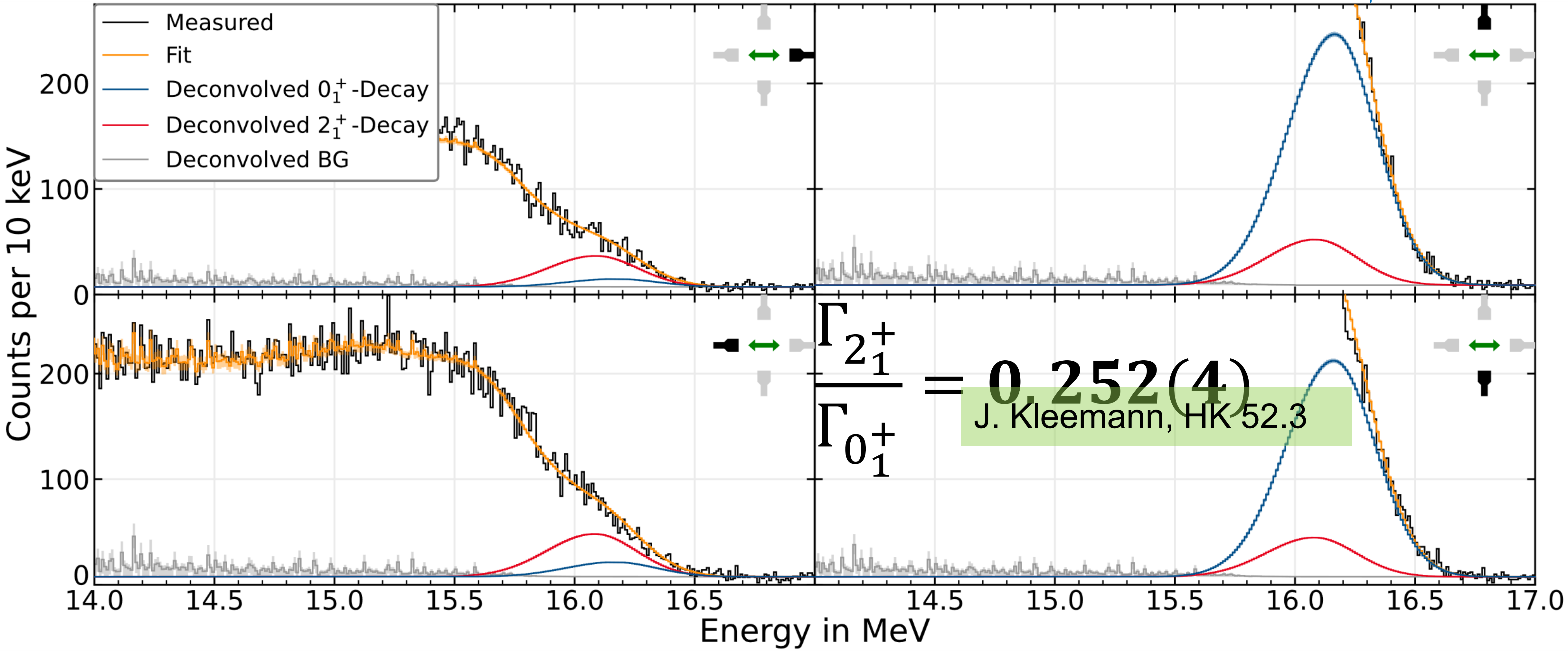


$$\frac{\Gamma_{2_1^+}}{\Gamma_{0_1^+}} \leq 0.0014$$

J. Kleemann, HK 52.3

^{154}Sm(γ,γ')@HIγS





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

J. Kleemann, HK 52.3

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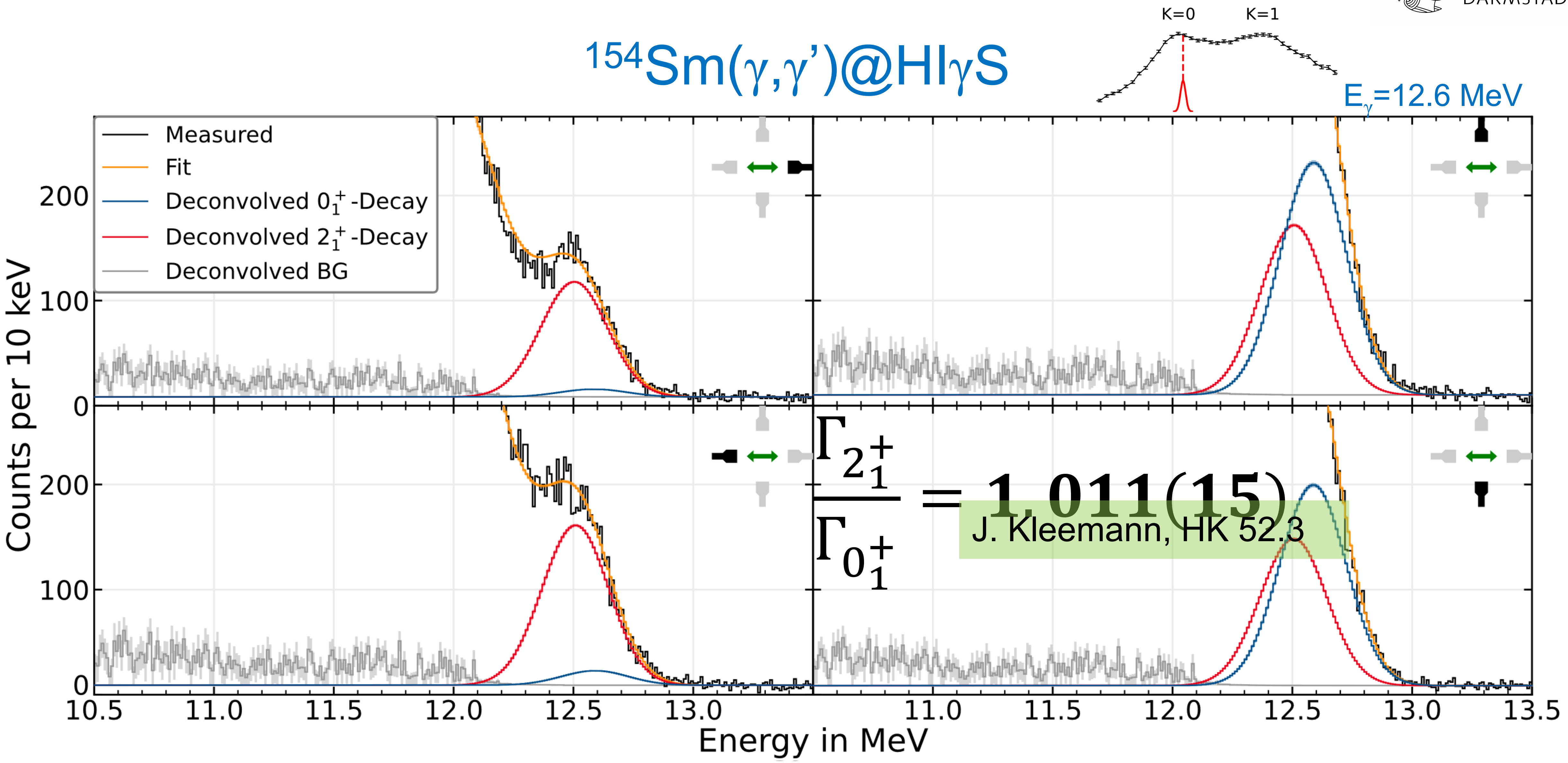
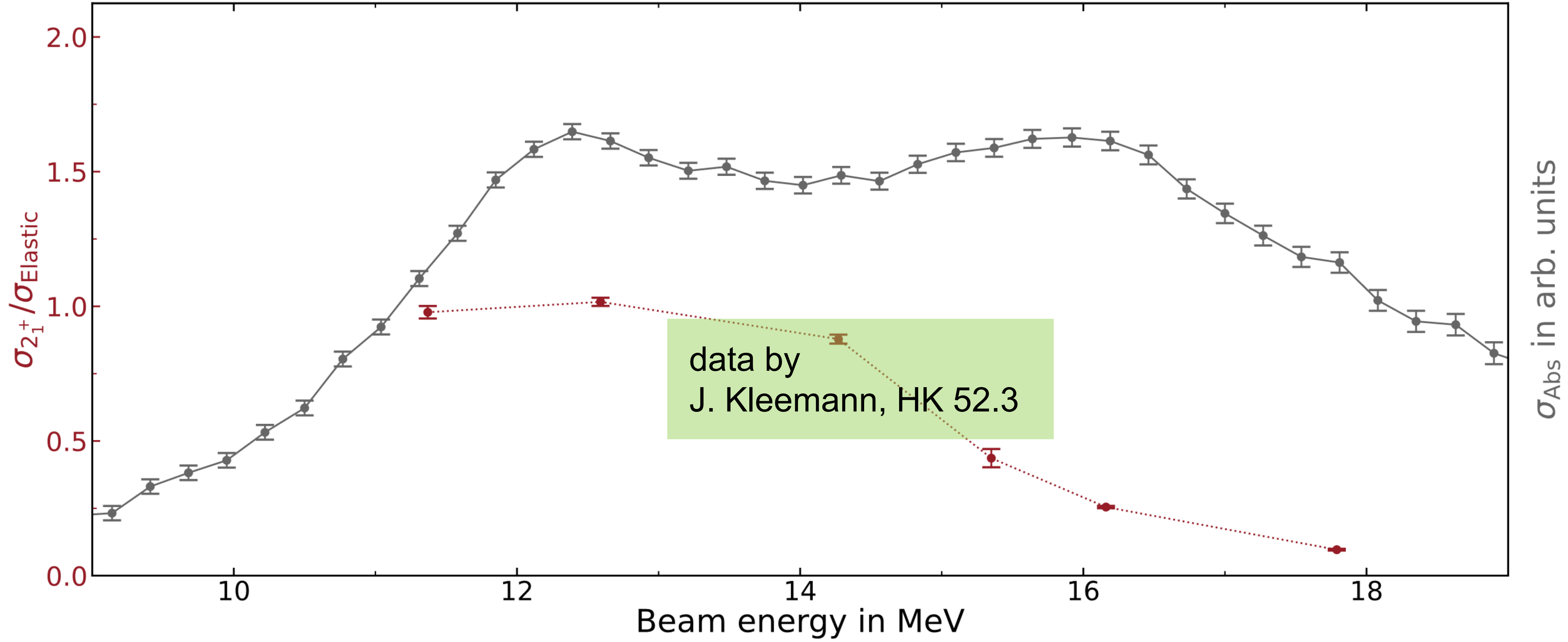
^{154}Sm(γ,γ')@HIγS



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

J. Kleemann, HK 52.3



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

- Thomson scattering interferes with GDR's γ-decay to 0_1^+

$$\sigma_{\mathrm{Elastic}}(E) = \frac{8\pi}{3}\left| f_{\mathrm{Th}} + f_{0_1^+\,\mathrm{NRF}}(E)\right|^2$$

⇒ Scattering amplitudes $\mathbf{f}_{\mathbf{NRF}}(\mathbf{E}) \in \mathbb{C}$ from Standard LOrentzian

$$\sigma_{\mathrm{Abs}}(E) = \sum_{k=1}^{3} \sigma_k \frac{E^2\Gamma_k^2}{\left(E_k^2 - E^2\right)^2 + E^2\Gamma_k^2}$$

see: D. Drechsel, B. Pasquini, M.Vanderhaegen, Phys. Rep. **378**, 99 (2003).

through optical theorem and dispersion relations

⇒ Geometrical model relates decay into ground-state rotational band: $\frac{\sigma_{2_1^+}}{\sigma_{\mathrm{Elastic}}}$

see: E.G. Fuller and E. Hayward, Nucl. Phys. **30**, 613 (1962).

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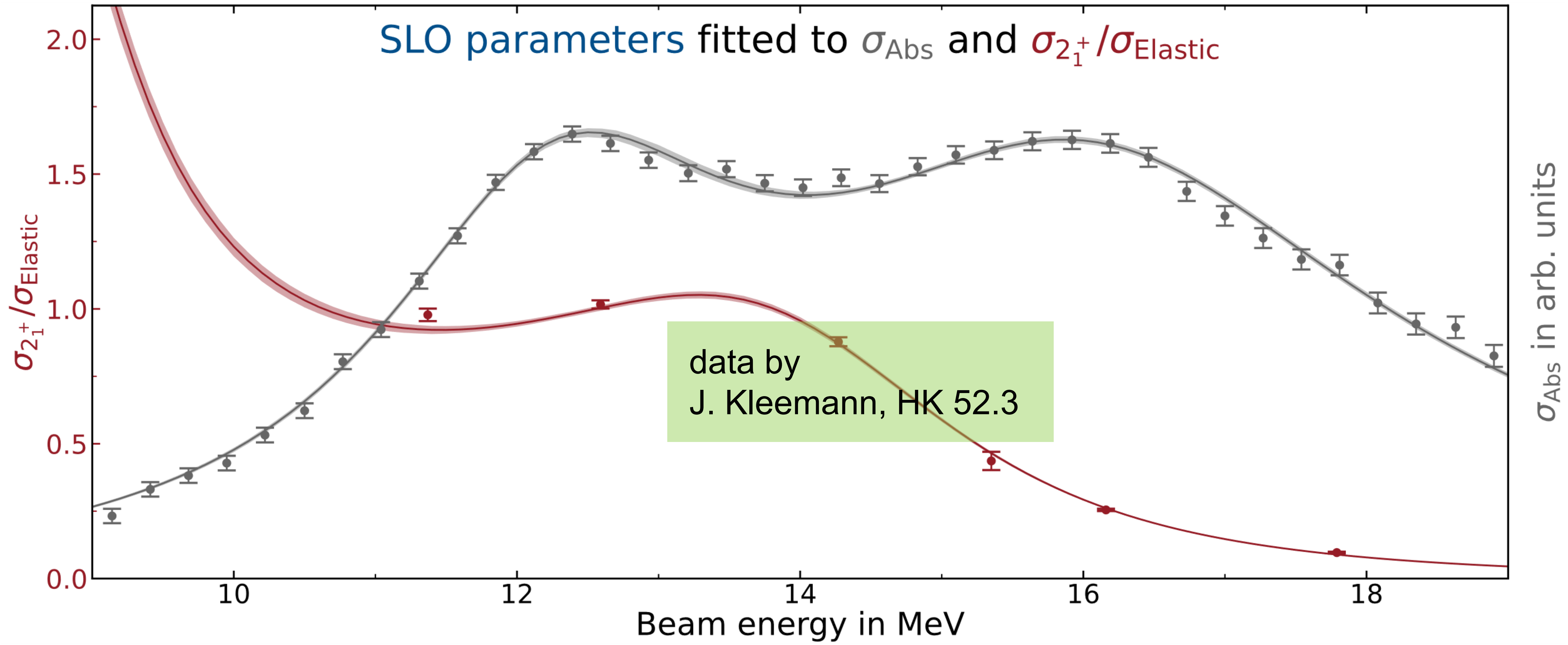
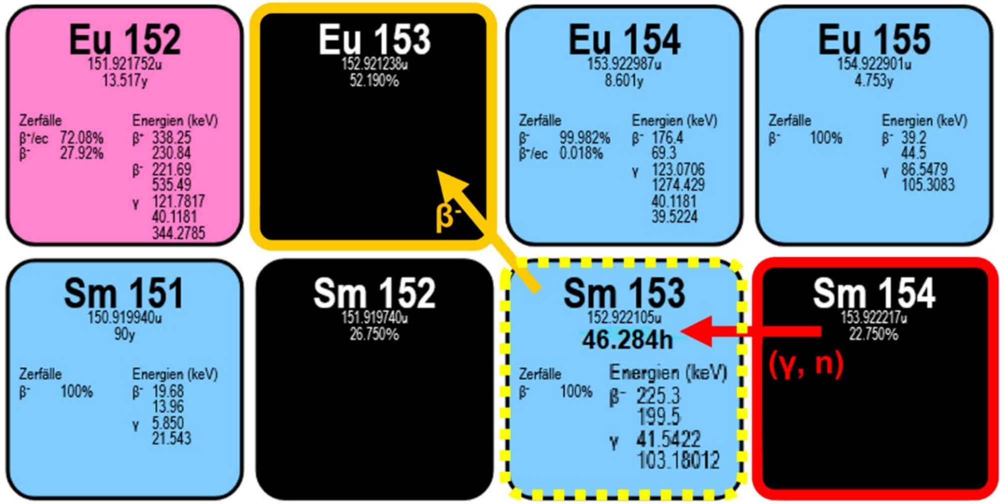
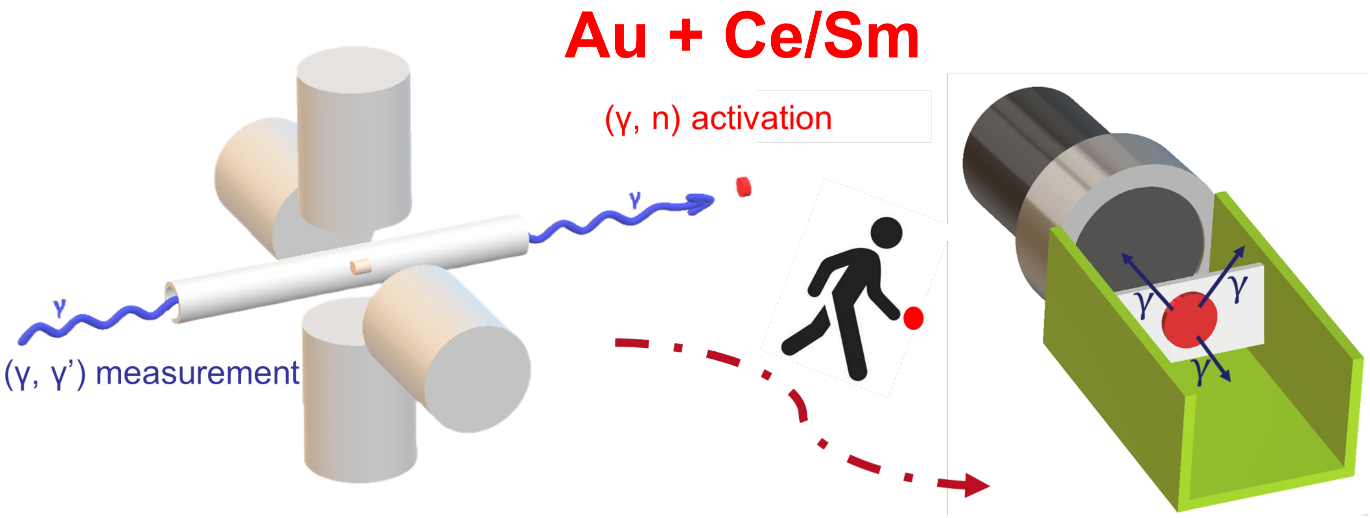


Simultaneous activation measurement

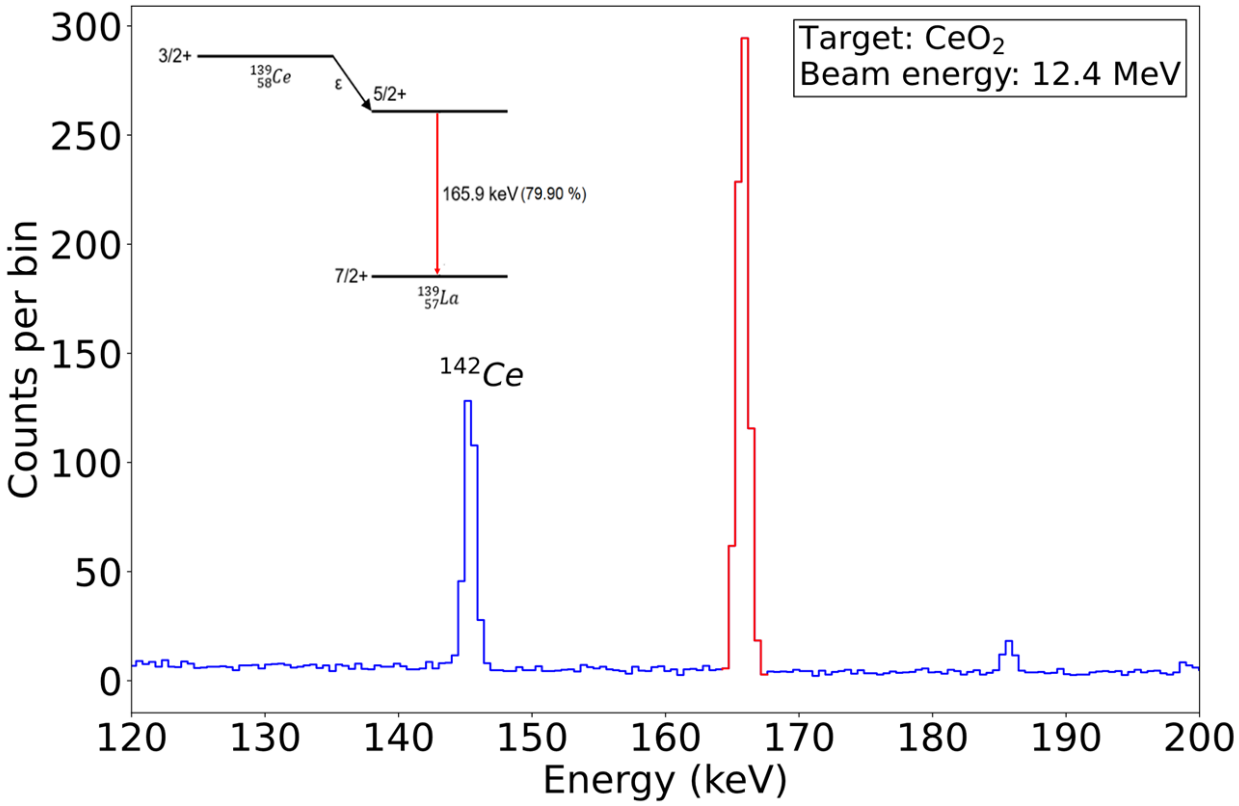
- Photon flux from $^{197}Au(\gamma,1n)^{196}Au$ cross section

➢ Absolute $^{154}Sm/^{140}Ce(\gamma,1n)$ cross sections

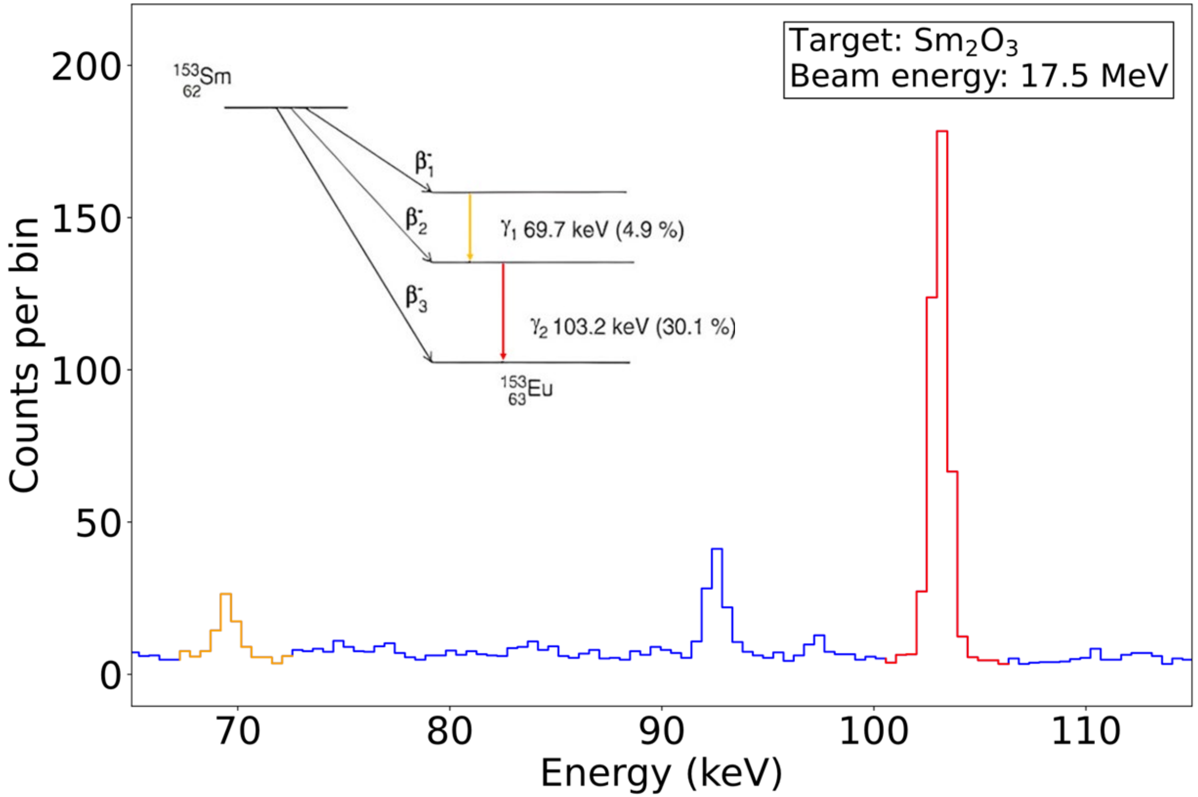




activity from
^{140}Ce(γ,1n)^{139}Ce @ HIγS



activity from
^{154}Sm(γ,1n)^{153}Sm @ HIγS



initial photon flux from ^{197}Au(γ,1n)^{196}Au data from Fultz et al.

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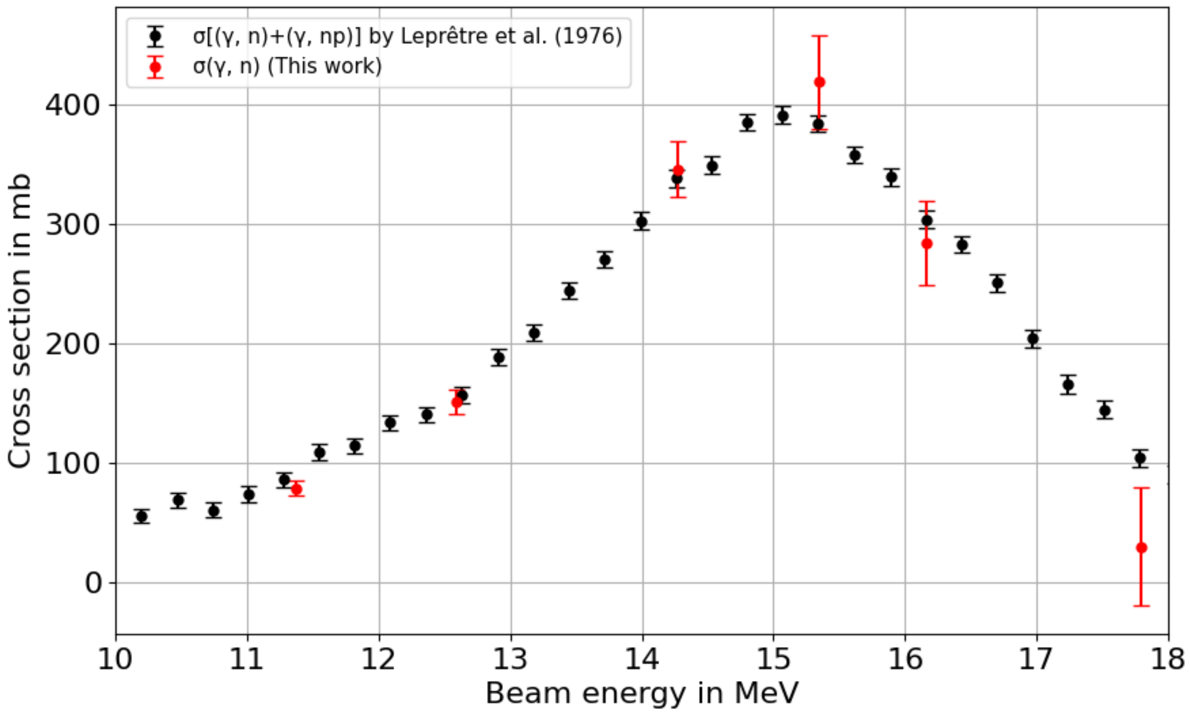
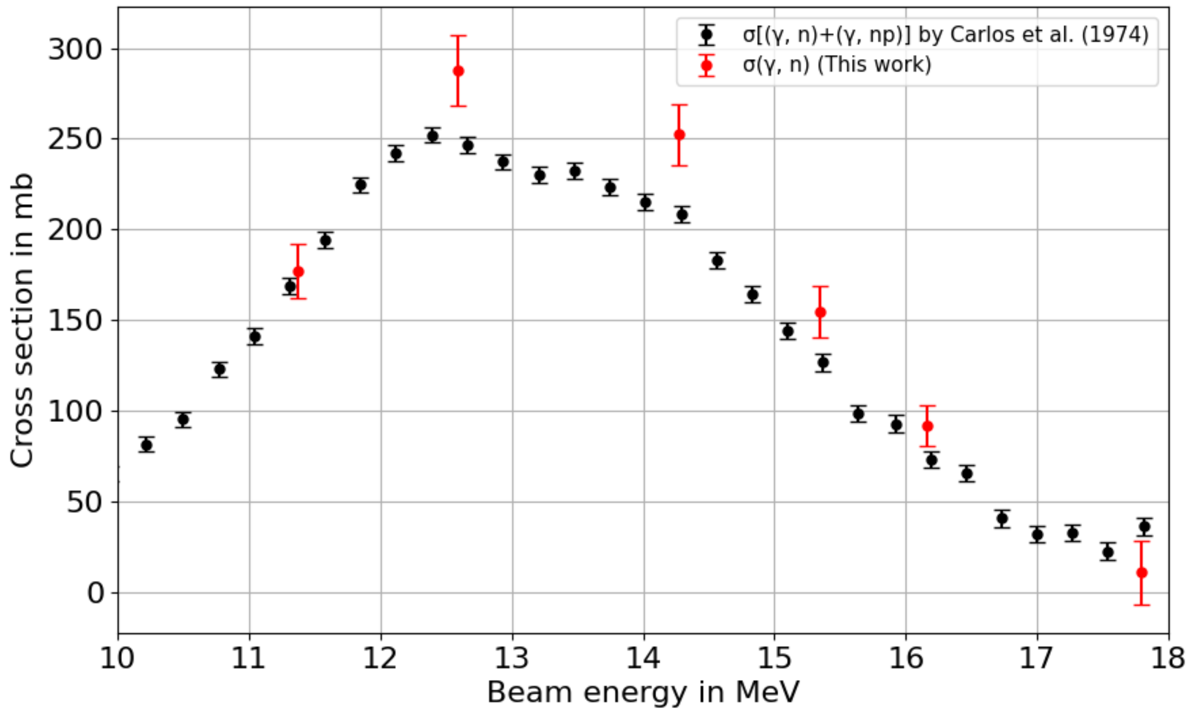
$^{140}Ce(\gamma,1n)^{139}Ce$ @ HIγS



$^{154}Sm(\gamma,1n)^{153}Sm$ @ HIγS



K. Prifti, HK 52.1

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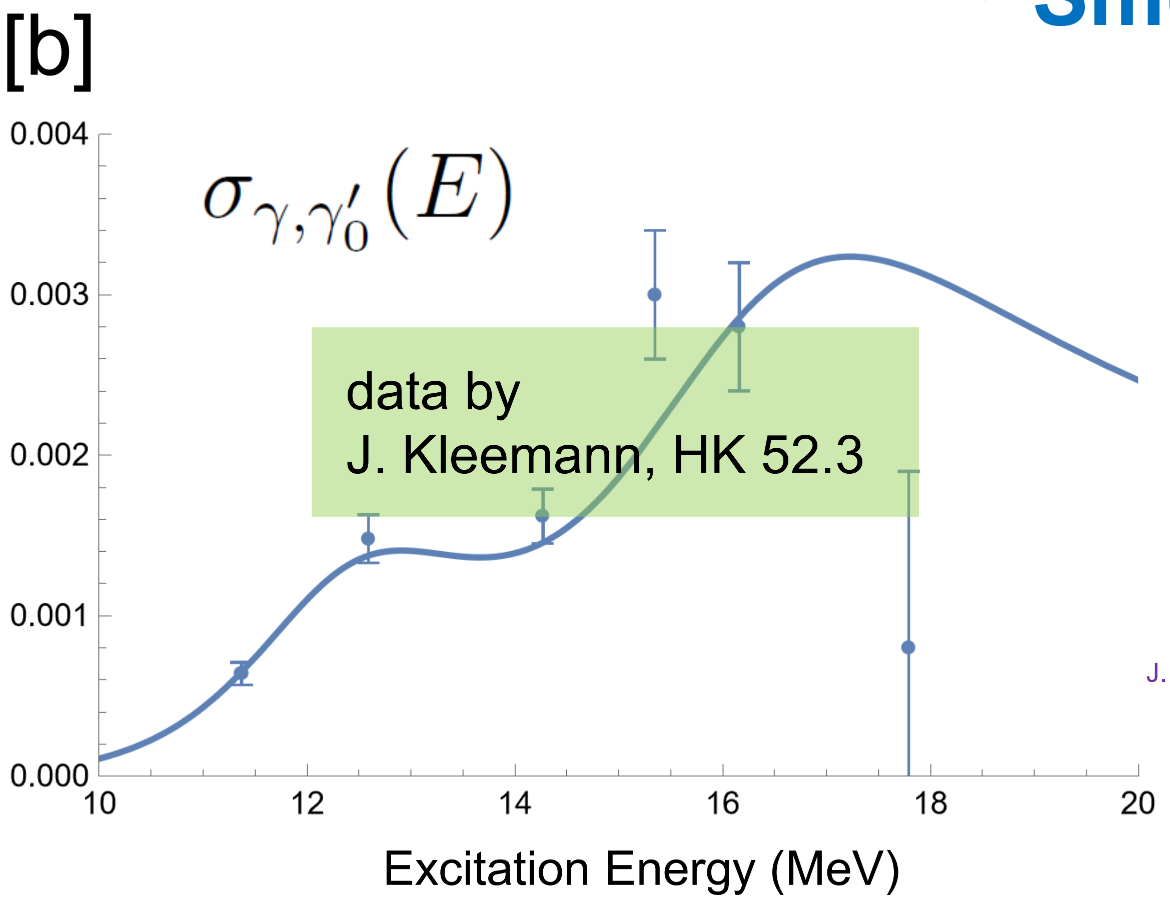
$^{154}Sm(\gamma,\gamma_0')$

Absolute NRF cross section of GDR obtained from dispersion relation



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

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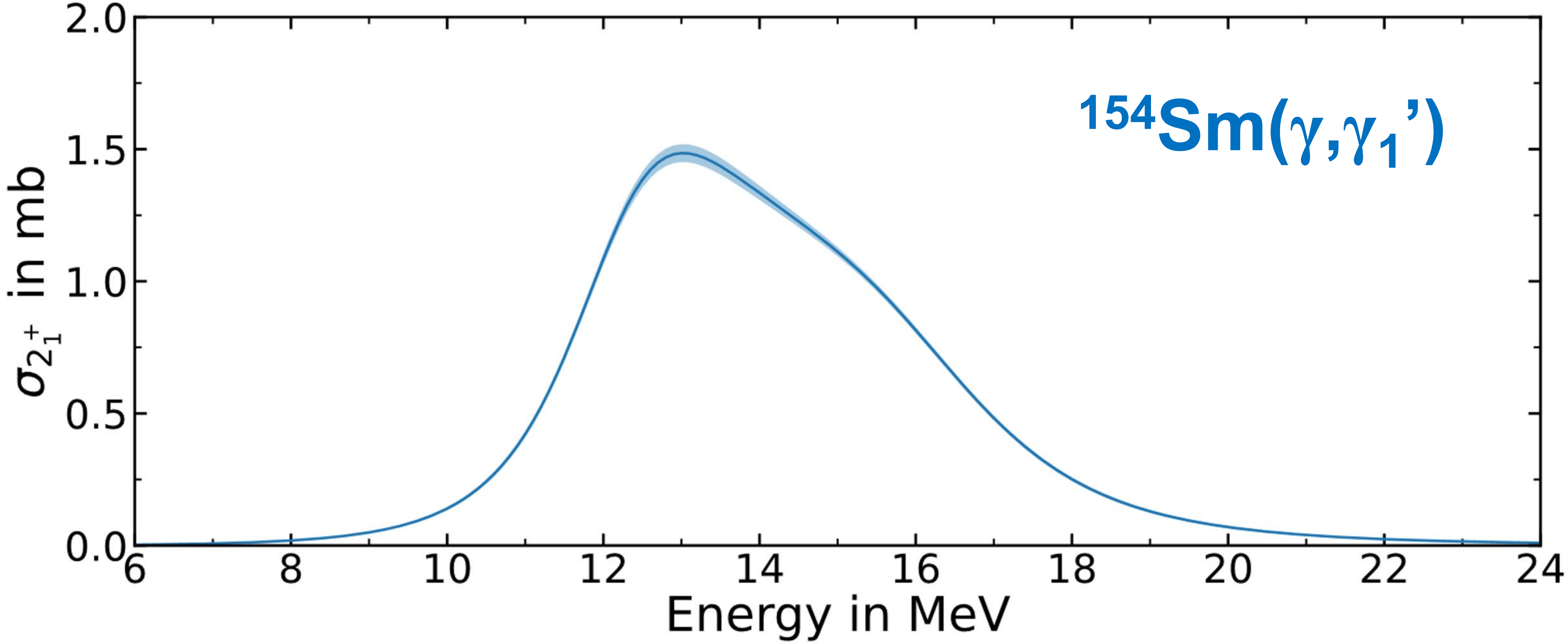

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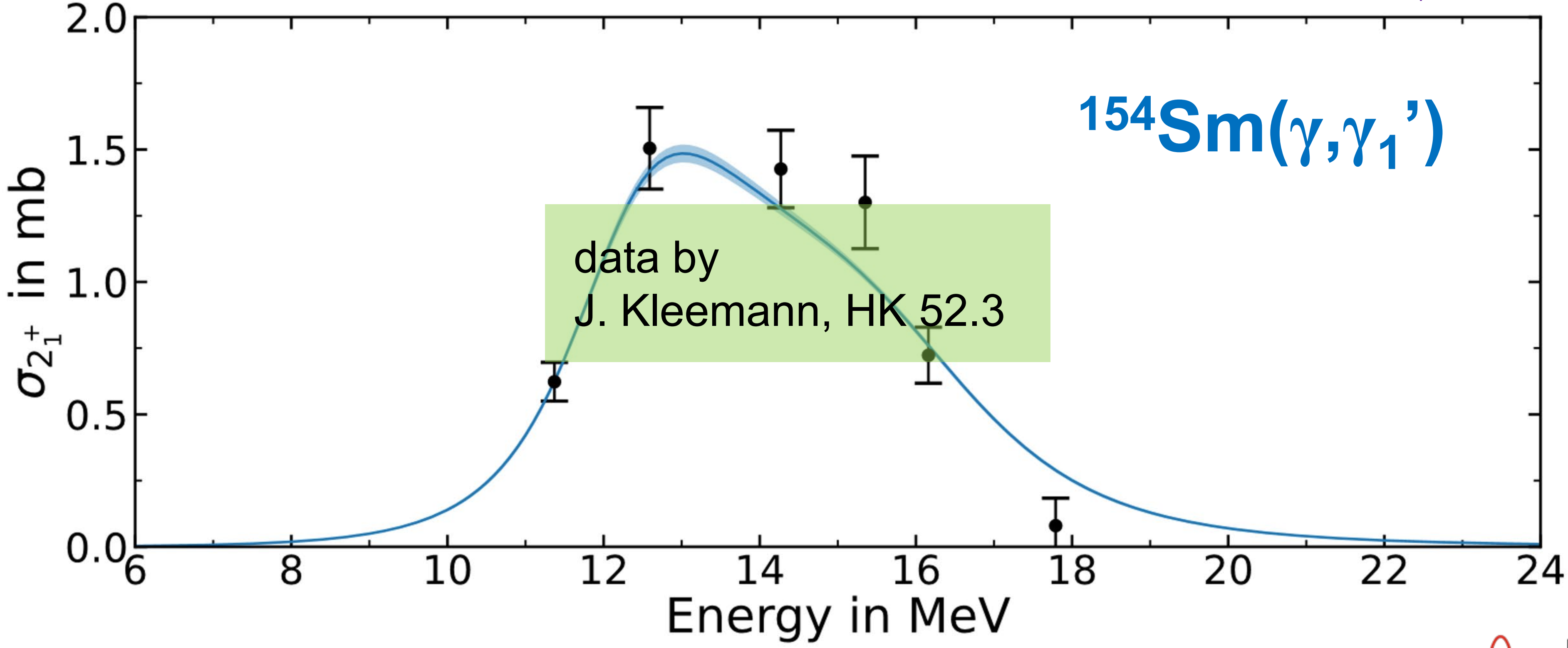
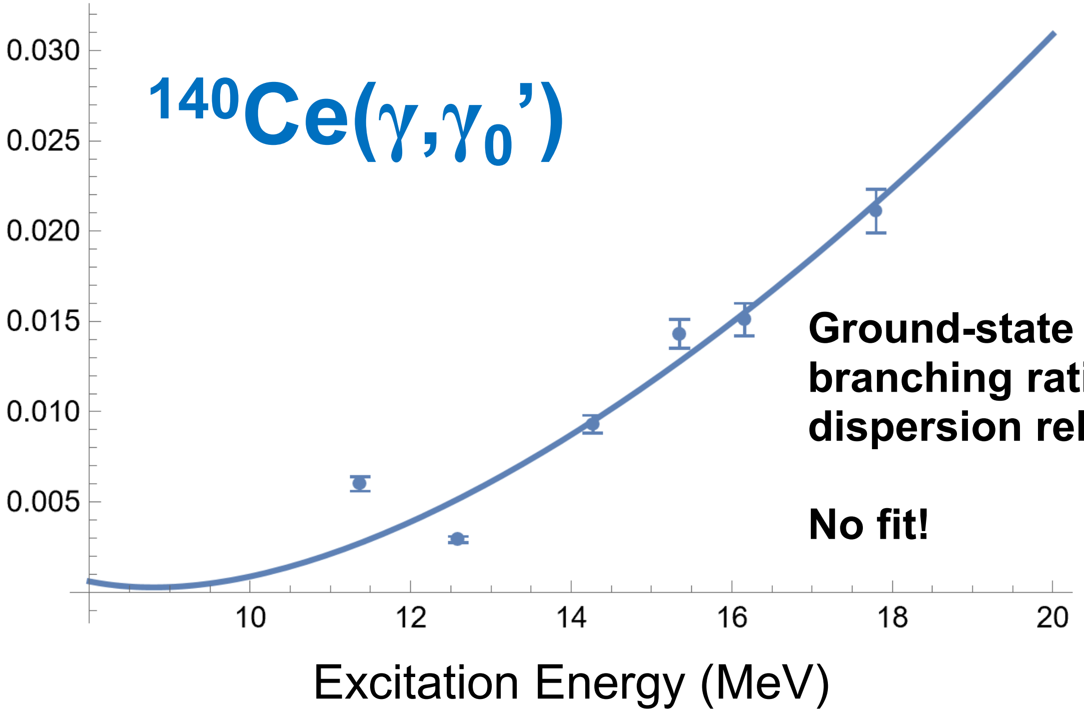


data: $\frac{\sigma_{\gamma,\gamma'_0}(E)}{\sigma_{\gamma,1n}(E)}$

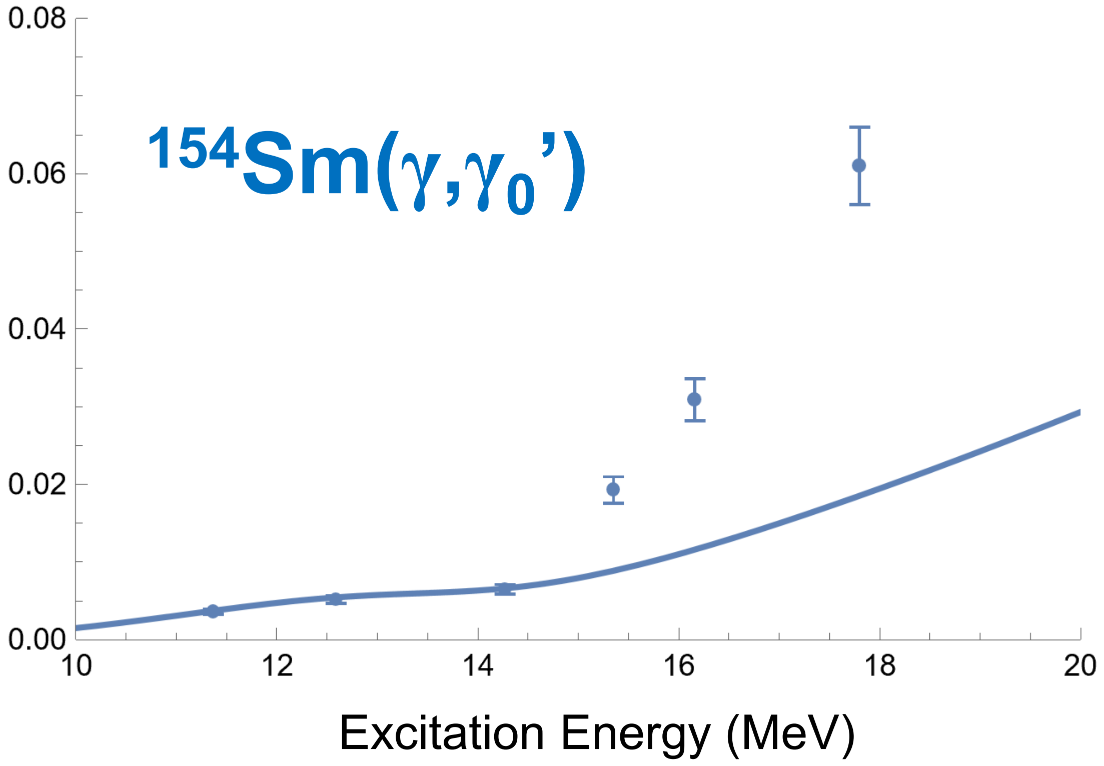
theory: $\frac{\sigma_{\gamma,\gamma'_0}(E)}{\sigma_{\mathrm{abs}}(E)}$

$$\mathrm{BR}_\gamma(E) = \frac{\sigma_{\gamma,\gamma'_0}(E)}{\sigma_{\gamma,1n}(E)}$$



Ground-state γ–decay branching ratio from dispersion relations

No fit!



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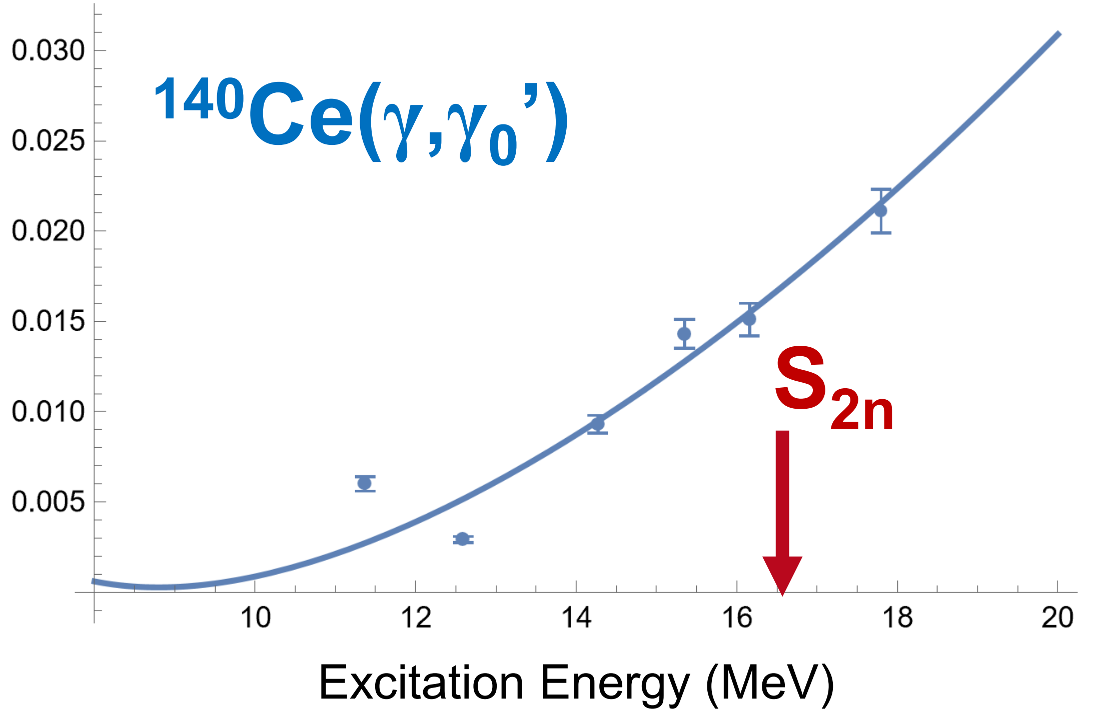
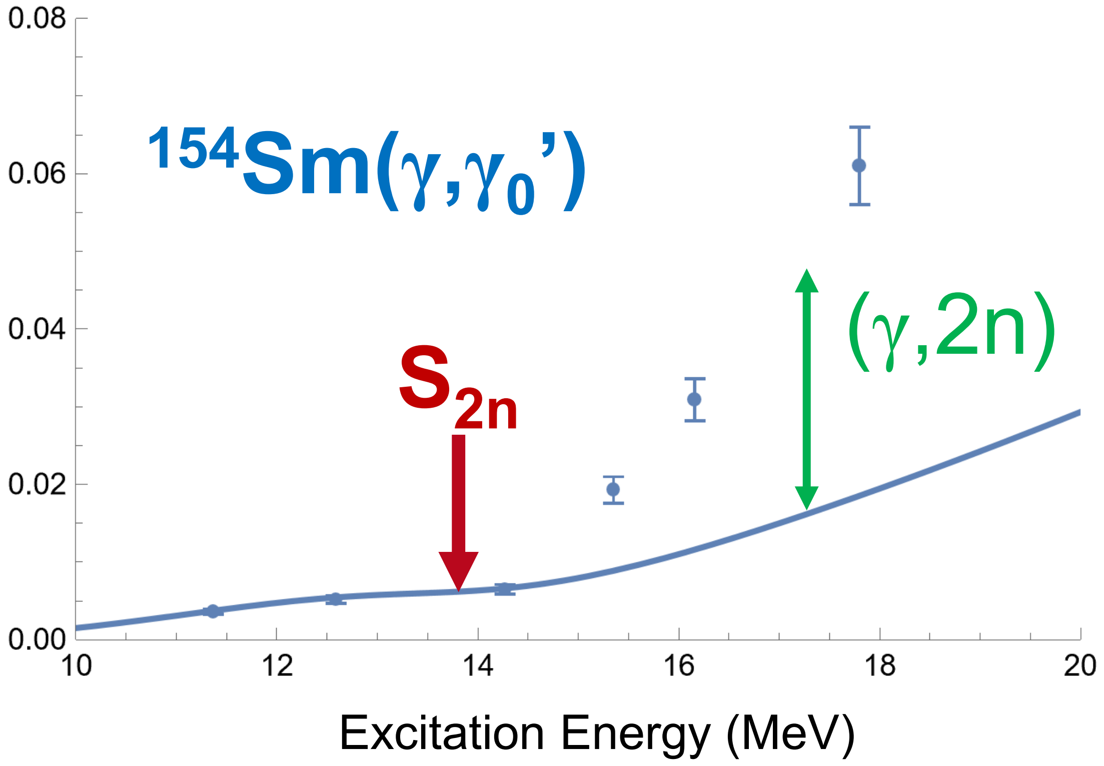
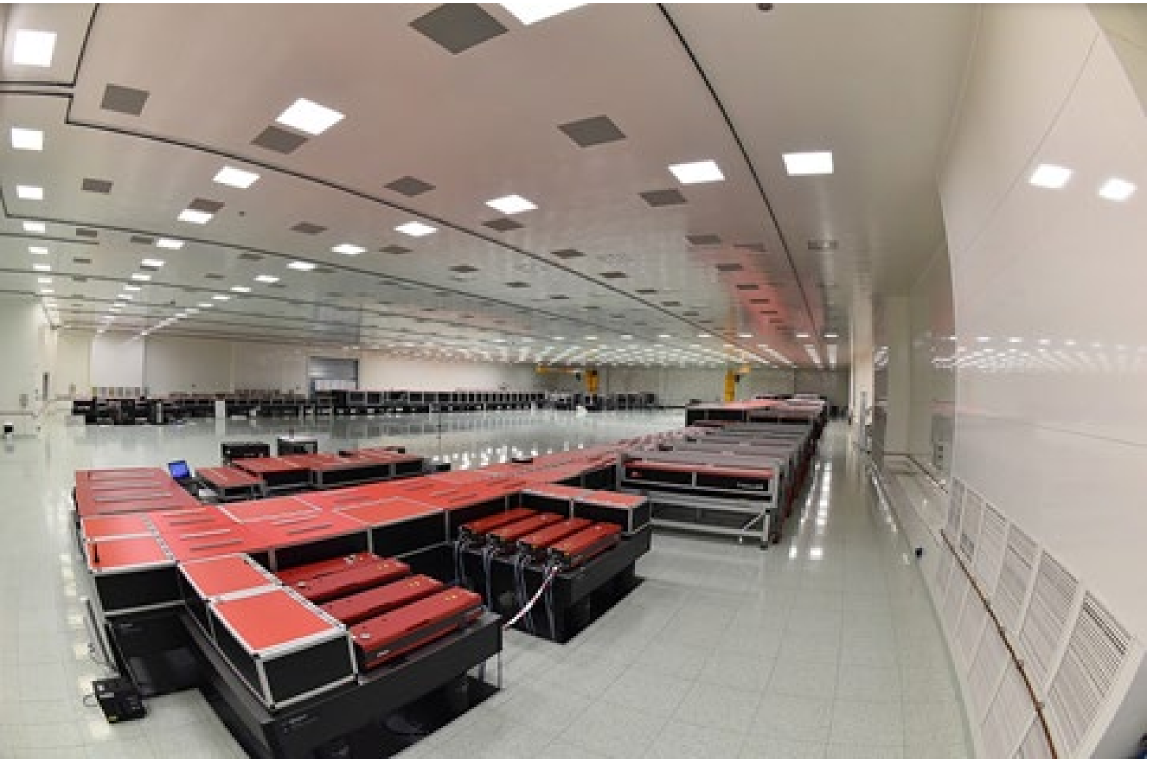


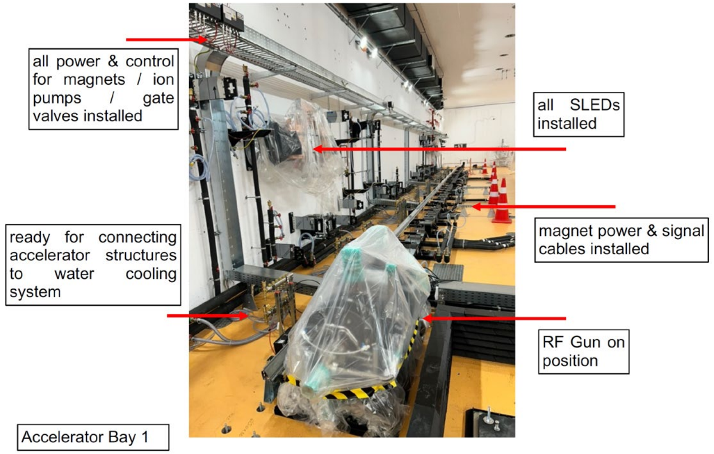


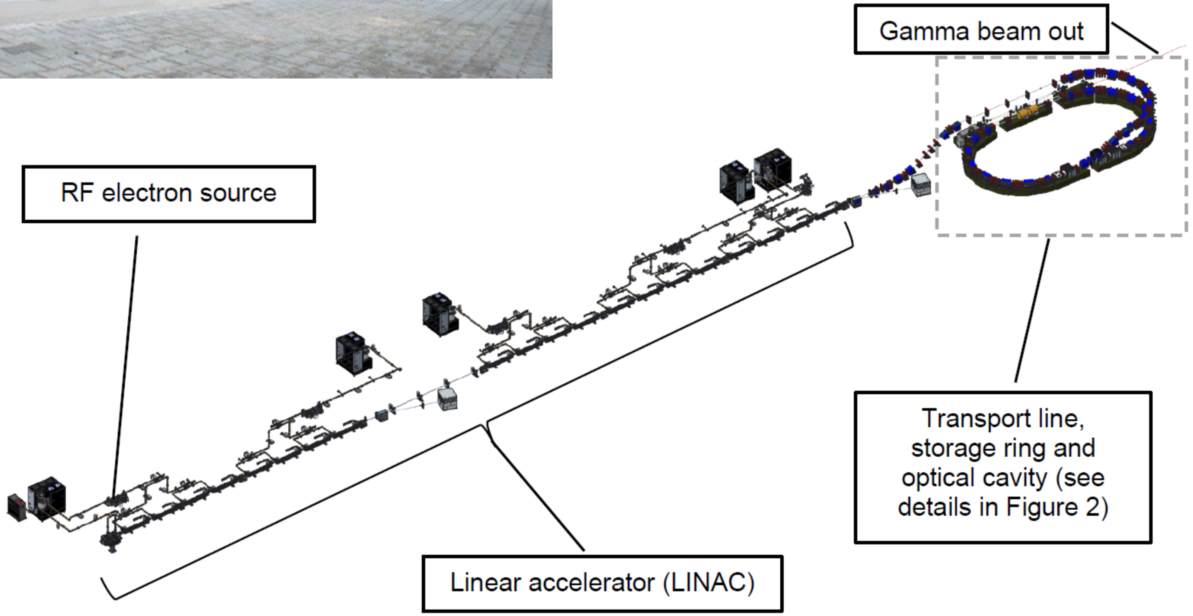
EXTREME LIGHT INFRASTRUCTURE AT BUCHAREST

ELI-NP with two 10-PW laser beams



VEGA status – January 2024





European infrastructure
World‘s highest-power laser in user operation

European LCB γ–beam under construction

Perspectives:

Towards a 4th generation gamma-ray source

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Perspectives:

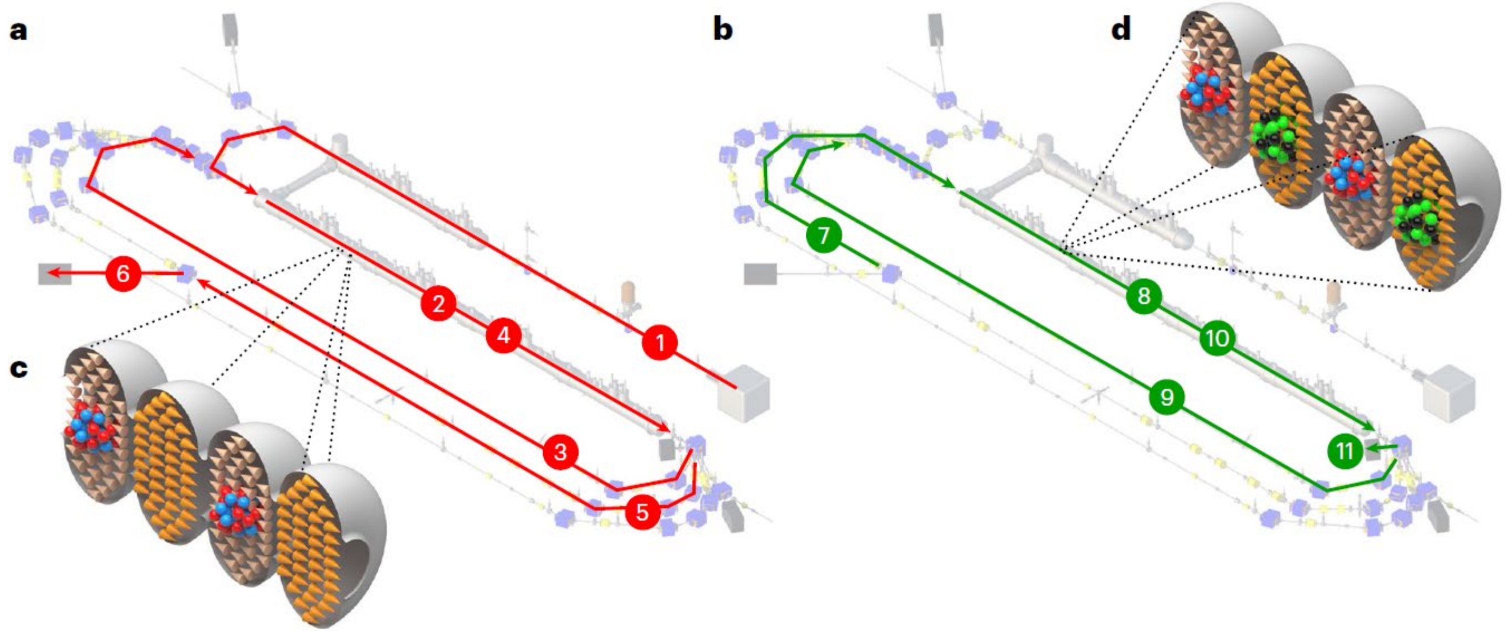
Towards a 4^{th} generation gamma-ray source

Use LINAC instead of storage ring! (for better emittance)

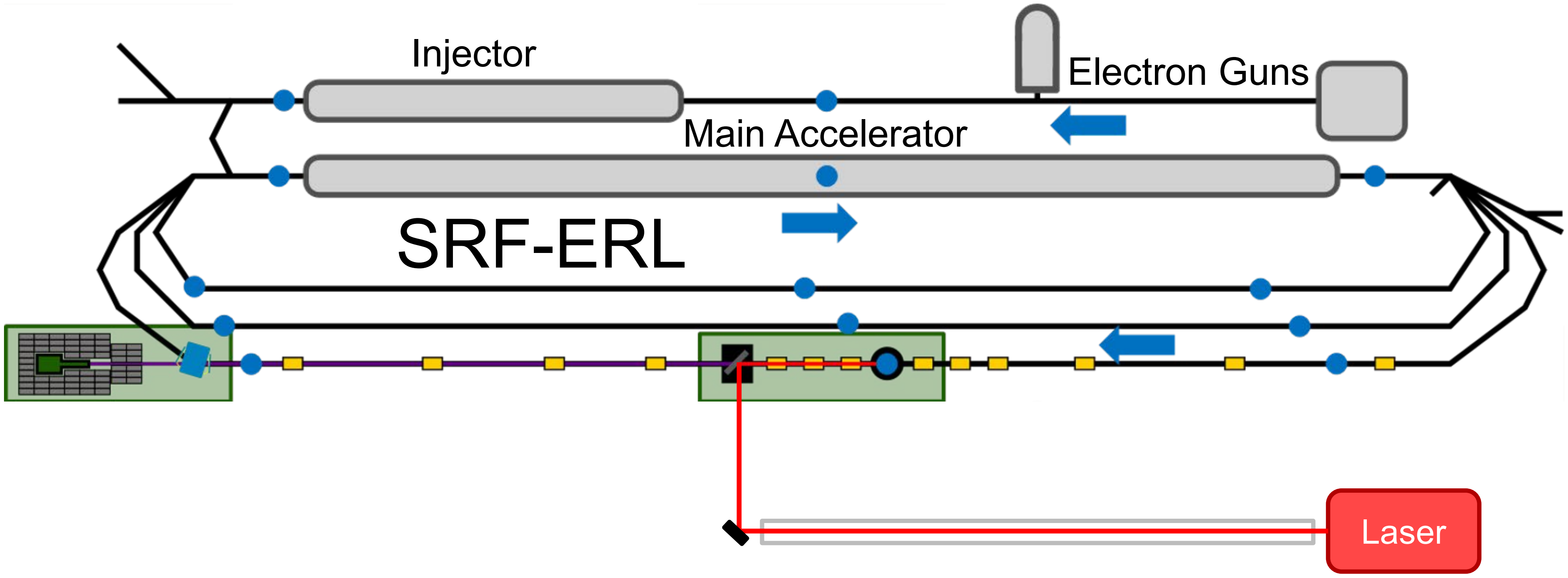
- High-current requires energy-recycling (requires superconductivity)
- High energy requires multiturn operation

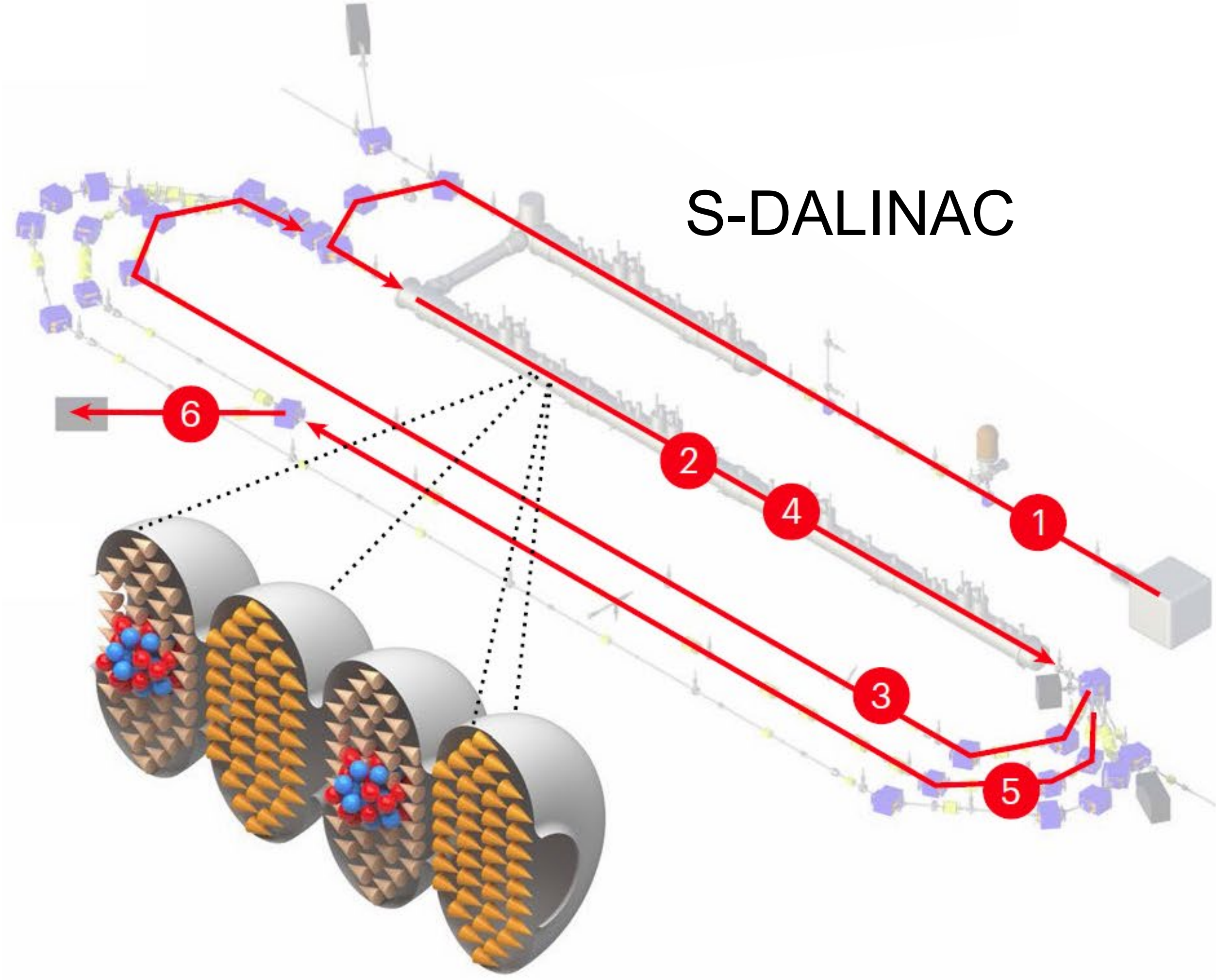
➢ “multiturn superconducting radio-frequency Energy-Recovery LINAC“ (**multiturn SRF-ERL**)

PRINCIPLE OF AN ENERGY-RECOVERY LINAC (ERL)



- LINAC provides best-possible emittance
- Largest luminosity requires largest-possible current
- Multi-turn SRF-ERL ideal as „photon-electron collider“
- Technology development towards „4th-generation light source“


Injector
Electron Guns
Main Accelerator
SRF-ERL
Laser



Conventional two-fold Acceleration (CTA)		
(1)	Injection	5.00 MeV/c
(2)	1^{st} acceleration	23.66 MeV/c
(3)	1^{st} recirculation	0° phase shift
(4)	2^{nd} acceleration	41.61 MeV/c
(5)	2^{nd} recirculation	0° phase shift
(6)	Beam dump	

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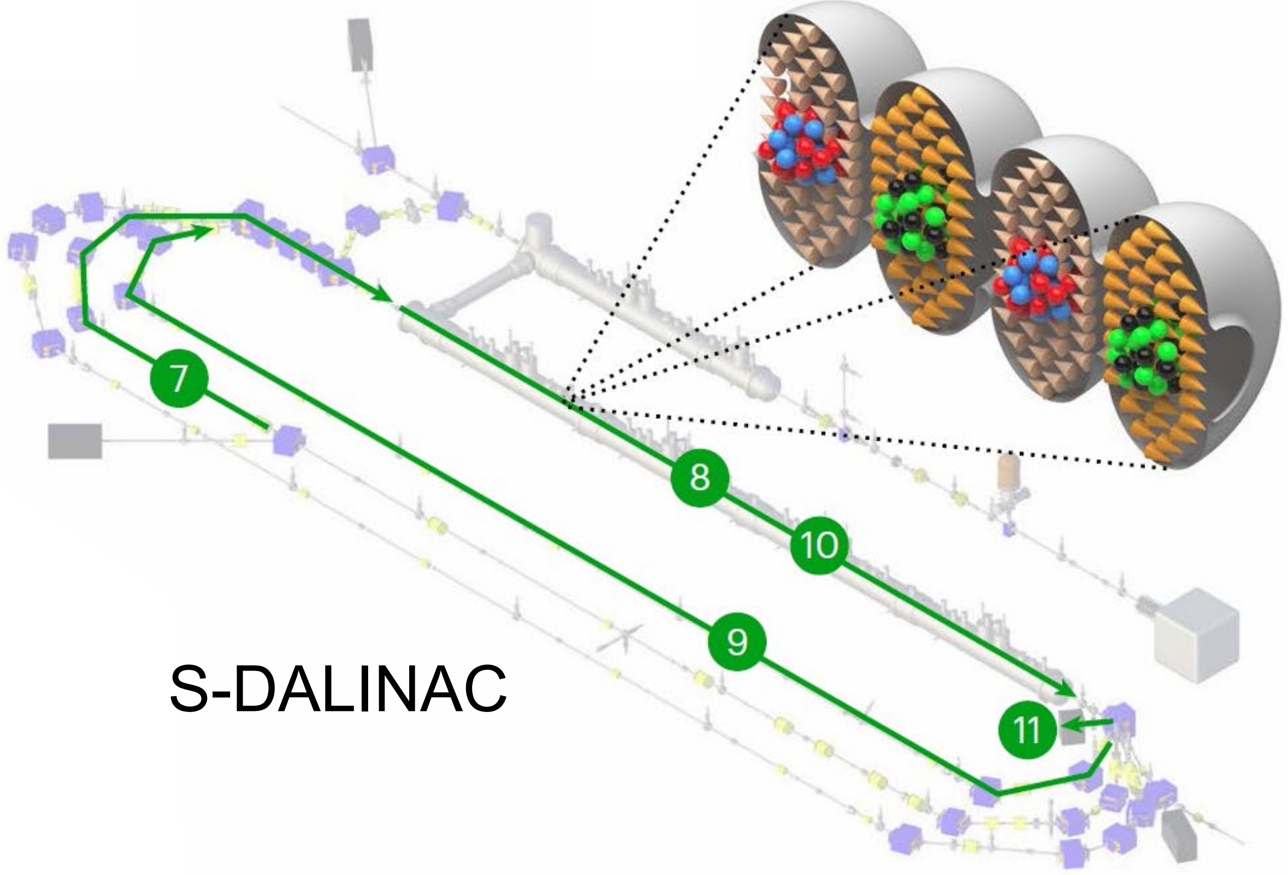
Two-fold Energy Recovery (TER)		
(1) – (6)	As before	41.61 MeV/c
(7)	2^{nd} recirculation	180° phase shift
(8)	1^{st} deceleration	23.66 MeV/c
(9)	3^{rd} recirculation	0° phase shift
(10)	2nd deceleration	5 MeV/c
(11)	Low energy beam dump	



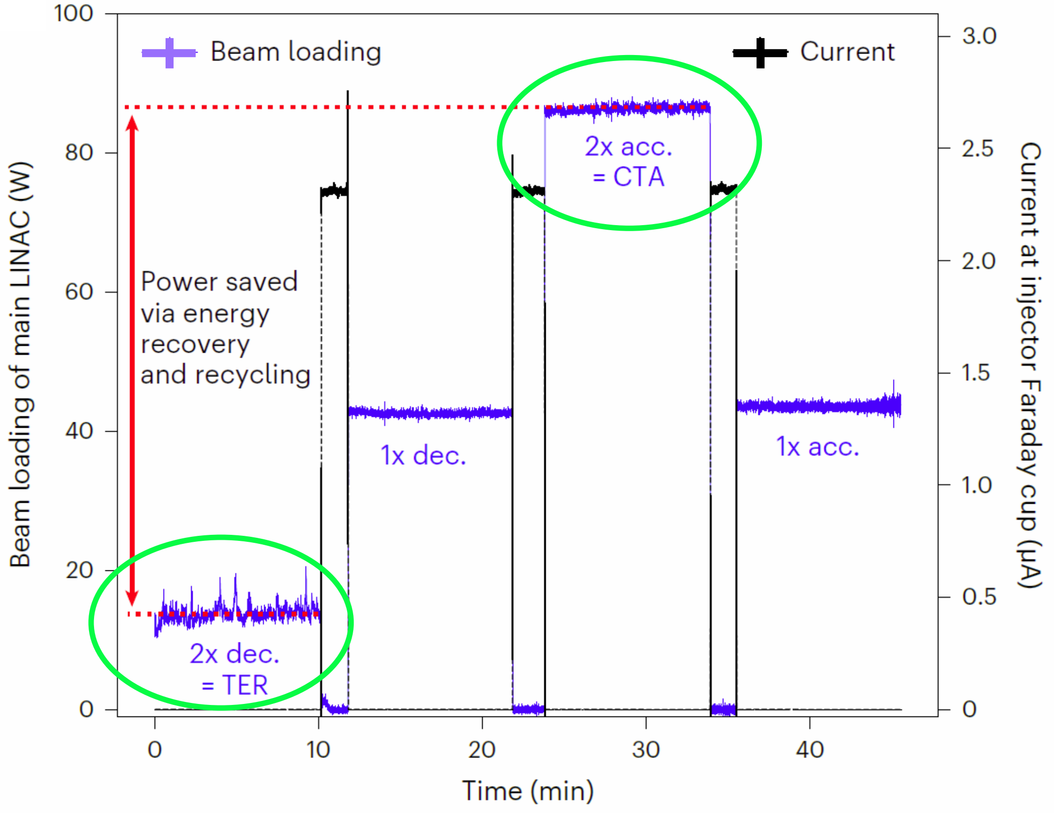
- Measurement of beam loadings of two-fold acceleration $P_{\mathrm{b,CTA}}$ and two-fold ERL $P_{\mathrm{b,TER}}$
- Energy recovery efficency

$$\eta = \frac{P_{\mathrm{b,CTA}} - P_{\mathrm{b,TER}}}{P_{\mathrm{b,CTA}}}$$

- Stable operation with beam current of 2.3 μA:

Mode	Beam loading
CTA	86.3 ± 0.3 W
TER	13.8 ± 1.1 W

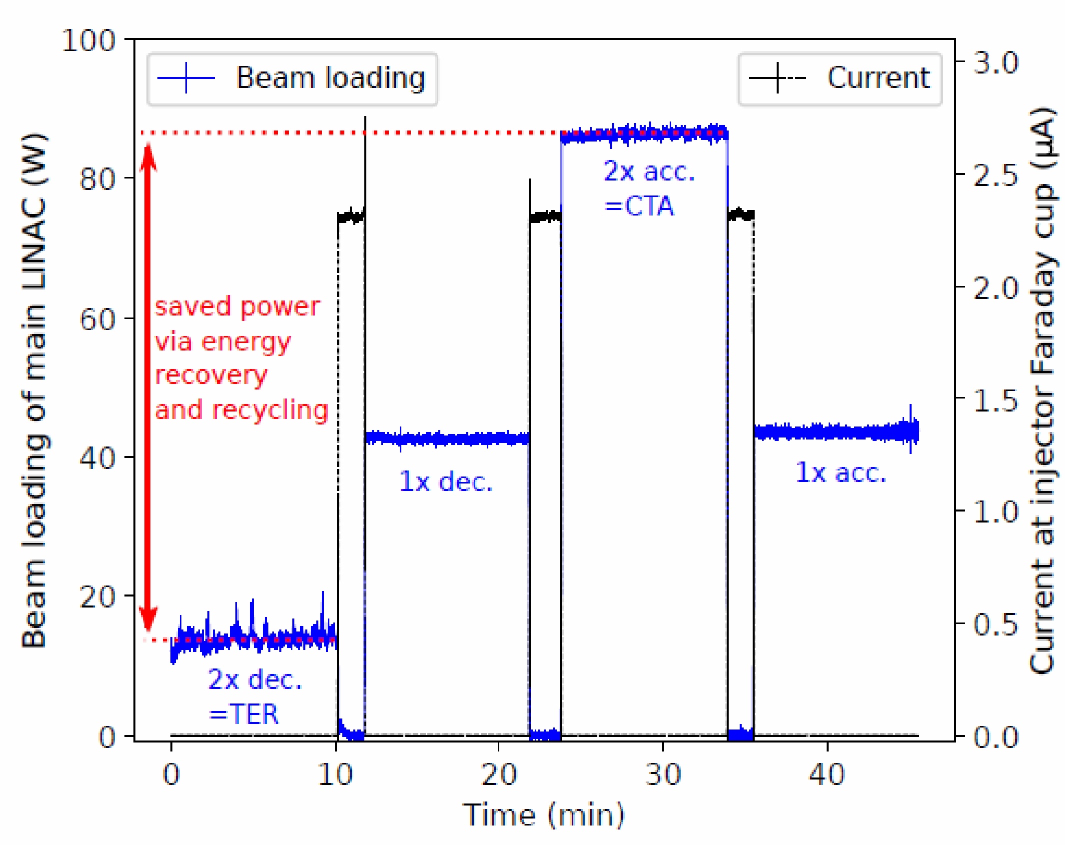
➢ $\eta = 84.0 \pm 1.2\%$

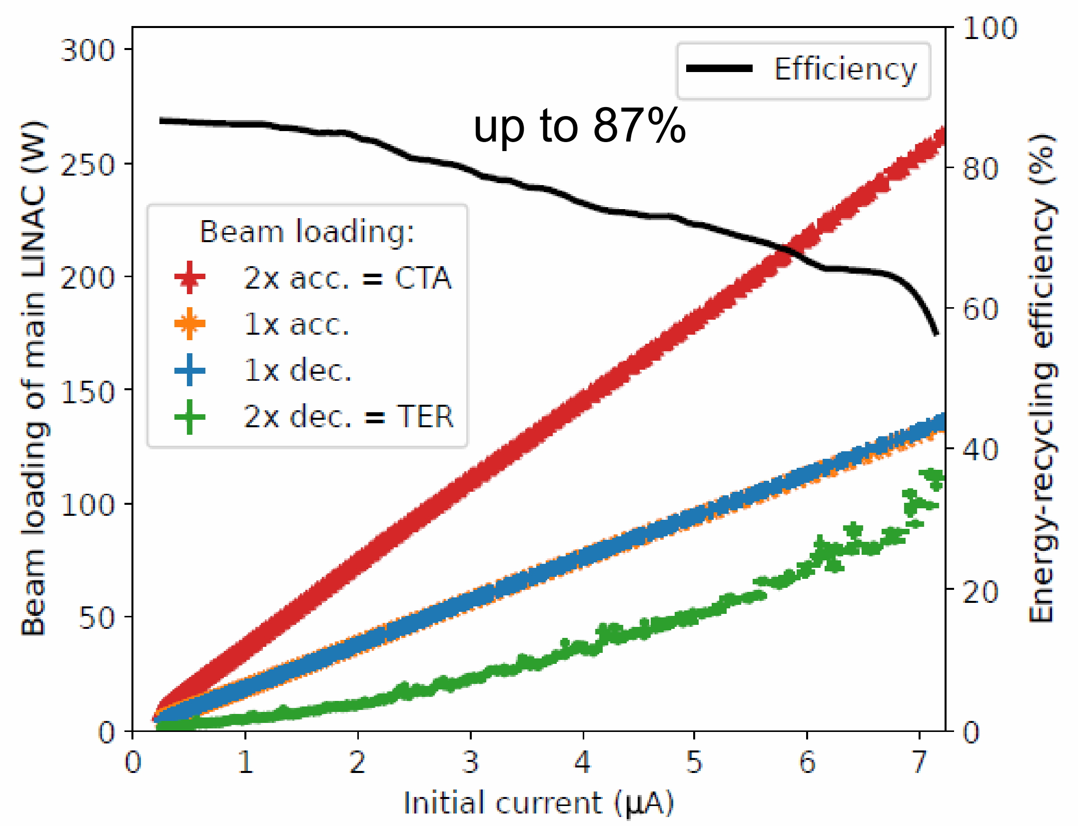


F. Schliessmann *et al.* Realization of a multi-turn energy recovery accelerator. *Nat. Phys.* **19**, 597 (2023).

https://doi.org/10.1038/s41567-022-01856-w

First direct measurement of energy recycling in a multiturn ERL





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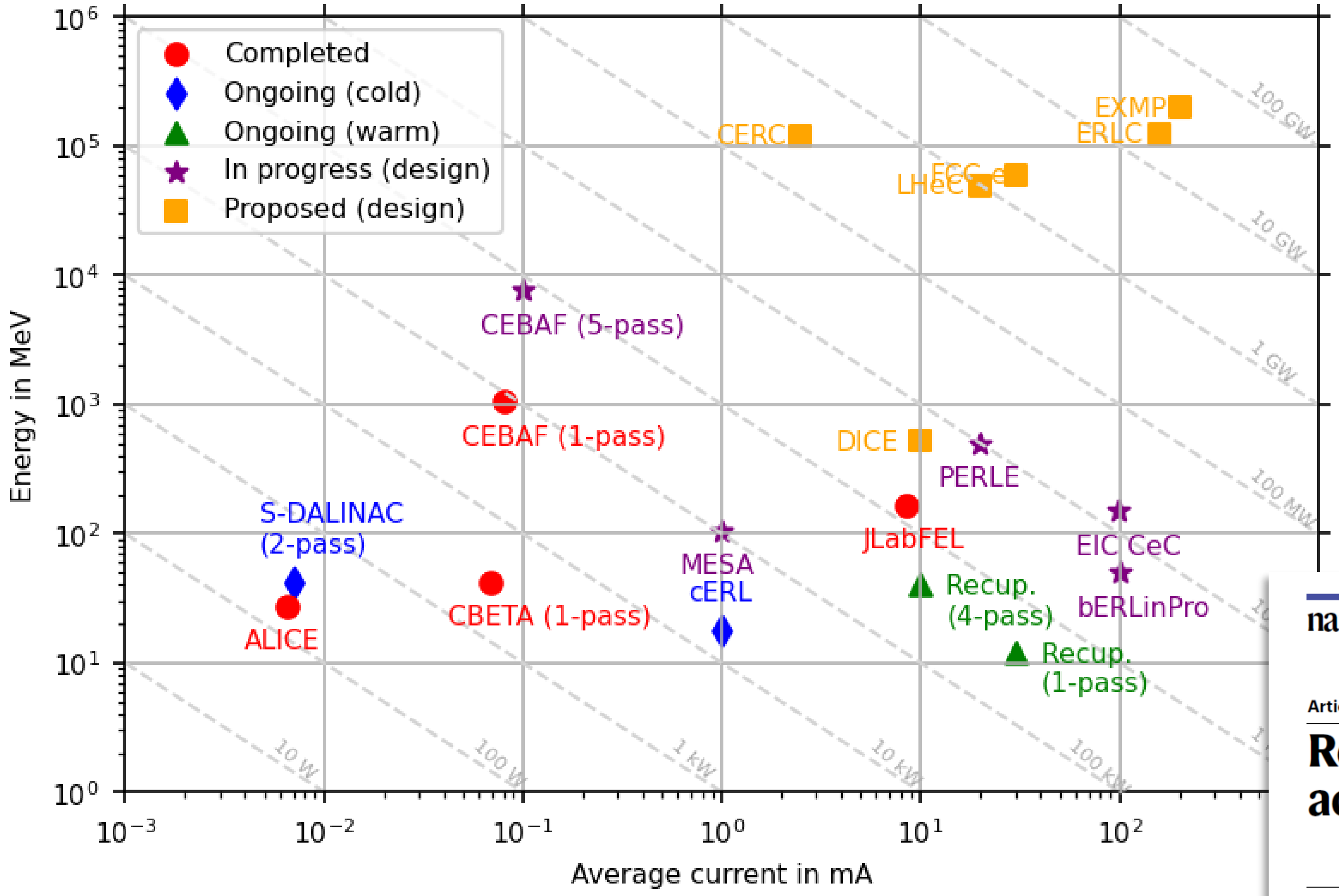
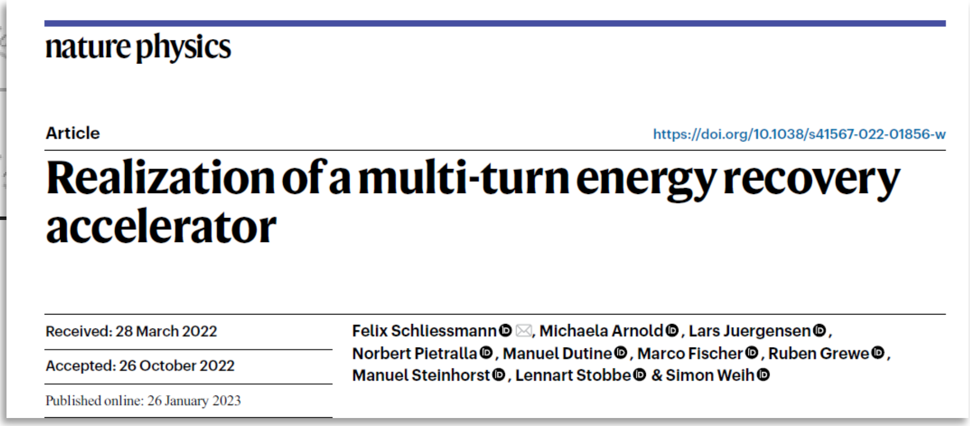


@S-DALINAC

Energy-recycling measured directly in multiturn SRF-ERL.

efficiency of up to 87% measured



nature physics

Article

https://doi.org/10.1038/s41567-022-01856-w

Realization of a multi-turn energy recovery accelerator

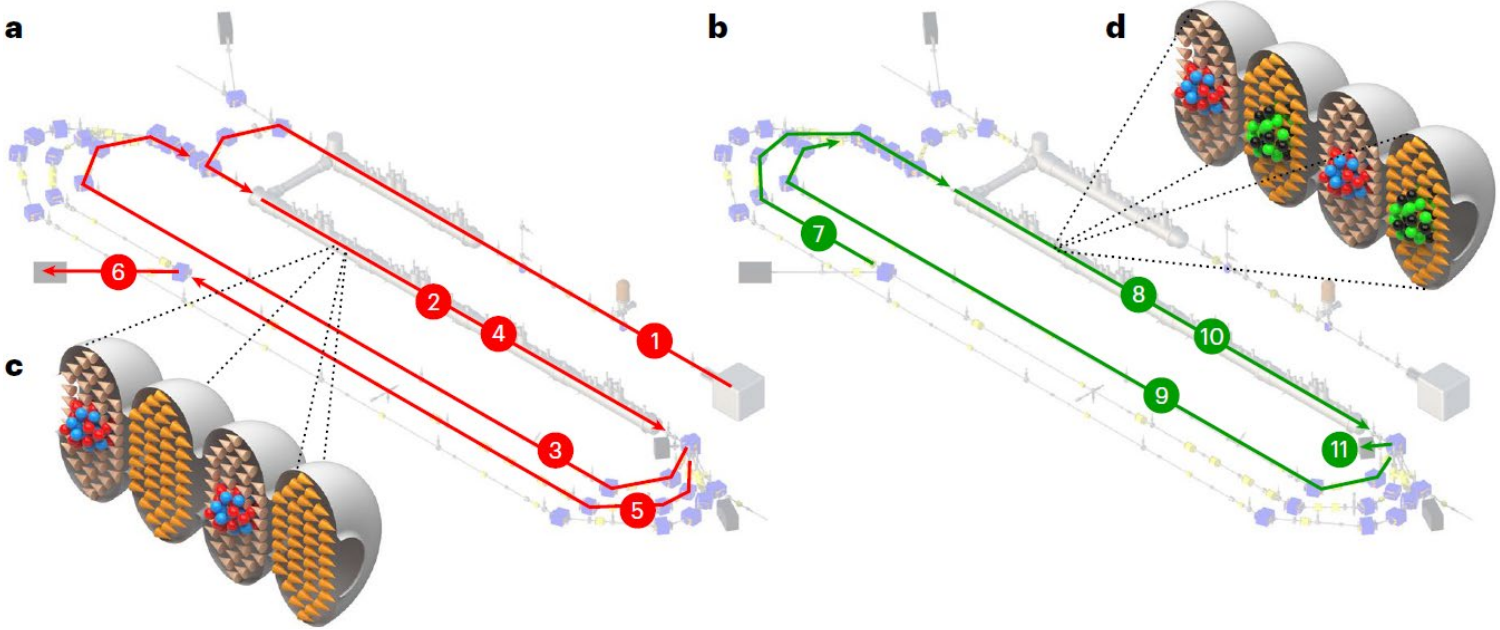
Received: 28 March 2022

Accepted: 26 October 2022

Published online: 26 January 2023

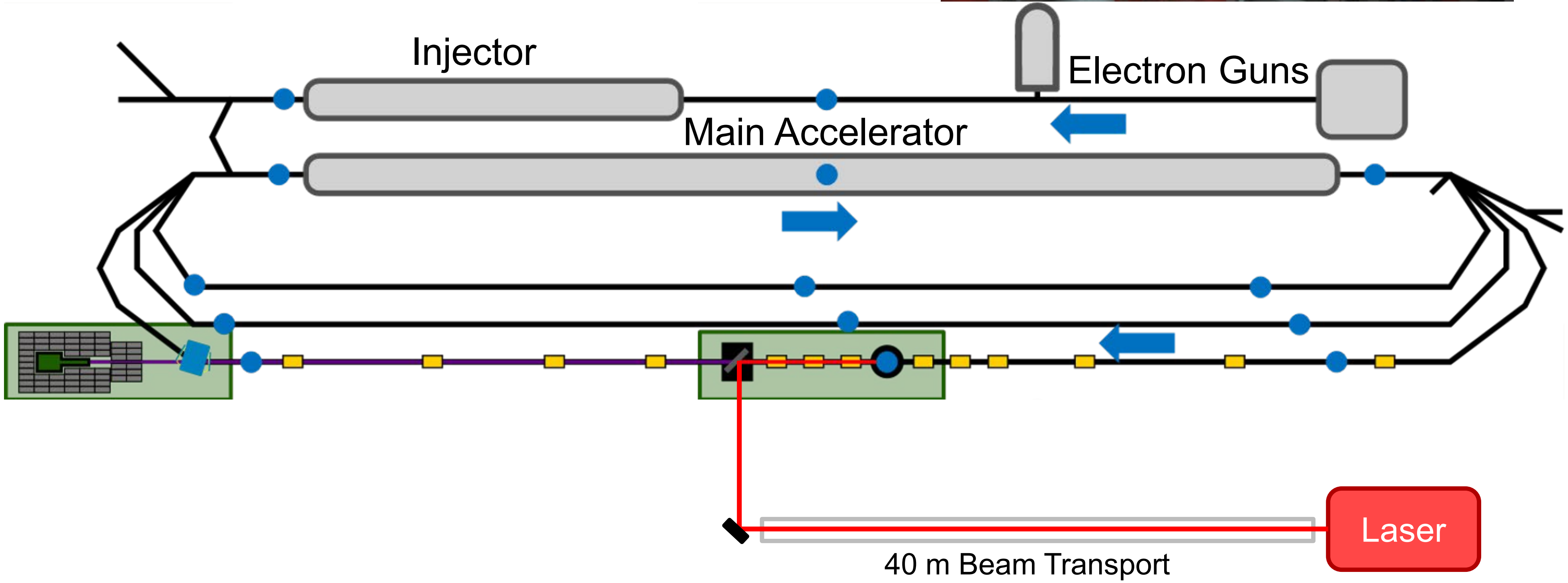
Felix Schliessmann, Michaela Arnold, Lars Juergensen, Norbert Pietralla, Manuel Dutine, Marco Fischer, Ruben Grewe, Manuel Steinhorst, Lennart Stobbe & Simon Weih

DEVELOPMENT TOWARDS 4TH-GENERATION LIGHT SOURCE



- Multi-turn SRF-ERL ideal as „photon-electron collider“
- Development of electron-laser interaction point
- Collision Laser delivered in July 2023

  FUGG INST 163/608-1 in the amount of 604 k€, DFG/State of Hesse



Higher photon energy preferred

Head-On Collision ✓

- For higher Energy
- Easier overlap

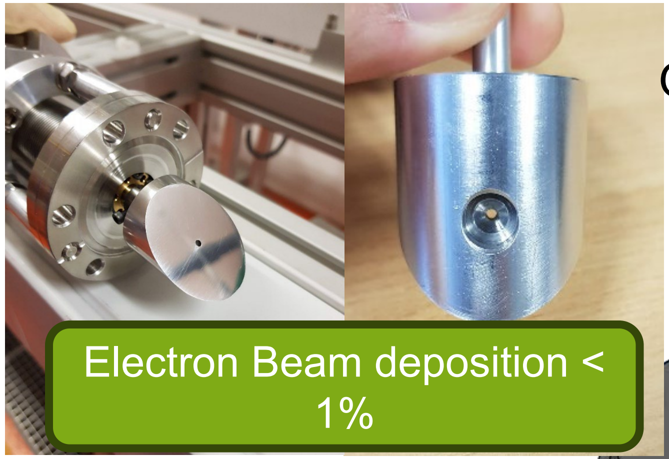
High Laser Pulse Energy (N_L)

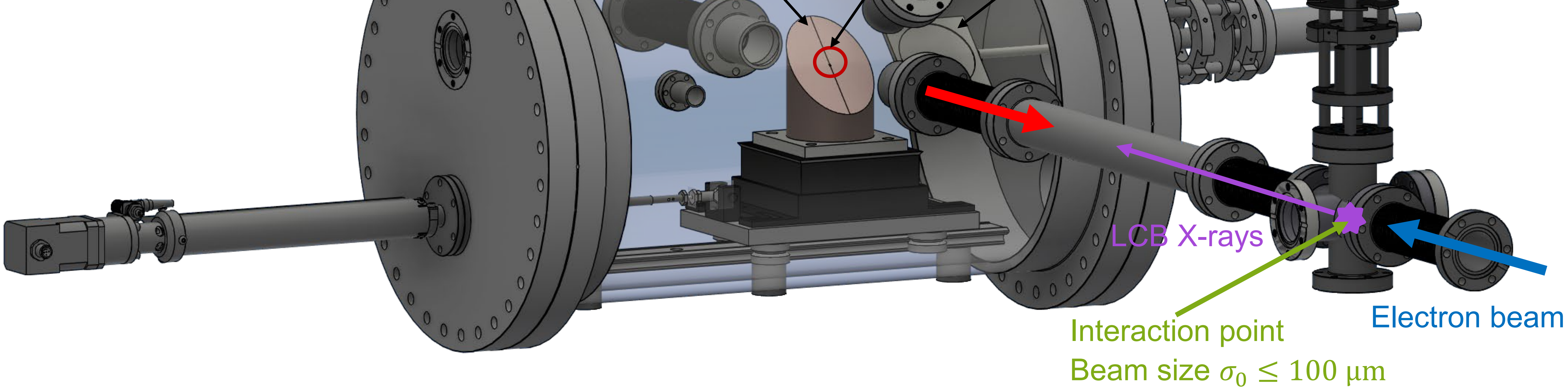
High scattering frequency (f)

Small beam size at IP

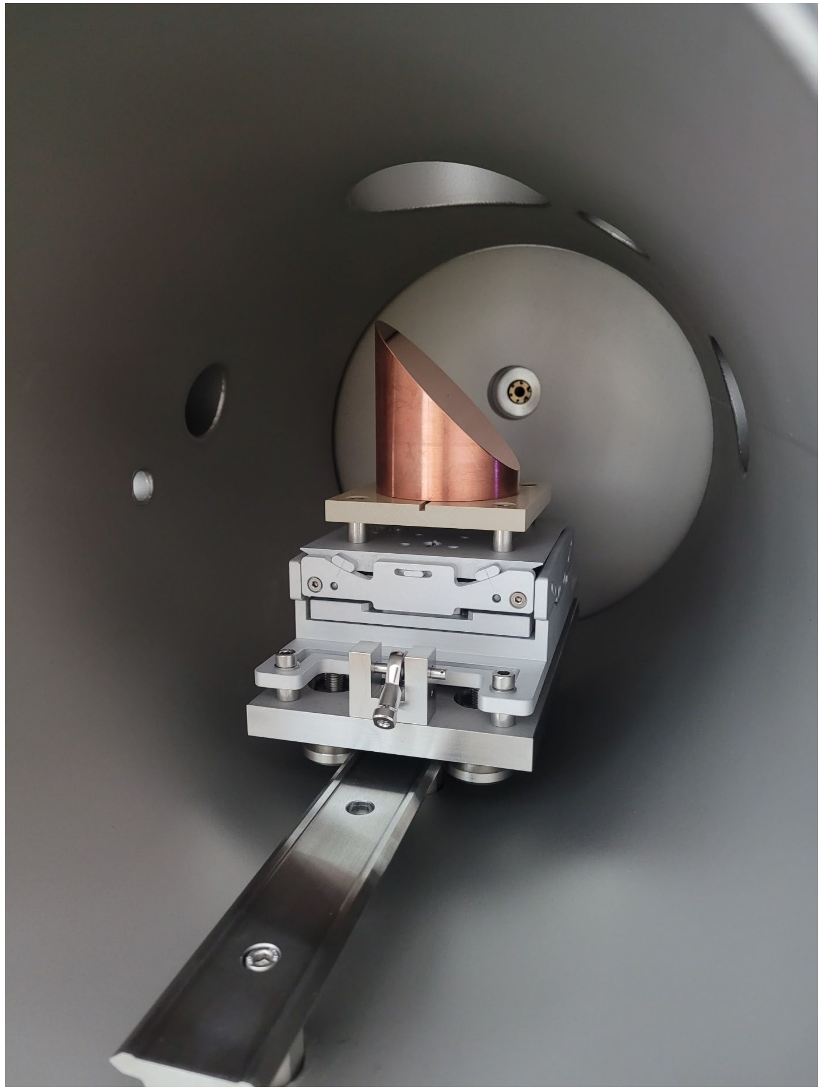
Low M^2

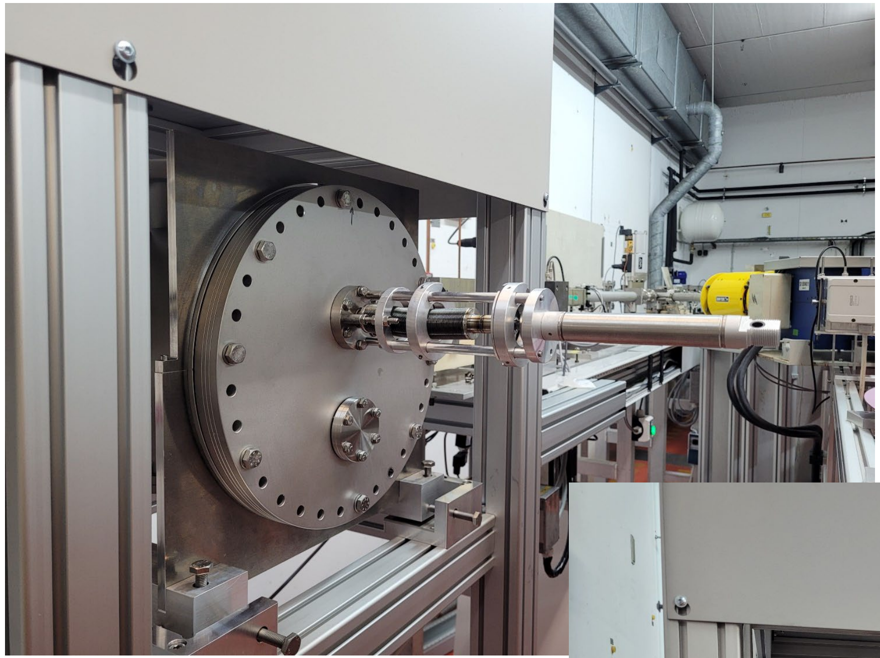
Low $\sigma_{\Delta E_p}$; $\frac{\sigma_{\Delta E_L}}{E_L} \leq \frac{\sigma_{\Delta E_e}}{E_e}$

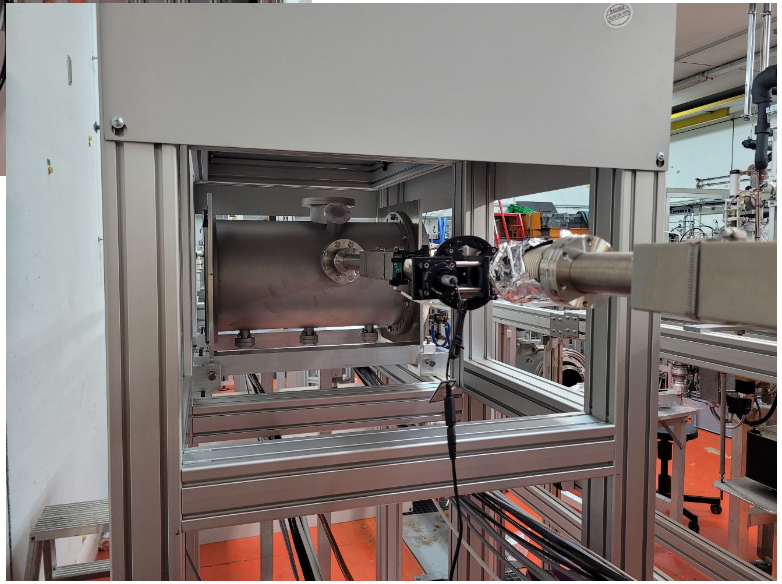

Electron Beam deposition < 1%

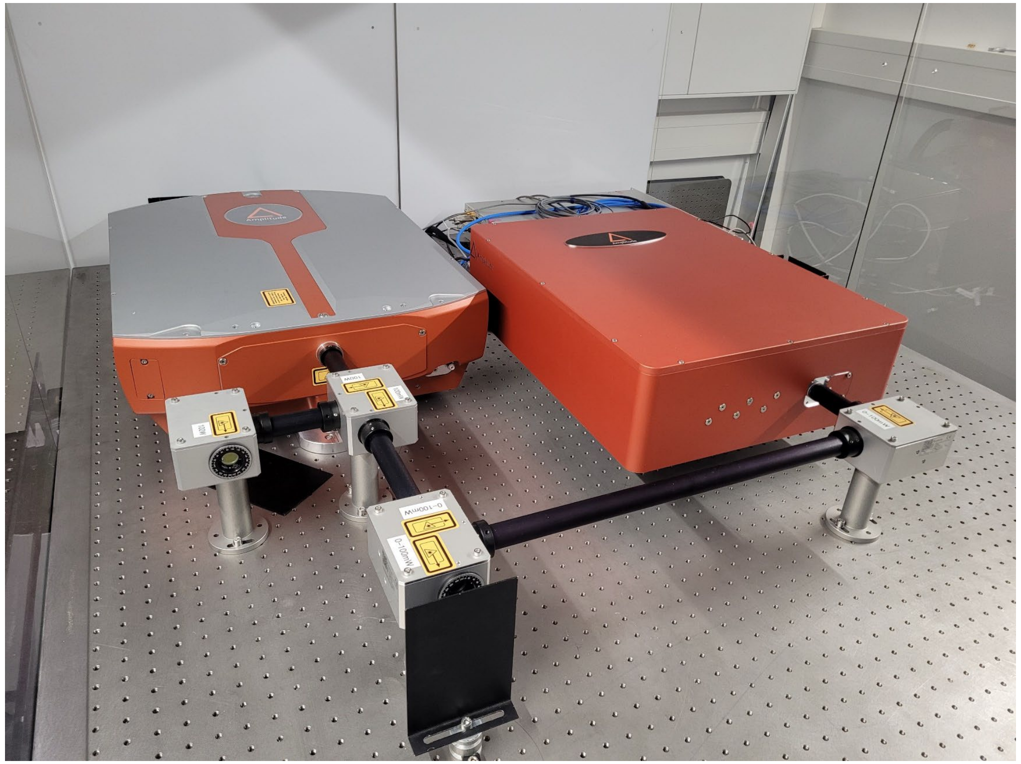

Off-Axis Parabolic Mirror
Laser
1.7 mm opening (Laser reflectivity 98 %)
Alignment target
LCB X-rays
Interaction point
Beam size $\sigma_0 \leq 100\ \mu\text{m}$
Electron beam

COUPLING CHAMBER OF LCB-SOURCE









FUGG INST 163/608-1 in the amount of 604 k€, DFG/State of Hesse

Amplitude – Laser Tangor 100

- λ =1030 nm (Ytterbium)
- $\frac{\Delta\lambda}{\lambda} \sim 2 \cdot 10^{-4}$
- P_{avg} =100 W
- $E_{Pulse} \leq 0.5$ mJ
- f =200 kHz – 40MHz
- $M^2 < 1.3$
- $\sigma_z = 3$ ps

Higher Harmonic Generation

- SHG: $\lambda = 515$ nm, $\eta > 50$ %
- THG: $\lambda = 343$ nm, $\eta > 25$ %

Higher photon energy preferred

Head-On Collision ✓

- For higher Energy
- Easier overlap

High Laser Pulse Energy (N_L) ✓

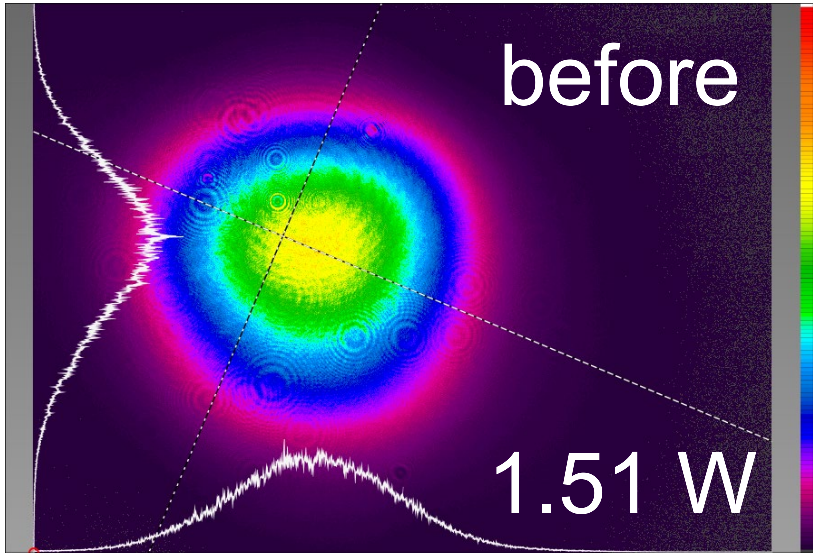
High scattering frequency (f) ✓

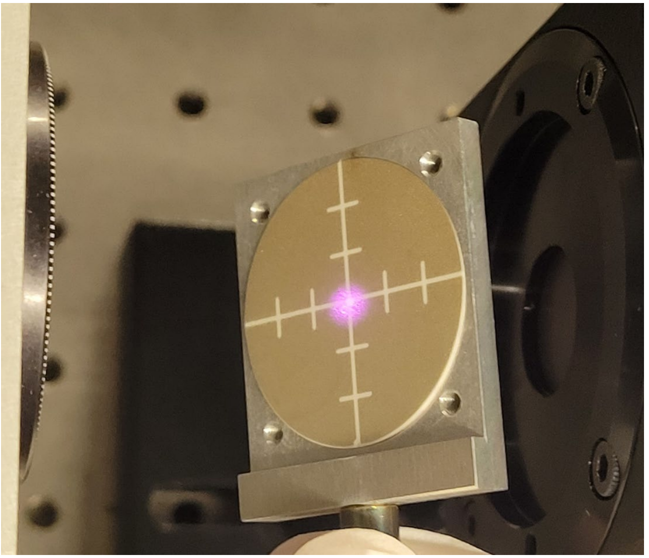
Small beam size at IP ✓

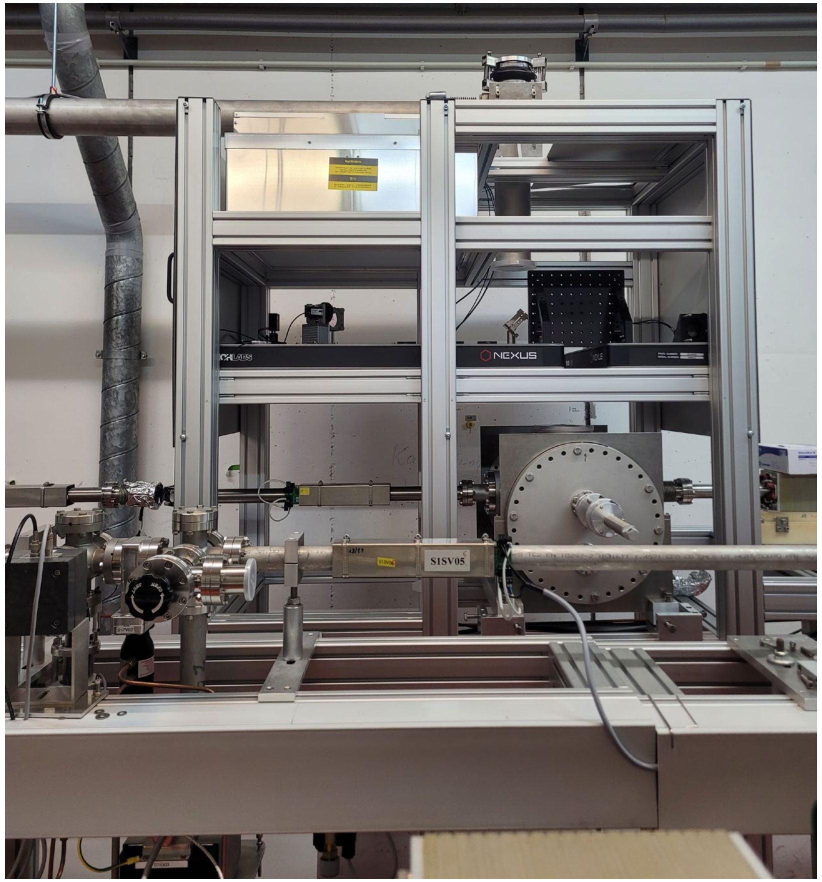
Low M^2 ✓

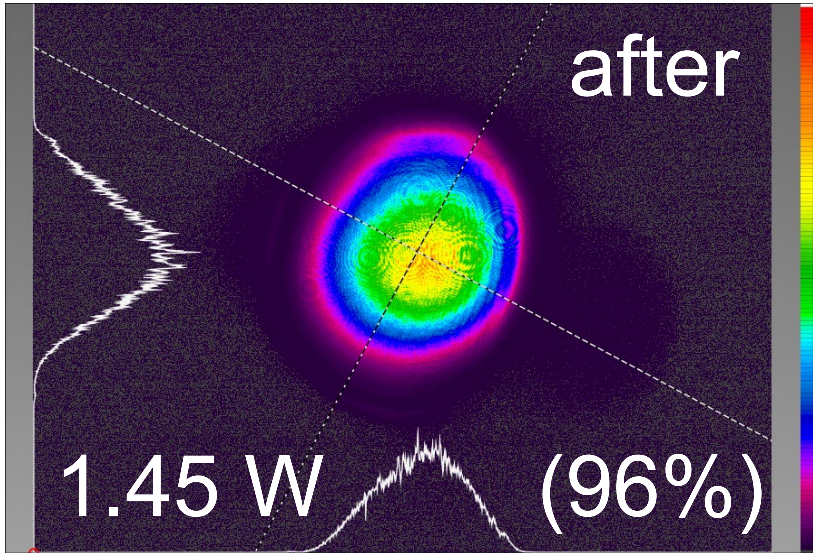
Low $\sigma_{\Delta E_p}$; $\frac{\sigma_{\Delta E_L}}{E_L} \leq \frac{\sigma_{\Delta E_e}}{E_e}$ ✓

LASER BEAM TRANSPORT









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Nuclear Photonics IRTG 2891

Perspectives:

Preparing the next generation science leaders

International Research Training Group GRK 2891

(TU Darmstadt – UNSTP Bucharest)

SCIENCE PROGRAM OF INT'L RESEARCH TRAINING GROUP

laser physics
plasma physics

- Enhancing laser fields by complex targets
- Laser-driven γ–ray and neutron production

accelerator physics

- Tailored laser pulses for particle acceleration
- Spectral control in laser-driven ion acceleration
- Developments for brilliant γ–ray sources
- Instrumentation towards a 4th generation γ–ray source

nuclear theory

- Dipole response of heavy nuclei: PDR & GDR
- Photonuclear reactions on actinides and fission dynamics
- Nuclear astrophysics with photonuclear reactions

experimental nuclear physics

- High-precision nuclear structure and statistical properties

➢ Each topic consists of 4 interrelated research-training projects

➢ All projects commonly supervised at Darmstadt and at Bucharest

Nuclear Photonics

PHD POSITIONS CONTINUOUSLY AVAILABLE

110 PhDs in Nuclear Photonics until 2033

Cohort structure at TUDa

	Σ	First funding period					Second funding period			
		Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9
Cohort 1 *"Grp A"*	11 +2									
Cohort 1 *"Grp B"*	2 +2									
Cohort 1 *"Grp C"*	2 +1									
Cohort 2 *"Grp A"*	11 +2									
Cohort 2 *"Grp B"*	2 +2									
Cohort 2 *"Grp C"*	2 +1									
Cohort 3 *"Grp A"*	11 +2									
Cohort 3 *"Grp B"*	2 +2									

additional opportunities for late-comers

start of new cohort after 3 years

57 PhD positions @ TU Darmstadt

Recruitment procedure

- visit web-page
- apply for PhD position
- ranking for
  - ✓ application documents
  - ✓ interviews
- feedback from IRTAB
- decision in Board of RTs

Equivalent recruitment procedure at Bucharest

TECHNISCHE UNIVERSITÄT DARMSTADT

SUMMARY

1 **Status**: Recent Examples on Contemporary Topics of Nuclear Structure Physics

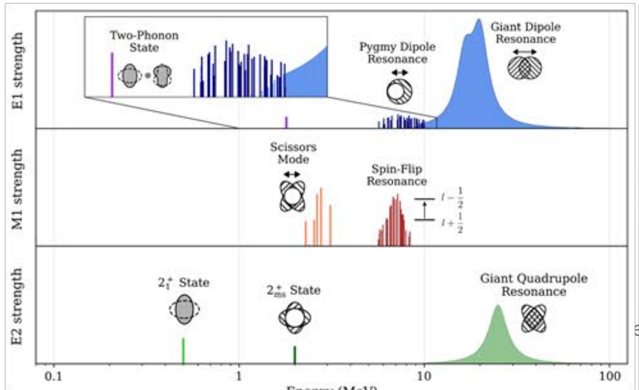
A) E2: Quadrupole collectivity of Sn isotopes (**NRF relative to calibration standard**)

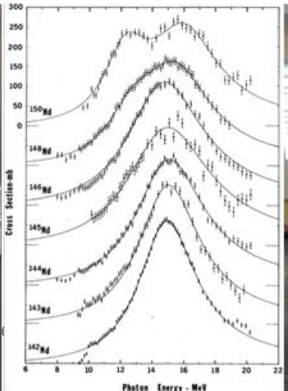
B) M1: Evidence for 2-body currents (**generation of a standard: Relative Self-Absorption**)

C) E1: γ-decay of the Giant Dipole Resonance (**NRF beyond particle separation threshold**)

2 **Perspectives**: Accelerator Technology towards a 4th-generation γ–ray Source (**ERL-LCB**)

3 **Perspectives**: International Research Training of next-generation Scientists





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3 **Perspectives**: International Research Training of next-generation Scientists

Thank you very much!

in memoriam Prof. Ulli Kneißl