Nuclear Photonics:
Basic facts, opportunities, and limitations

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TECHNISCHE UNIVERSITÄT DARMSTADT

SFB 634

SFB 1245

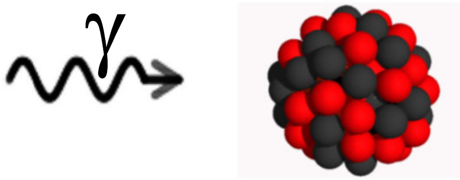
GRK 2128

ACCELENCE

Nuclear Photonics:

An attempt of a definition

„***Nuclear Photonics*** is the cross-disciplinary field of Physics and Engineering which addresses ***controlled*** photo-nuclear reactions with artificial γ-ray beams and their applications.“



„controlled“

- excitation / manipulation of single nuclear quantum states / groups of states

„artificial gamma-ray beams“

- usage of artificially shaped γ-ray beams w.r.t. spectral intensity profile

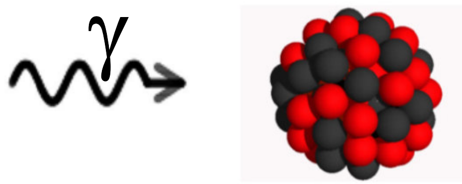
„cross-disciplinary“

- integrates techniques from nuclear physics, quantum optics, accelerator science

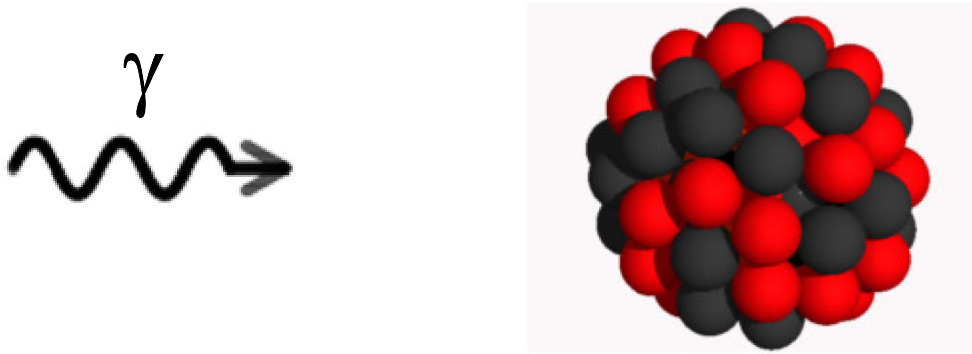
Very boldly: “Nuclear Photonics is a newly emerging field of science.”

Outline

- **Basic facts on Photonuclear Reactions**
    - Size of photonuclear cross sections
    - Gamma-ray beam – target interaction
    - Examples
        - Selective excitation of nuclear quantum states
        - Applications in Nuclear Resonance Fluorescence
- **Manipulation of spectral intensity profile**
    - Nuclear Self-Absorption
    - Examples
- **Limitations**
- **Conclusion**



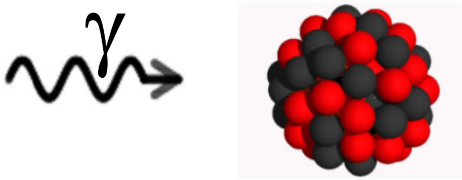
Photonuclear Reactions



What happens?

Elastic Scattering: Nuclear Thomson

Klein-Nishina:
$$\frac{d\sigma_{pol}}{d\Omega}(\vartheta,\varphi) = \frac{1}{2} r_0^2 \left(\frac{E'_\gamma}{E_\gamma}\right)^2 \left[\frac{E'_\gamma}{E_\gamma} + \frac{E_\gamma}{E'_\gamma} - 2\sin^2\vartheta\cos^2\varphi\right]$$



$$r_0 = \frac{\alpha \hbar c}{Mc^2}$$

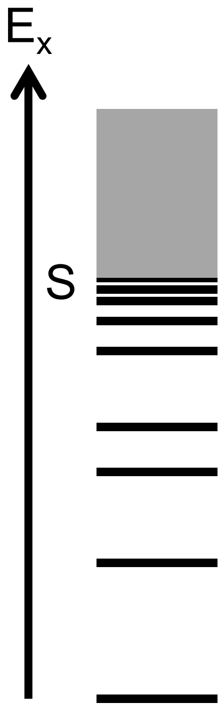
typical Compton cross section: **40 mb** (per electron)

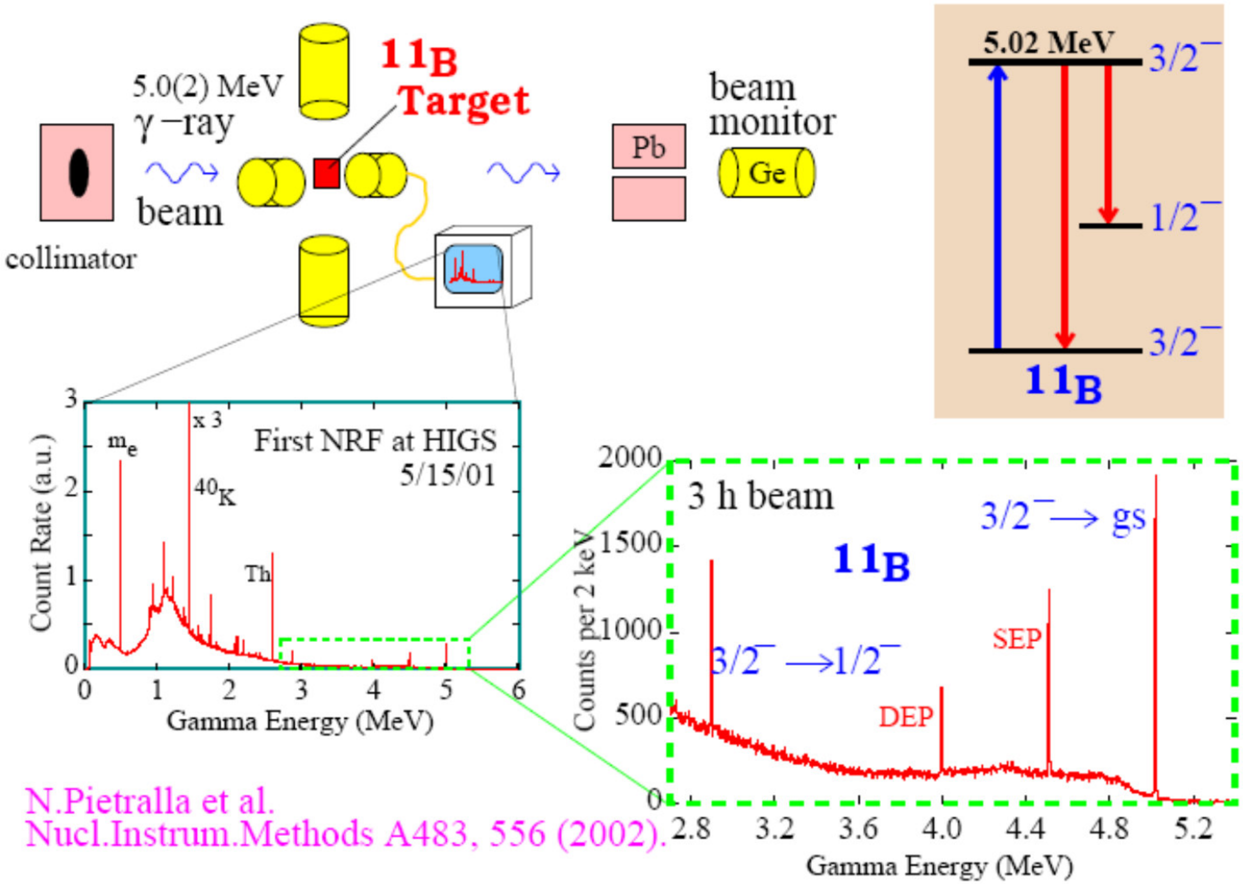
typical Nuclear-Thompson cross section (A=50): **4 pb**

10 orders of magnitude smaller, because $M_{A=50} / m_e = 10^5$

$\rightarrow$ focus here on inelastic scattering

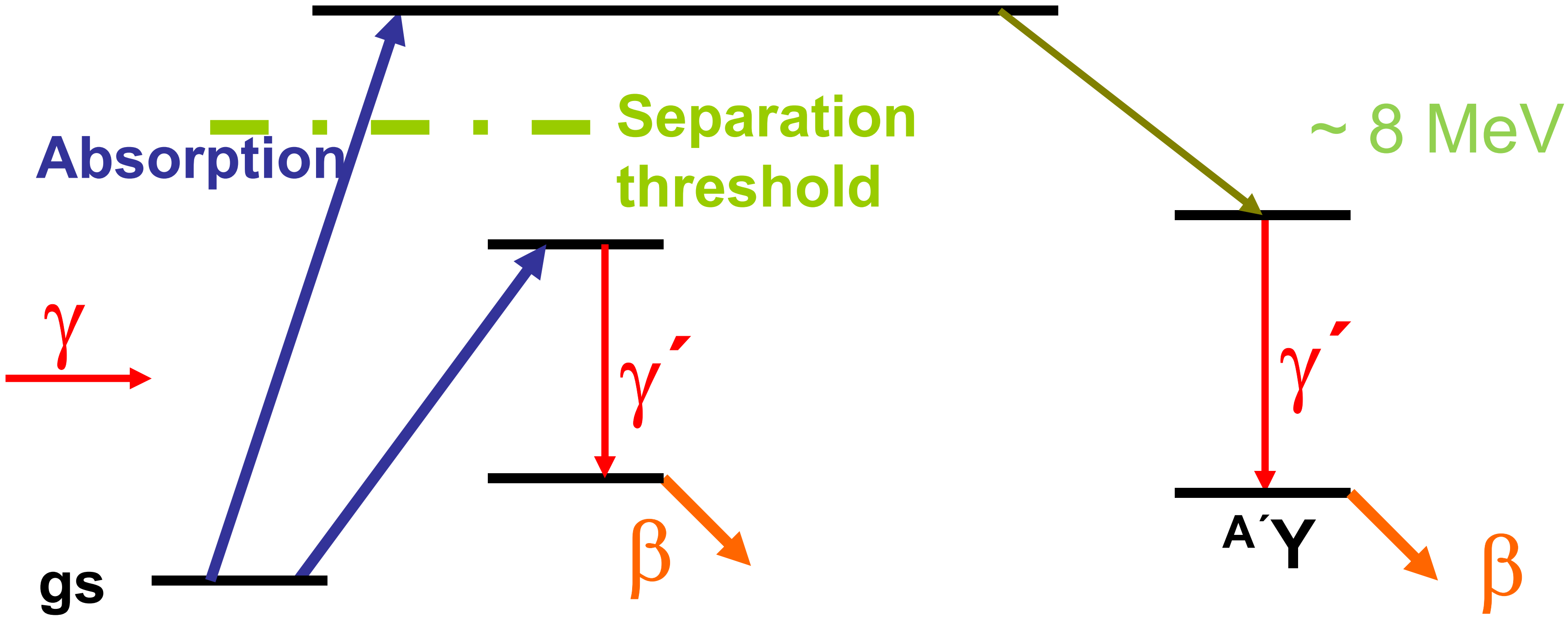
Inelastic scattering: Resonance Scattering





N.Pietralla et al.
Nucl.Instrum.Methods A483, 556 (2002).

Photonuclear Reactions



^{A}X

Nuclear Resonance Fluorescence (NRF)

Photoactivation

Photodesintegration (-activation)

Photofission

Photonuclear reactions in the continuum

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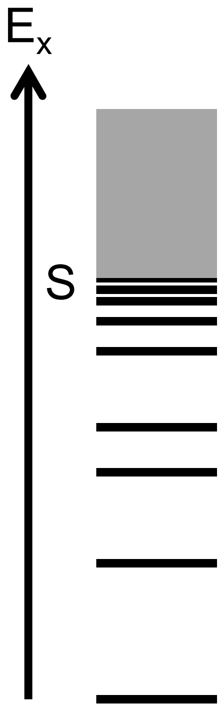
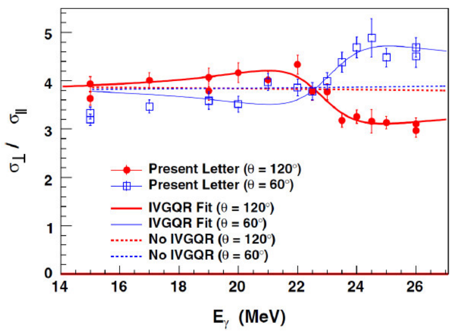
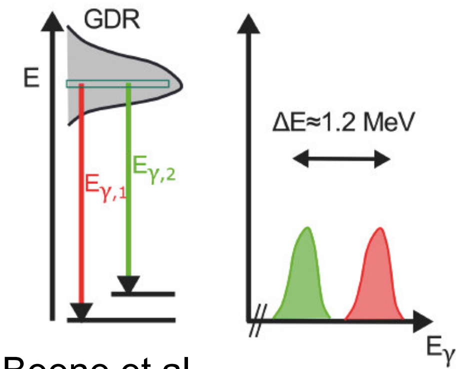


- (semi-)continuous-energy ejectiles
- energy-resolution obtained from incident γ-ray beam
- physics cases:
  - fine structure in the continuum
  - continuum-decay modes
  - multipole decomposition of resonances
- examples



S.Henshaw et al. (HIγS)



Beene et al.
Krasnahorkay, Ponomarev

Nuclear Resonance Fluorescence (NRF)

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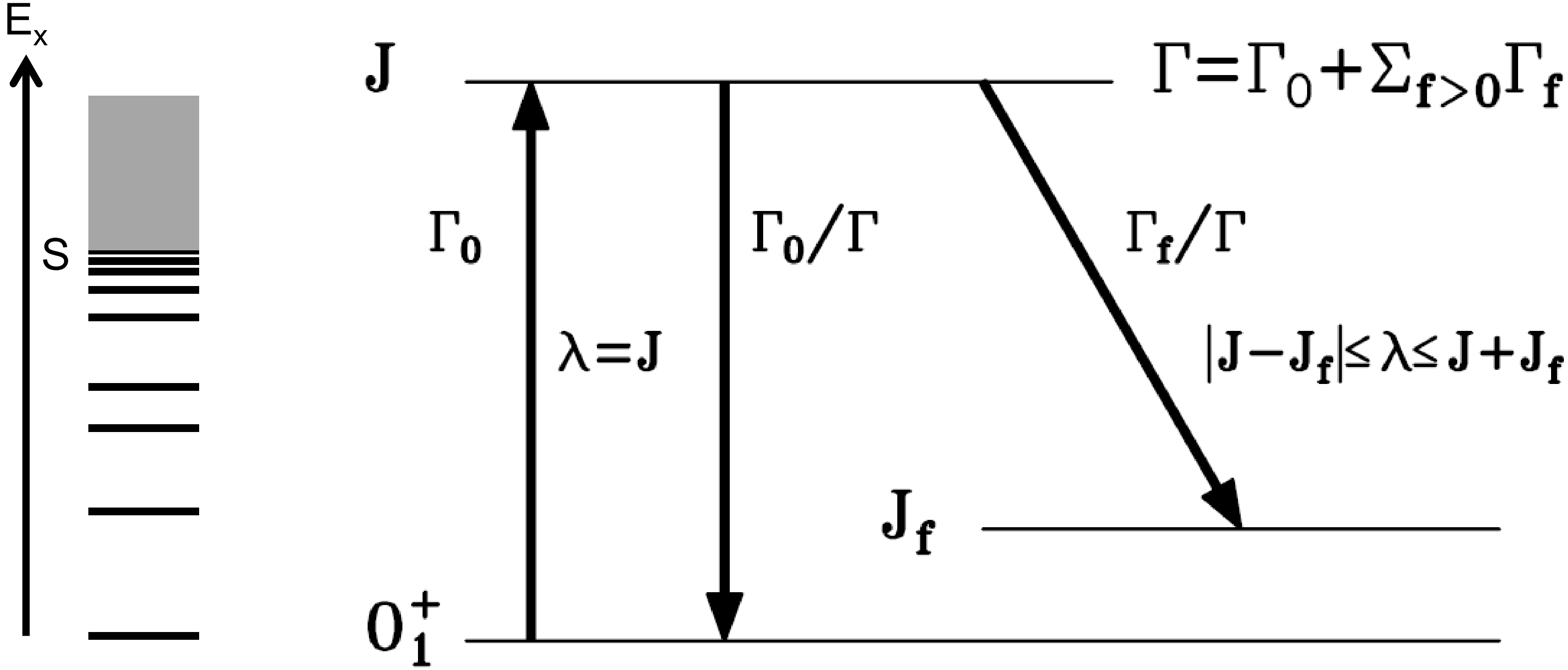

Metzger, Proc. Nucl. Phys. 7, 54 (1959).
Kneissl, Pitz, Zilges, Prog. Part. Nucl. Phys. 37, 349 (1996).
Kneissl, Pietralla, Zilges, J. Phys. G 32, R217 (2006).

NRF cross section

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- Breit-Wigner absorption resonance curve for isolated resonance
  - radioactive decay law and Fourier transform: $\Psi(t) \rightarrow \Psi(E)$

$$\sigma_a(E) = \pi \bar{\lambda}^2 \frac{2J+1}{2} \frac{\Gamma_0 \Gamma}{(E-E_r)^2 + (\Gamma/2)^2} = \frac{\sigma_0}{1 + (\frac{E-E_r}{\Gamma/2})^2} \quad \sim \Gamma_0/\Gamma$$

- On resonance ($E=E_r$) cross sections are very large.

$\rightarrow$ $\boldsymbol{\sigma_0 \cong}$ **200 b** (for $\Gamma_0=\Gamma$, E = 5 MeV)

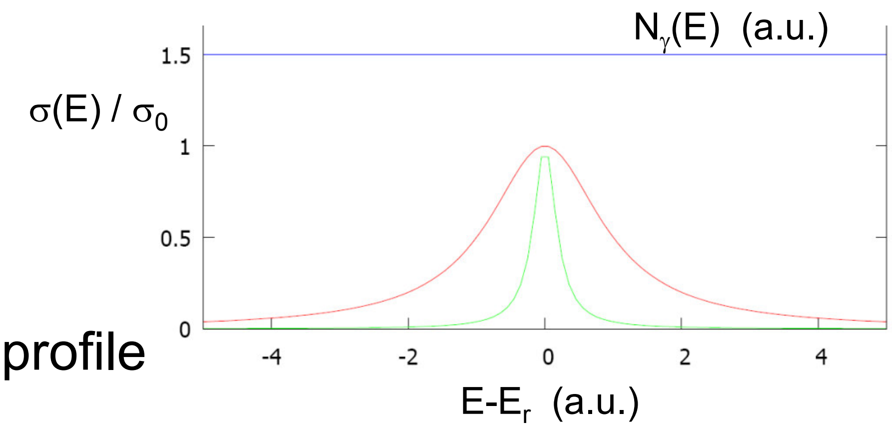
- Irrespective of multipolarity !
- However, resonances are very narrow (Γ_0)

NRF cross section

- Photonuclear excitation widths Γ_0 depend on nuclear wave functions

$$\Gamma_0 = c_\lambda \left(\frac{E_\gamma}{\hbar c}\right)^{2\lambda+1} |\langle \Psi_f \| \hat{T}_{\pi\lambda} \| \Psi_i \rangle|^2$$

- with typical widths Γ_0 for photonuclear excitations
  (use Weisskopf estimate for A=50 and use E=5 MeV)
  - E1 (use 1 mW.u.): 0.1 eV
  - M1: 2.6 eV
  - E2: 30 meV
  - M2: 0.6 meV
  - E3: 4 μeV

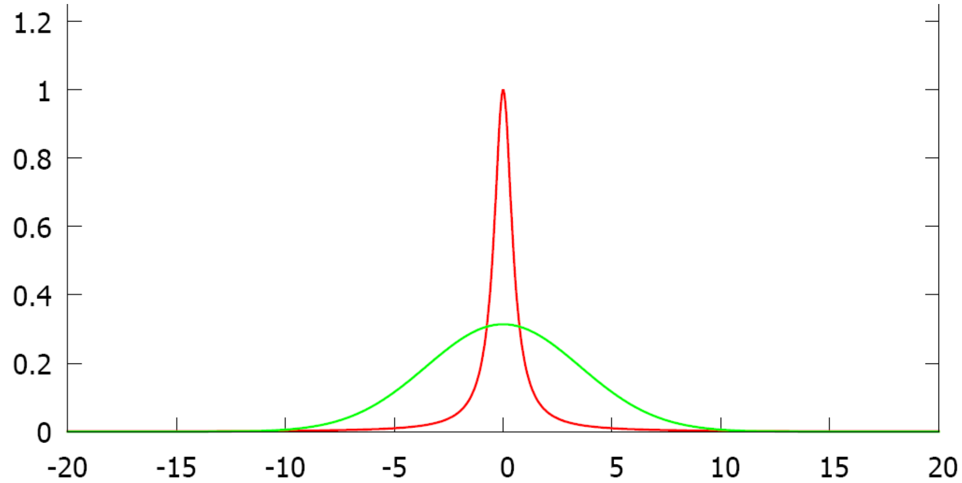


- much more narrow than photon beam profile
- → Integrated cross section

NRF cross section

Thermal motion of target nuclei lead to Gaussian Doppler-broadening of resonance (typical Doppler width $\Delta \approx$ few eV $> \Gamma$)

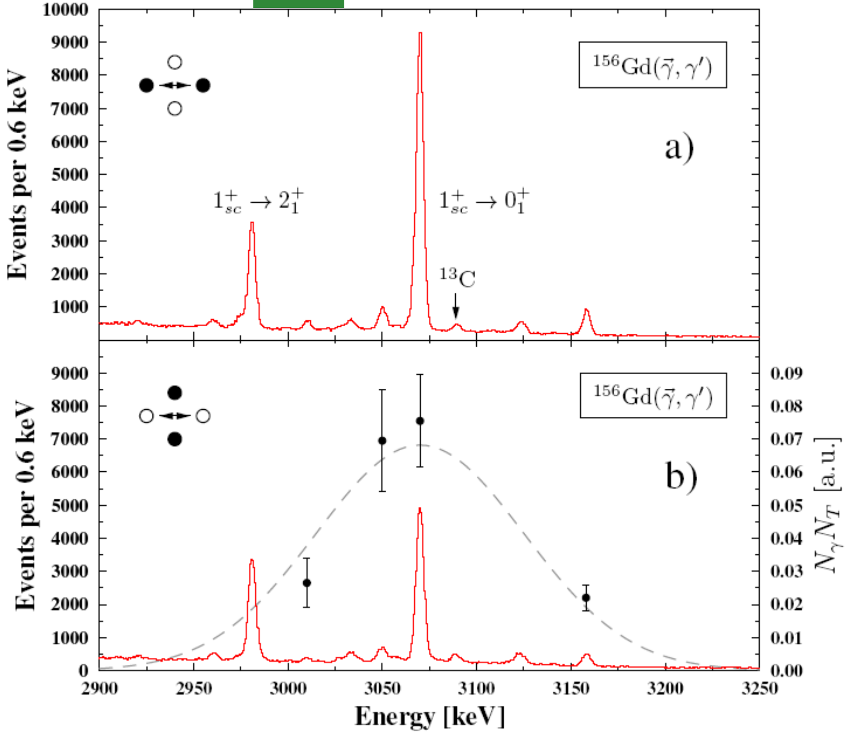
$$\sigma_a^D(E) = \frac{\pi}{2}\,\sigma_0\,\frac{\Gamma}{\Delta}\,e^{-\left(\frac{E-E_r}{\Delta}\right)^2}$$



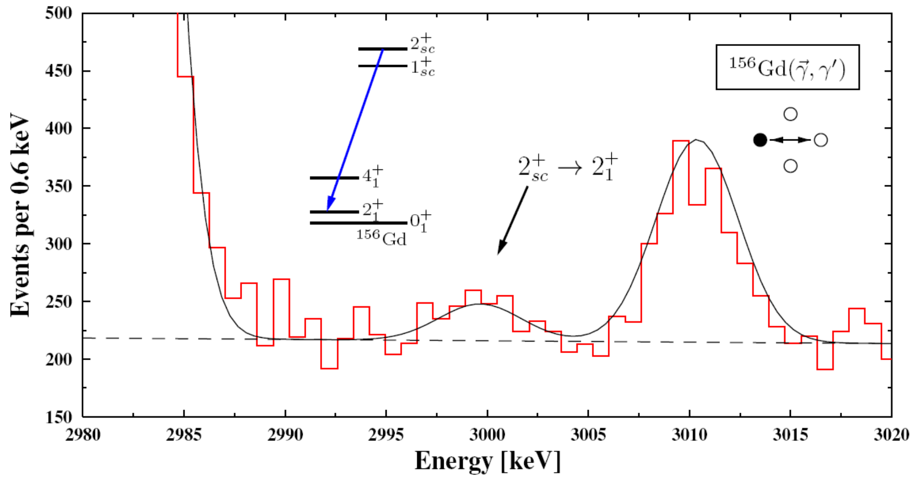
Energy-integrated absorption cross section: $I_a = \int \tilde{\sigma}_a^D(E)\,dE = \frac{\pi}{2}\,\sigma_0\,\Gamma \sim \Gamma_0$

Elastic-scattering cross section $\sim\Gamma_0^2/\Gamma$

Example: M1 and E2 NRF on ^{156}Gd



Excitation of Scissors Mode: M1



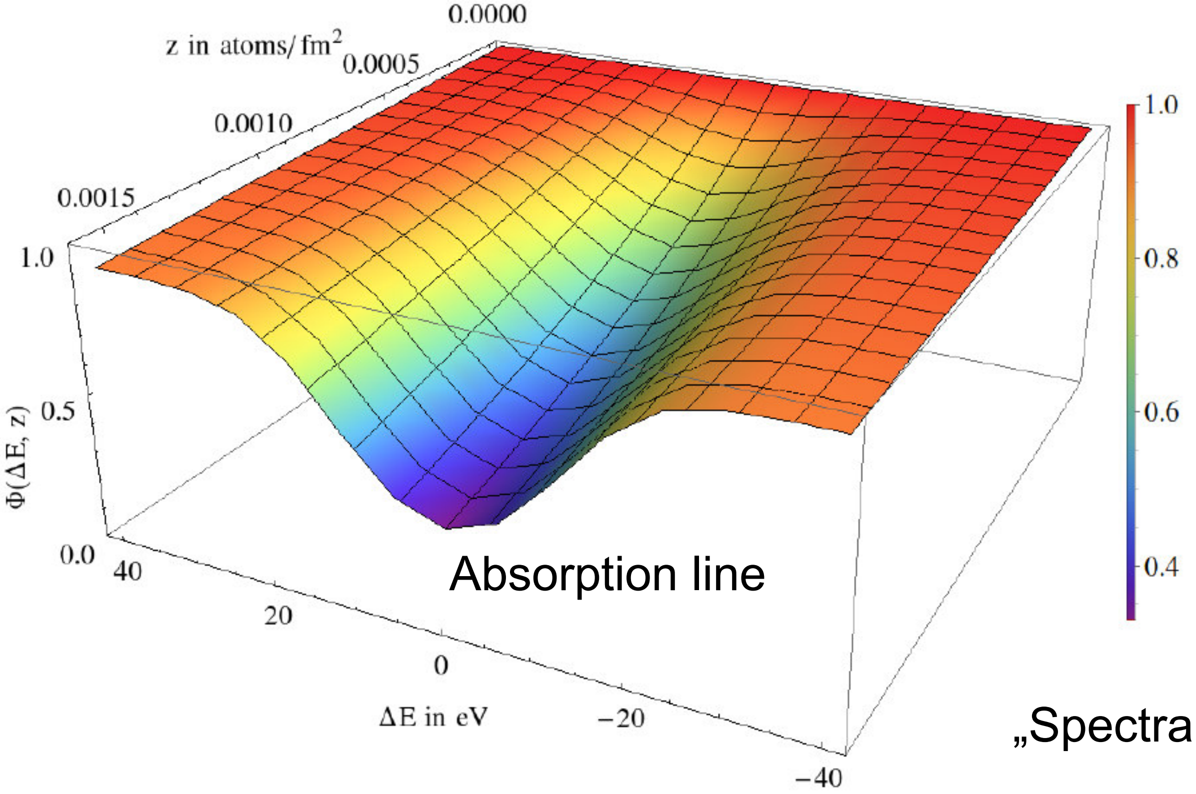
Excitation of rotational state on top of Scissors Mode: E2

First E2 NRF in deformed nucleus

T.Beck et al., to be submitted soon

Beam – Target Interaction: Self Absorption

Evolution of
Photon Flux
in Target



Absorption line

„Spectral shaping“

→ Nuclear Photonics

Absorption Density Profile

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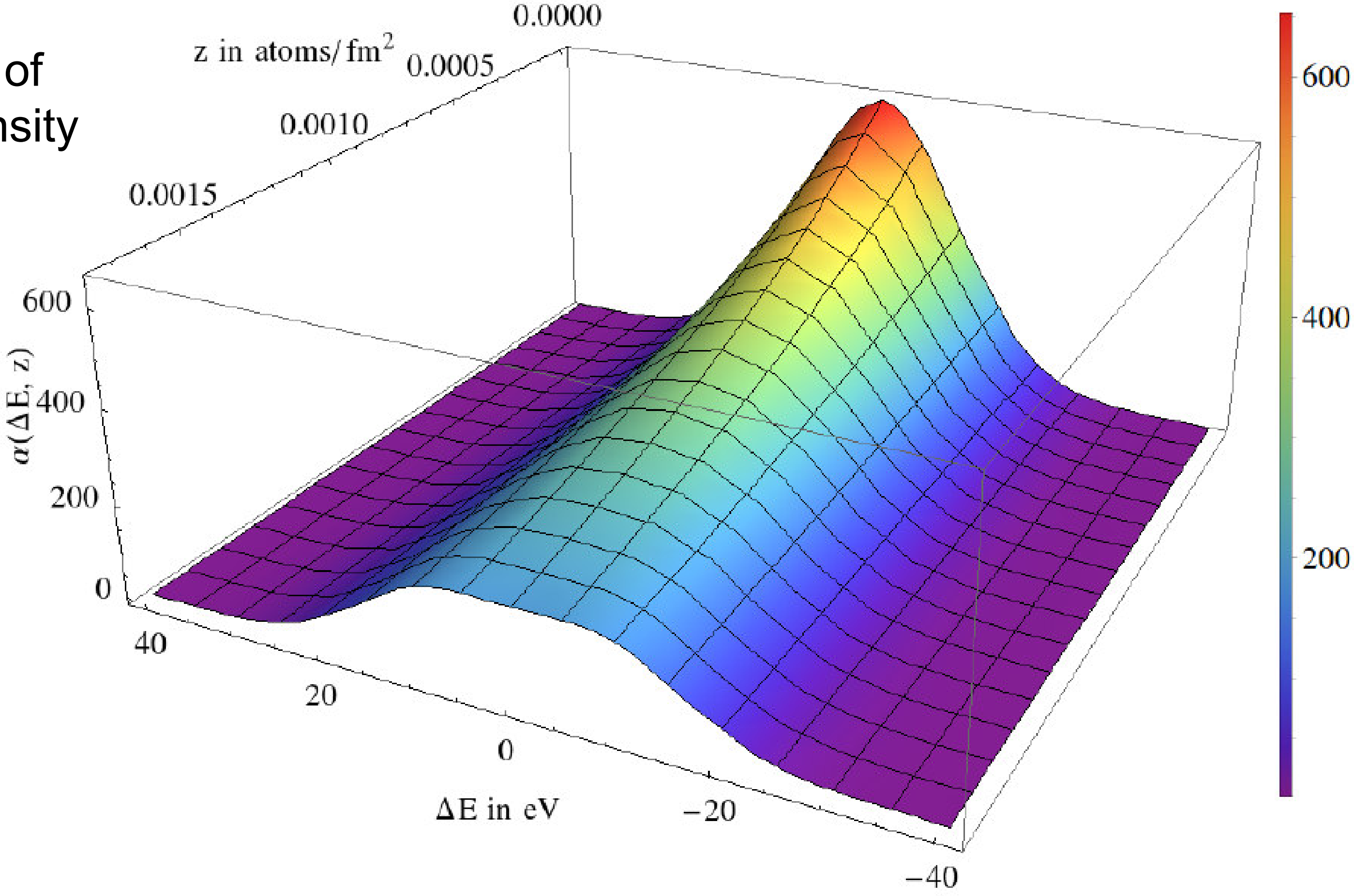
Evolution of
NRF intensity
in Target



Absorption Processes

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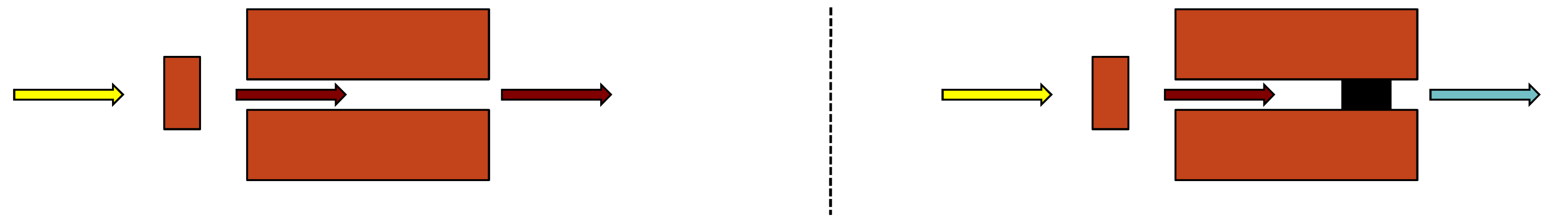
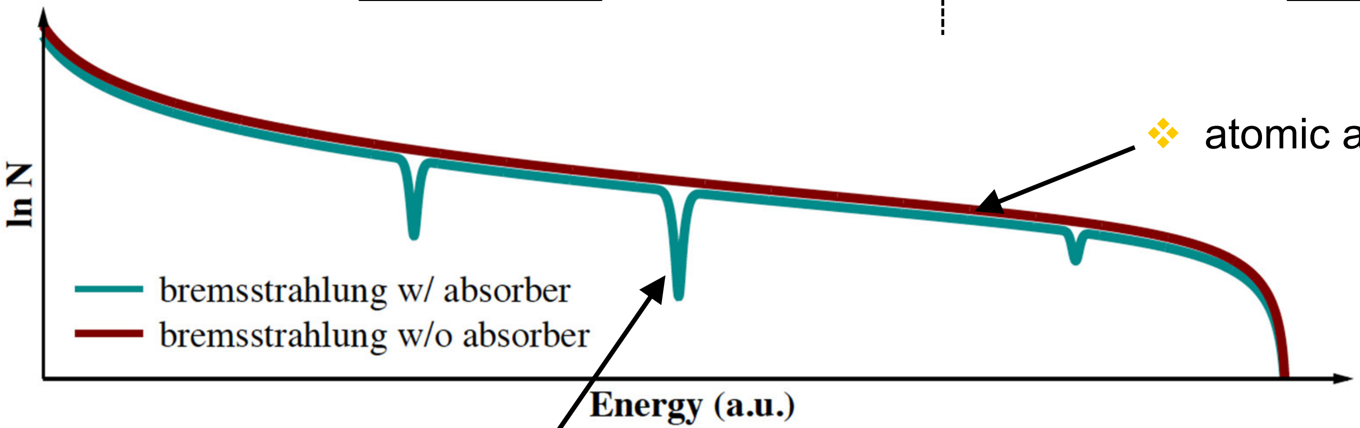
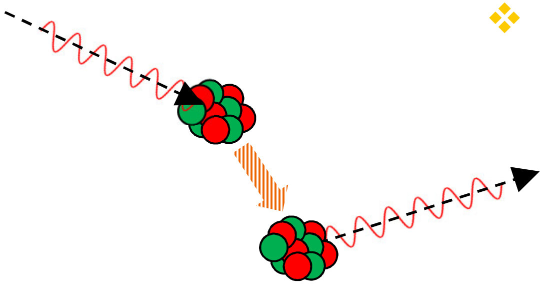
Absorption lines only a few eV wide!



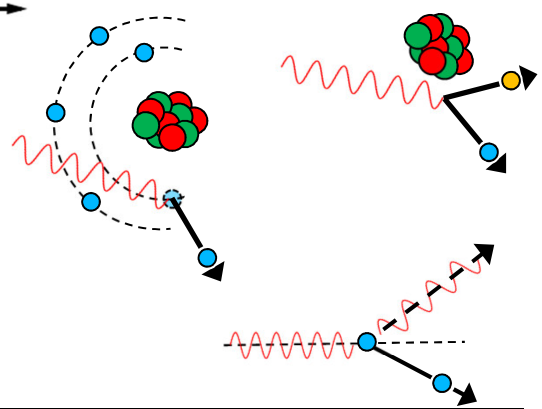


- atomic attenuation
  - several processes
  - contributes at each energy
  - independent of Γ_0



- resonant absorption
  - only at resonance energies
  - depends on Γ_0

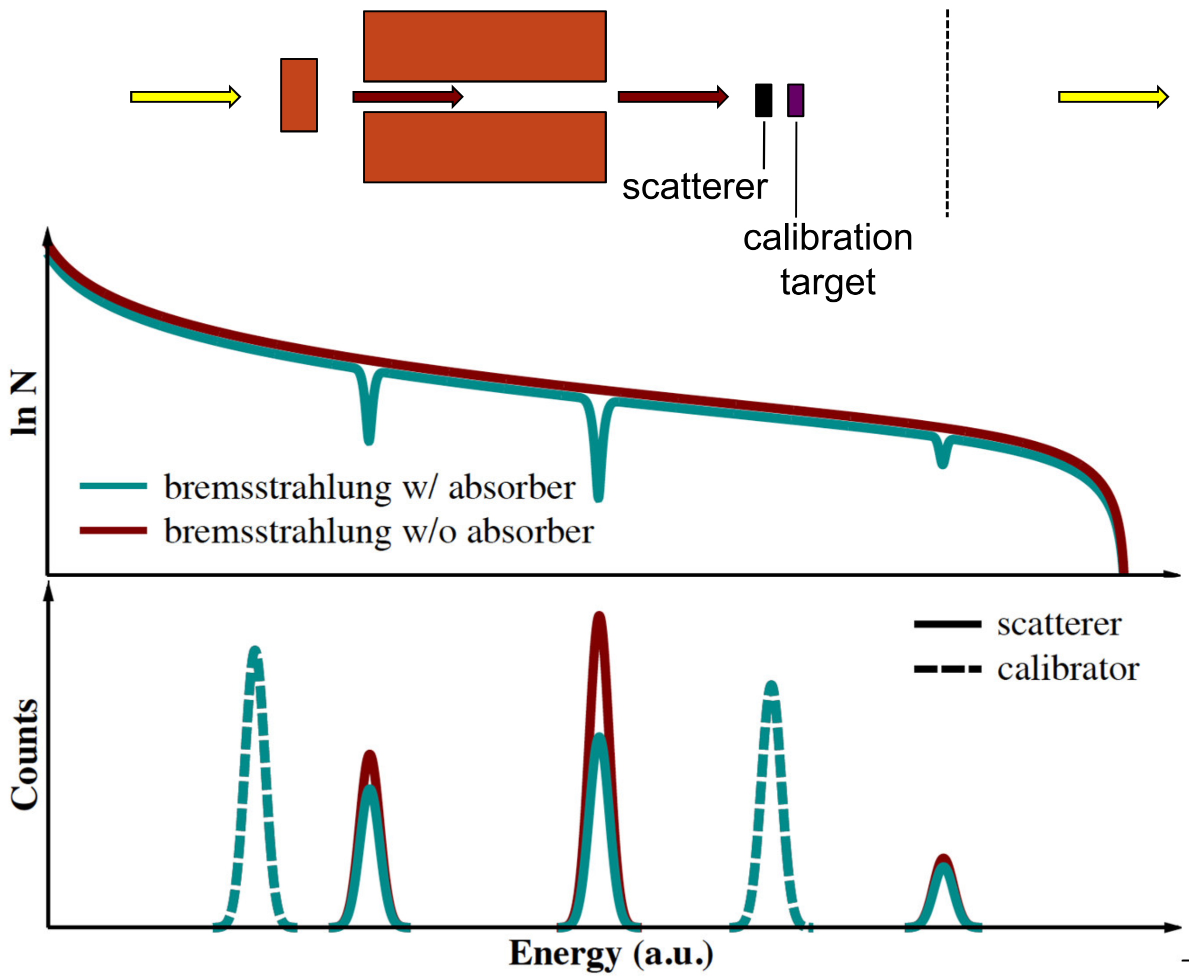
$$\sigma_a \propto \Gamma_0 \cdot e^{-\left(\frac{E-E_r}{\Delta}\right)^2}$$



Principle of Measurement and Self Absorption[1]

1 F. R. Metzger, Prog. in Nucl. Phys. **7** (1959) 53

Use scatterer made of absorber material as „high-resolution detector".



Self Absorption:
Decrease of Scattered Photons because of Resonant Absorption

$$R(\Gamma_0) = \frac{N_{\mathrm{woA}} - f \cdot N_{\mathrm{wA}}}{N_{\mathrm{woA}}}$$

$$f = \frac{N^{\mathrm{std}}_{\mathrm{woA}}}{N^{\mathrm{std}}_{\mathrm{wA}}}$$

Self Absorption Measurement on ^{6}Li
(Ch.Romig, TU Darmstadt, PhD thesis, 2014)

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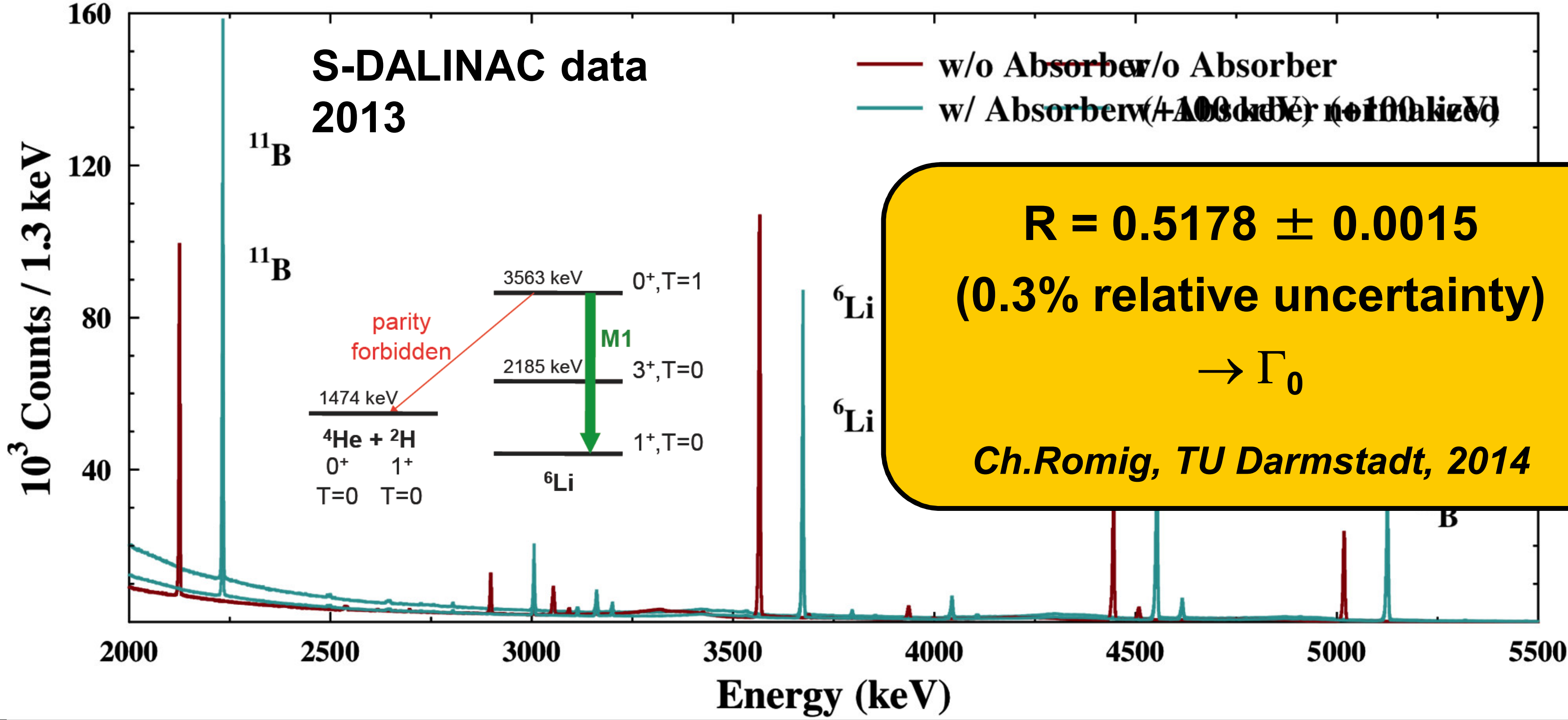
- scatterer: 5 g Li_2CO_3 (enriched to 95% in ^{6}Li)
- calibration target: 4.2 g ^{11}B (sandwiched)
- absorber: 10 g Li_2CO_3 (enriched to 95% in ^{6}Li)
- endpoint energy: 7.1 MeV
- 7 days w/o absorber
- 8 days w/ absorber



R = 0.5178 ± 0.0015
(0.3% relative uncertainty)
→ Γ_0

Ch.Romig, TU Darmstadt, 2014

Determination of Ground-State Transition Width and Branching Ratio to the Ground State

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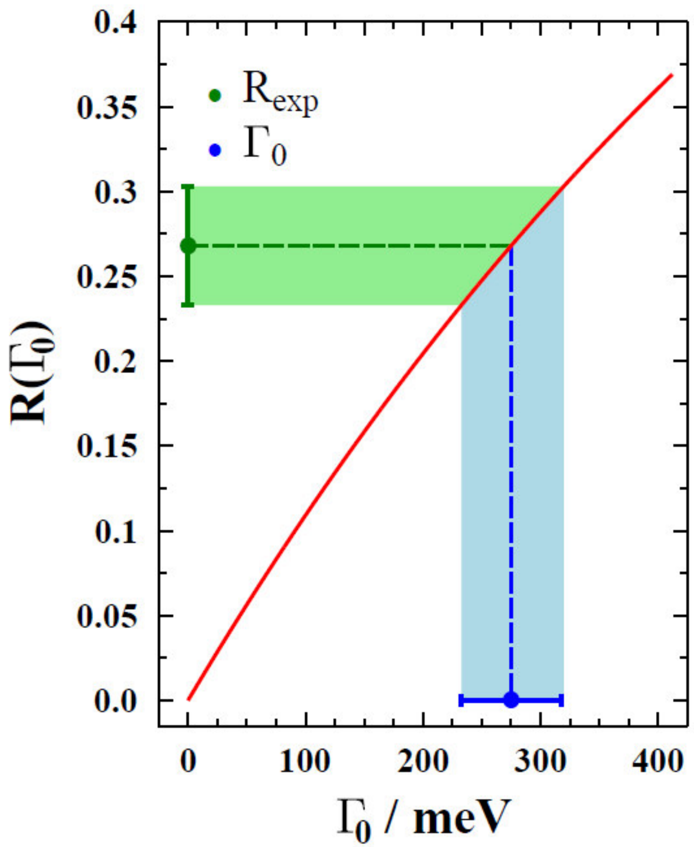
- calculate *R* as function of Γ_0
- self absorption R_{exp} determined experimentally
- comparison of experiment and calculation gives ground-state transition width Γ_0
- NRF measurement gives $\Gamma_0 \cdot \frac{\Gamma_0}{\Gamma}$
- thus total width Γ and branching ratio Γ_0/Γ to ground state can be determined

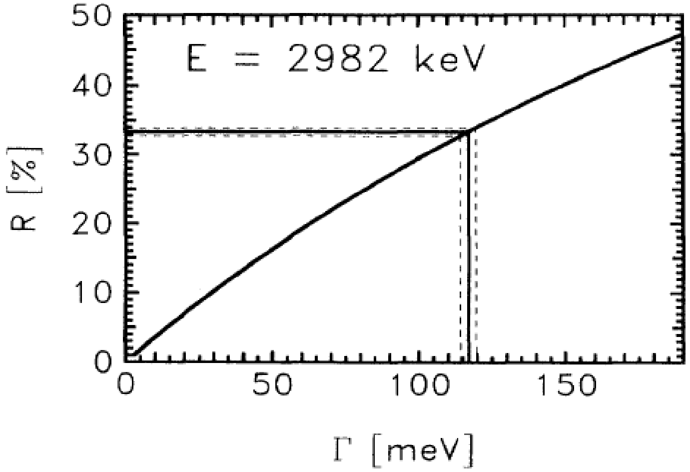


Precision Measurements on Γ_0

PHYSICAL REVIEW C VOLUME 51, NUMBER 2 FEBRUARY 1995

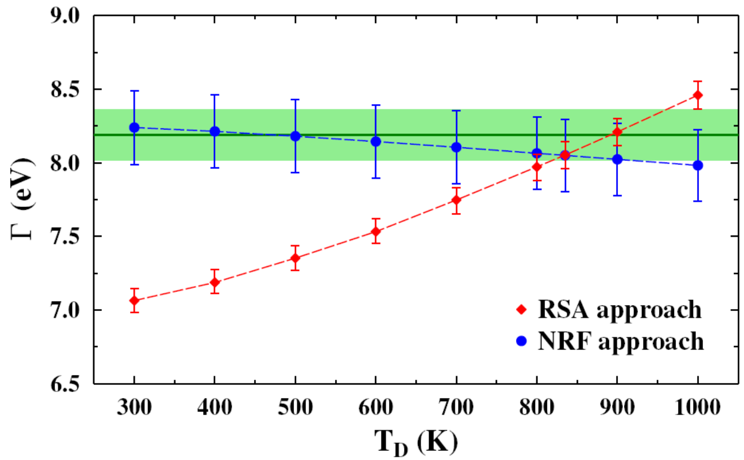
Absolute level widths in ^{27}Al below 4 MeV

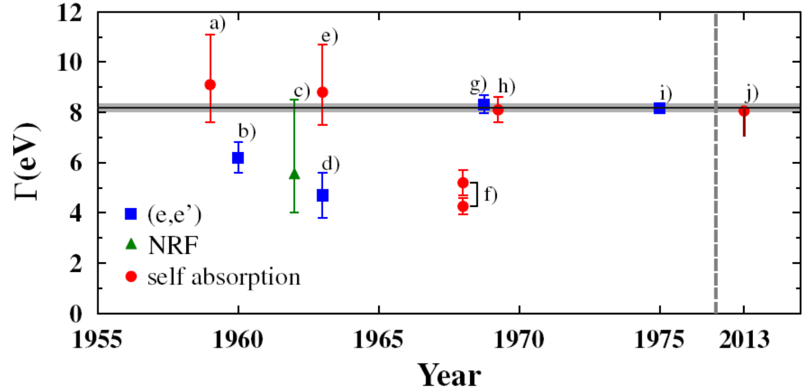
N. Pietralla,[1] I. Bauske,[2] O. Beck,[2] P. von Brentano,[1] W. Geiger,[2] R.-D. Herzberg,[1] U. Kneissl,[2] J. Margraf,[2] H. Maser,[2] H. H. Pitz,[2] and A. Zilges[1]
[1] *Institut für Kernphysik, Universität zu Köln, D-50937 Köln, Germany*
[2] *Institut für Strahlenphysik, Universität Stuttgart, D-70569 Stuttgart, Germany*
(Received 12 August 1994)



2% accuracy on photon flux calibration standards for NRF experiments

^{6}Li: ~ 1% accuracy achievable





C.Romig (Dissertation, TU Darmstadt, 2014)

Measurements on Branching Ratio Γ_0/Γ

Physics Letters B 744 (2015) 369–374

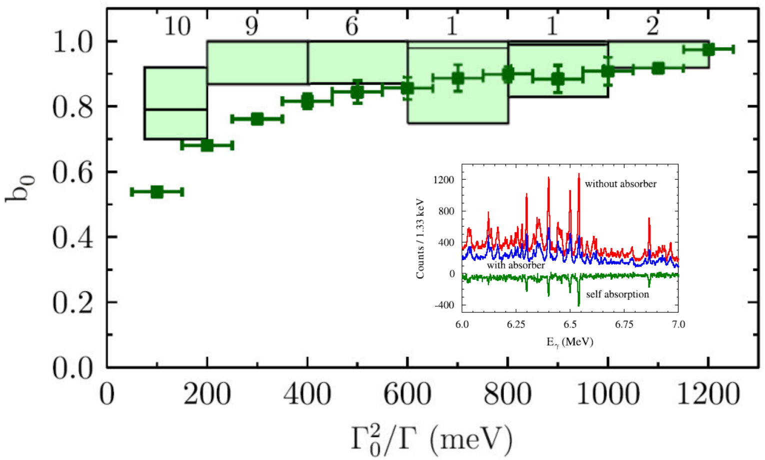
Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Direct determination of ground-state transition widths of low-lying dipole states in ^{140}Ce with the self-absorption technique

C. Romig[a,*], D. Savran[b,c], J. Beller[a], J. Birkhan[a], A. Endres[d], M. Fritzsche[a,1], J. Glorius[d,e], J. Isaak[b,c], N. Pietralla[a], M. Scheck[a,f,g], L. Schnorrenberger[a], K. Sonnabend[d], M. Zweidinger[a]



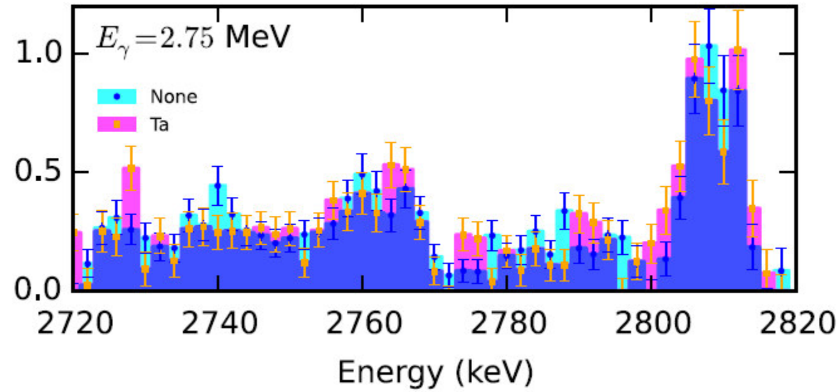
PRL 117, 142501 (2016) PHYSICAL REVIEW LETTERS week ending 30 SEPTEMBER 2016

Branching and Fragmentation of Dipole Strength in ^{181}Ta in the Region of the Scissors Mode

C. T. Angell,[*,†] R. Hajima,[†] and T. Shizuma[†]
Quantum Beam Science Center, Japan Atomic Energy Agency, Tokai-mura, Ibaraki 319-1184, Japan

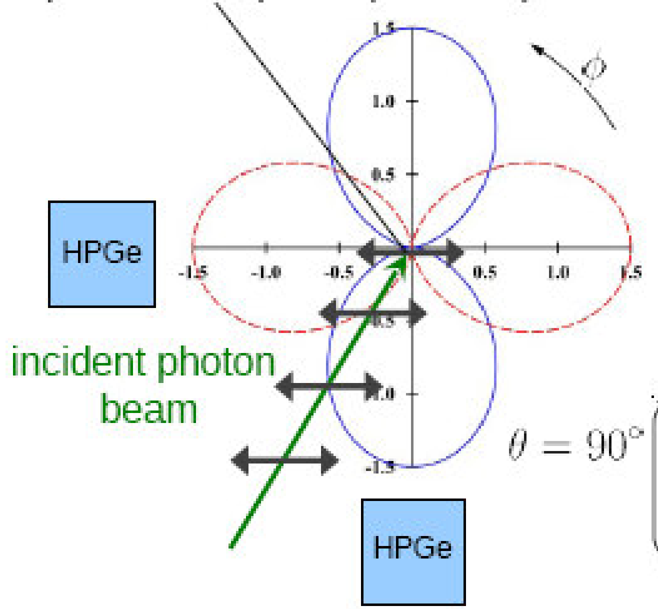
B. Ludewigt and B. J. Quiter
Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

(Received 4 March 2016; revised manuscript received 3 August 2016; published 26 September 2016)

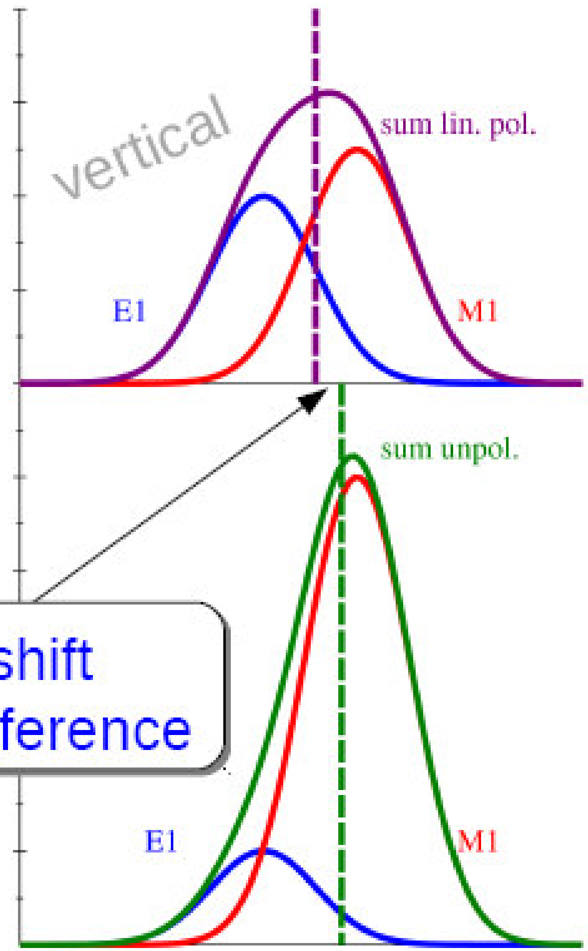


E_γ (MeV)	$R(n_a)$	$\langle I_{cs}\rangle^*$ (eV b)	$\langle b_0 I_{cs}\rangle^*$ (eV b)	$\langle b_0\rangle$
2.28	0.32 ± 0.07	12 ± 3	2.9 ± 0.3	$0.25^{+0.10}_{-0.06}$
2.75	0.14 ± 0.07	4 ± 2	1.8 ± 0.1	$0.5^{+0.7}_{-0.2}$

Polarization and Angular Distribution
here: Energy Splitting of ^{20}Ne Parity Doublet



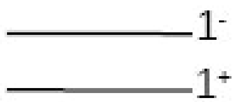
$$\varepsilon = \frac{N_{\parallel} - N_{\perp}}{N_{\parallel} + N_{\perp}}$$



Centroid shift
→ energy difference

Energy Splitting of ^{20}Ne Parity Doublet

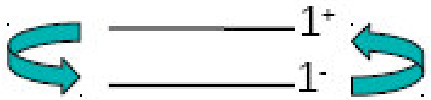
- before:



$$\Delta E = (7.7 \pm 5.3)\ \text{keV}$$

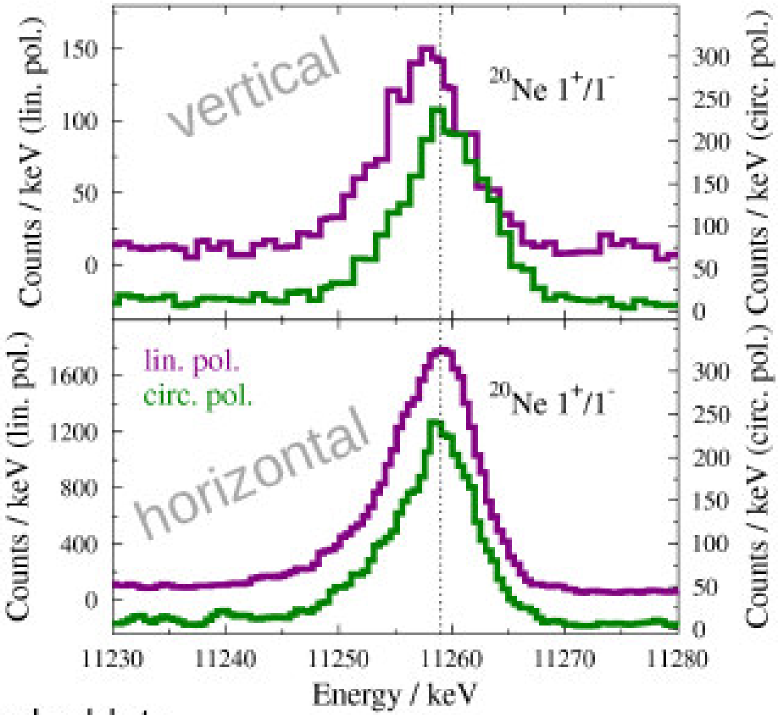
$$\frac{R_N}{\Delta E} = 670 \pm 700$$

- now:



$$\Delta E = (3.2 \pm 0.9)\ \text{keV}$$

$$\frac{R_N}{\Delta E} = 1610 \pm 670$$



- ^{20}Ne doublet:
  - strong M1: $\Gamma_{0,\ 1^+} = 11.2(20)$ eV [2]
  - weak E1: $\Gamma_{0,\ 1^-} = 0.39(5)$ eV [2]

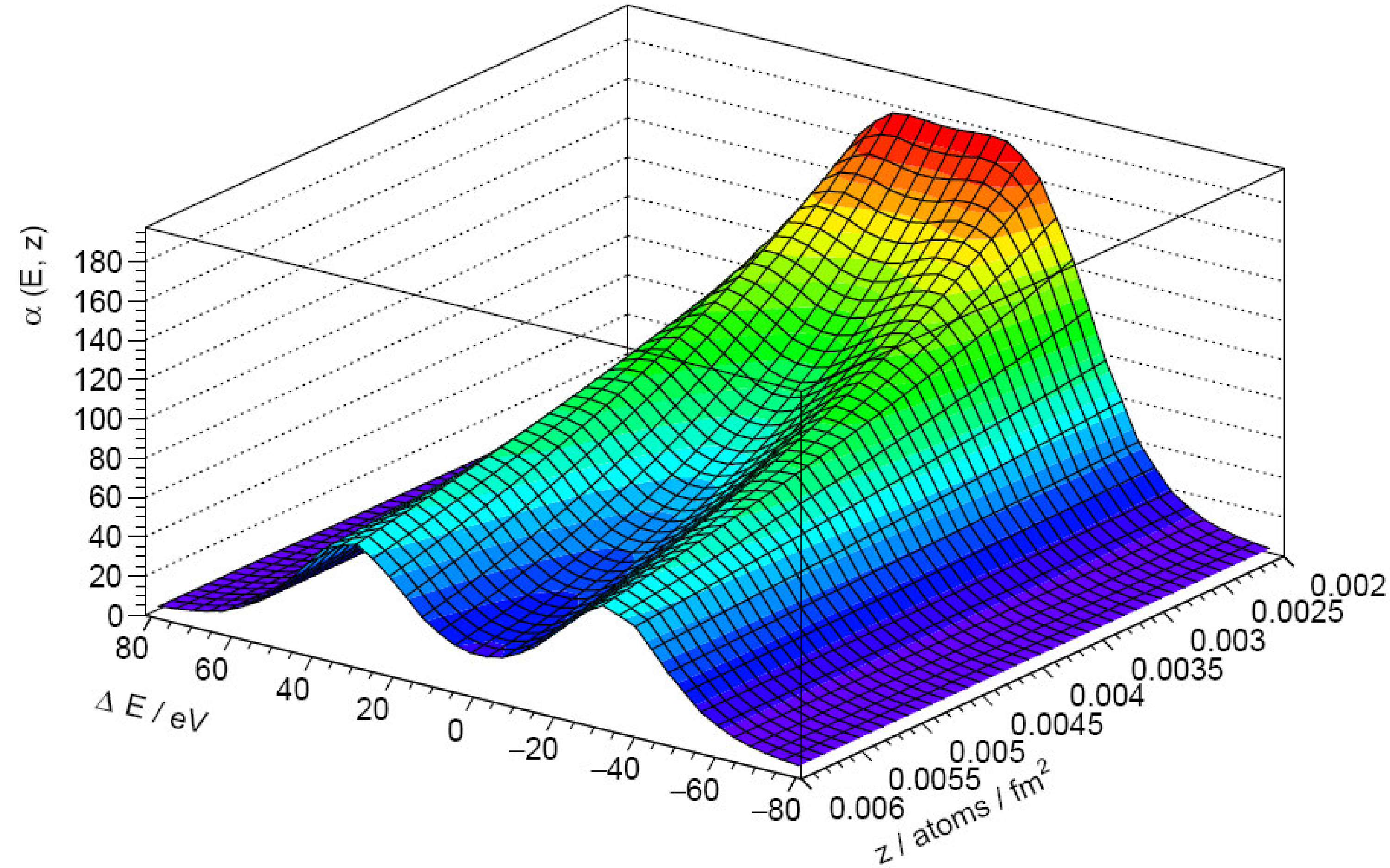
HIγS data

J.Beller et al., TU Darmstadt,

Phys. Lett. B 741, 128 (2015).

[2] D.R. Tilley et al., Nucl. Phys. A 636 (1998) 259

Shaping of Absorption Profile



Limitations
w.r.t. atomic quantum optics

- available γ-ray beams are not coherent
- cross sections are much smaller
- level lifetimes are smaller
- $\rightarrow$ double-photon excitation very difficult
  - assume $\tau \approx 1$ fs $\rightarrow$ useful γ-bunch length: ~ 0.3 μm
  - corresponds to 10^{-3} ^{o} for a 3 GHz – accelerator
  - half-value thickness: ~ 5 cm $\Rightarrow$ ~ 1 nucleus / b
  - necessary flux for double-γ excitation: ~ 1 γ / (eV b fs) = 10^{39} γ / (eV cm^2 s)

- spectral shaping of γ-ray flux by absorption $\rightarrow$ loss of intensity

Conclusions

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"Nuclear Photonics is an emerging field of science."

„***Nuclear Photonics*** is the cross-disciplinary field of Physics and Engineering which addresses ***controlled*** photo-nuclear reactions with artificial γ-ray beams and their applications."

„controlled"

- excitation / manipulation of single nuclear quantum states / groups of states

„artificial gamma-ray beams"

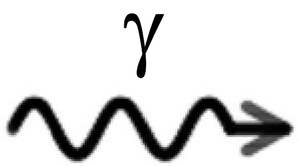
- usage of artificially shaped γ-ray beams w.r.t. spectral intensity profile

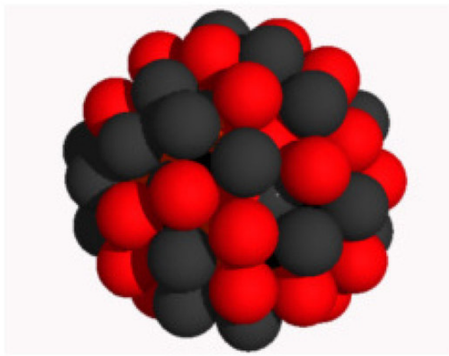
„cross-disciplinary"

- integrates techniques from nuclear physics, quantum optics, accelerator science

Thank you very much !

at $10^5 – 10^7\ \gamma$ / (eV s) at CERN - ERL





S-DALINAC at TU Darmstadt

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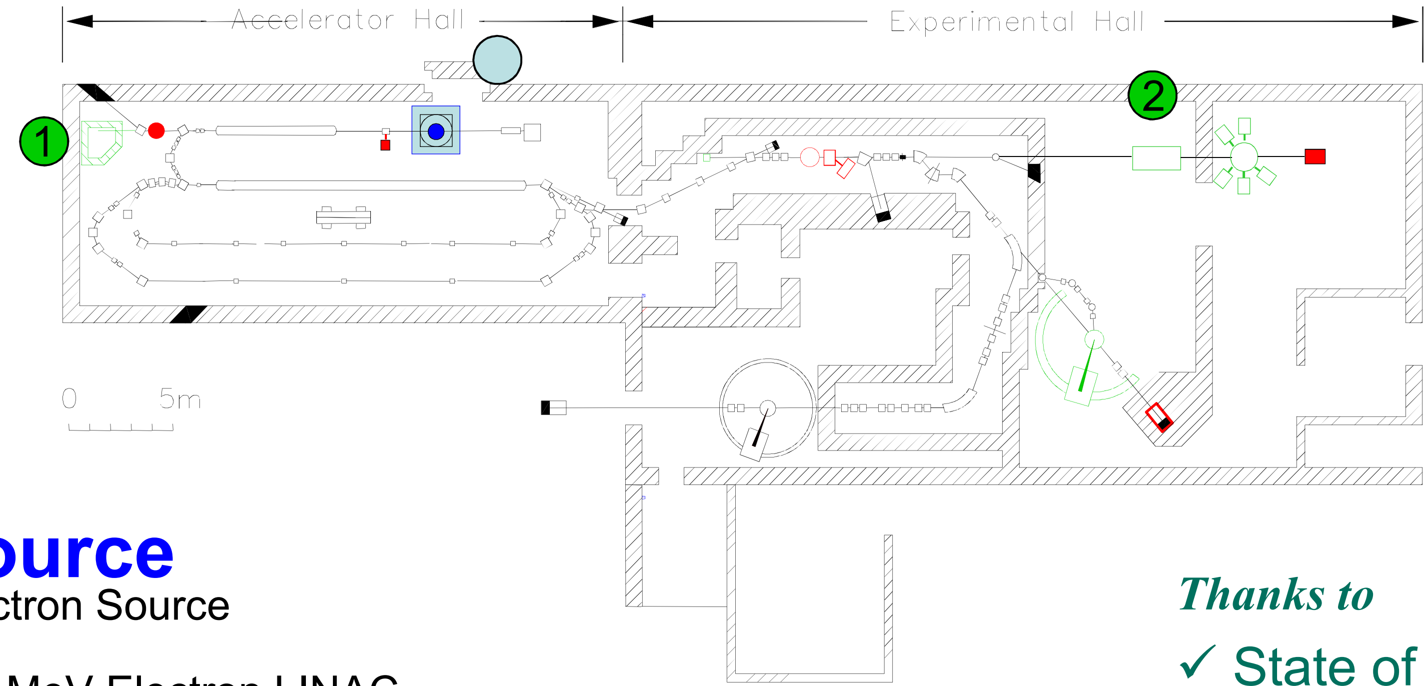


Source

Electron Source

130 MeV Electron LINAC

Photon Experiments

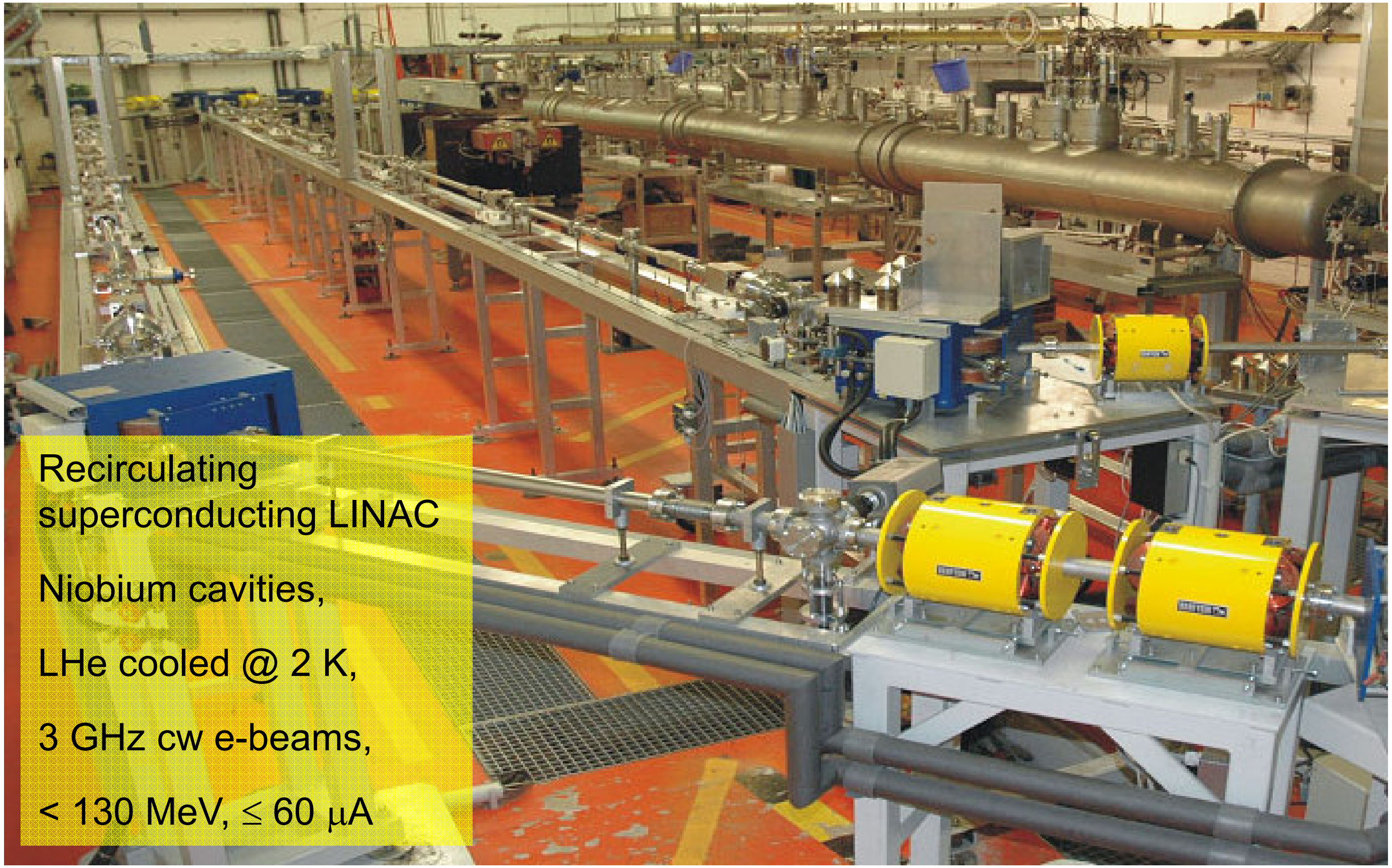
1 10 MeV Injector: Photon Scattering / Photofission

2 < 30 MeV Tagger: Photodesintegration / Photon Scattering

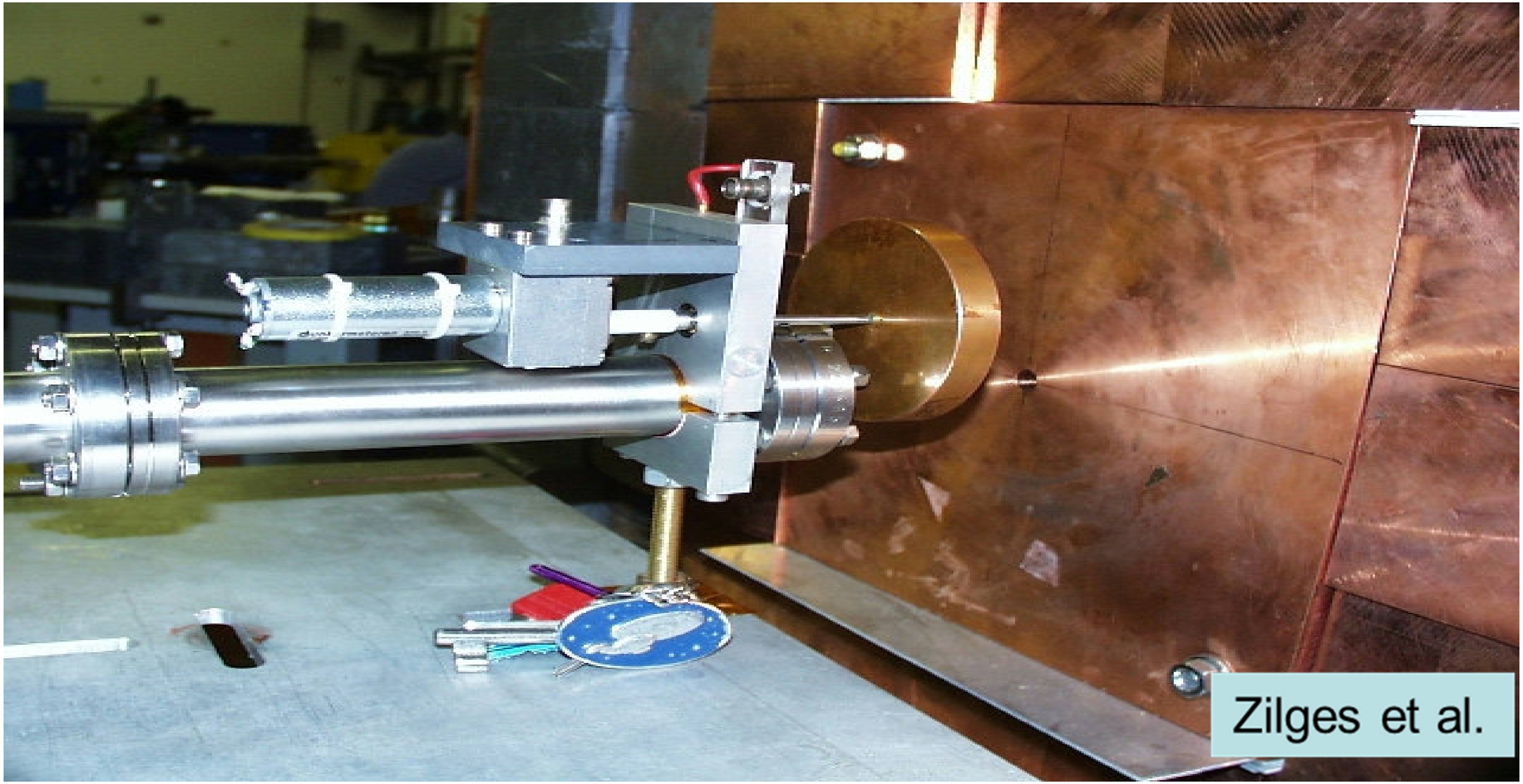
Thanks to

- ✓ State of Hesse
- ✓ TU Darmstadt
- ✓ DFG

S-DALINAC at TU Darmstadt



Bremsstrahlung-Site



Darmstadt Low-Energy Photon Scattering Site at S-DALINAC

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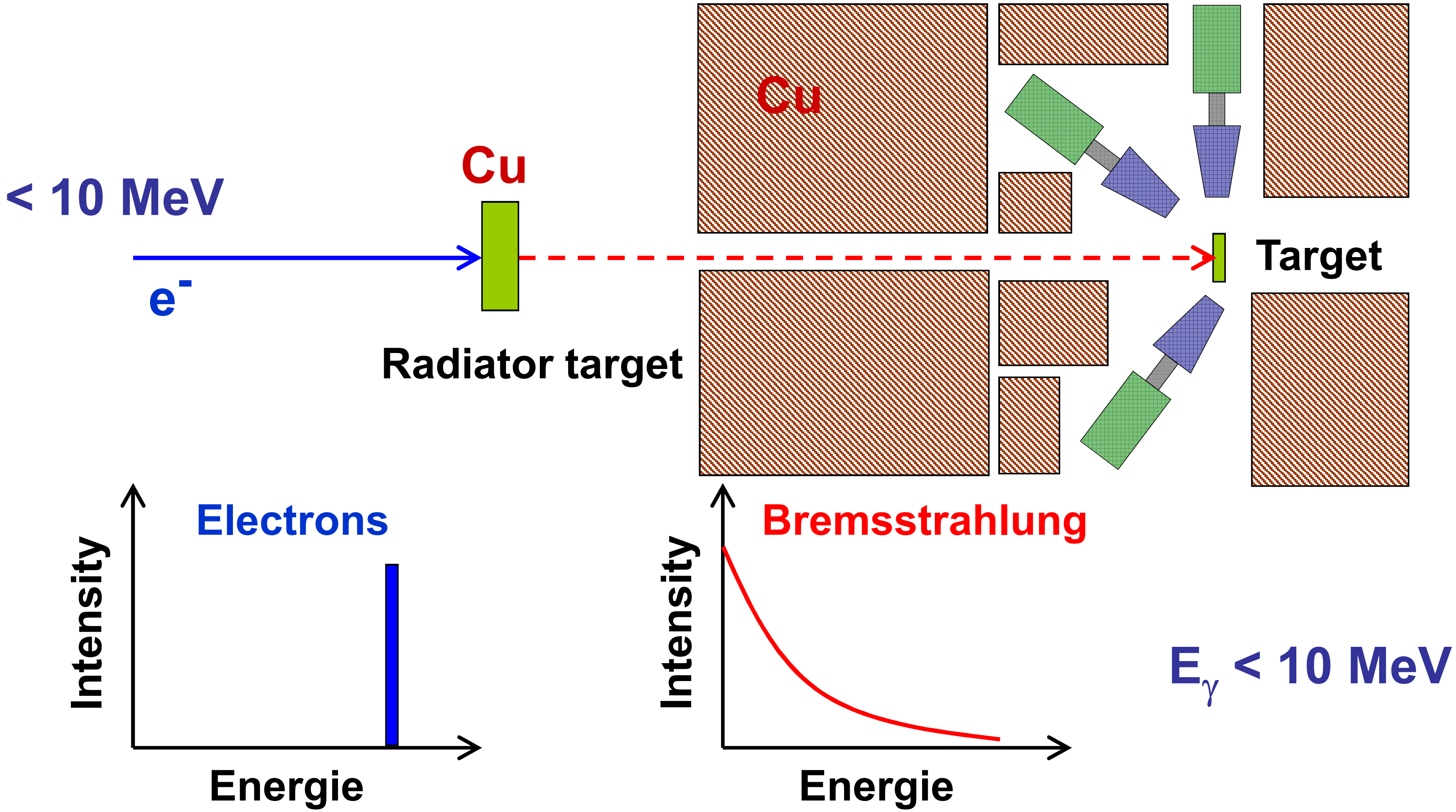
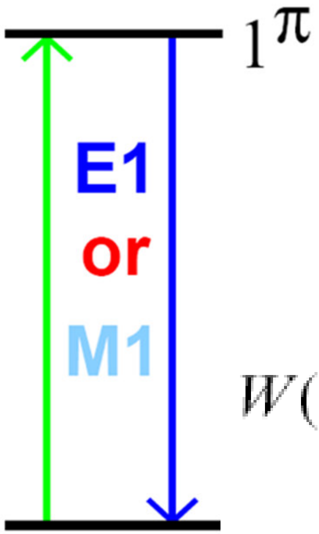
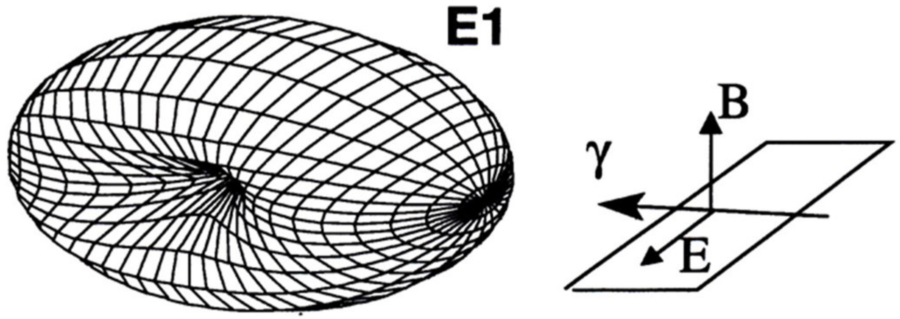
K.Sonnabend et al., NIM A (2011).



Parity quantum number π for J=1 states





$$W(\theta,\phi) = 1 + \tfrac{1}{2}[P_2(\cos\theta) + \tfrac{1}{2}\pi_1 \cos(2\phi) P_2^{(2)}(\cos\theta)]$$

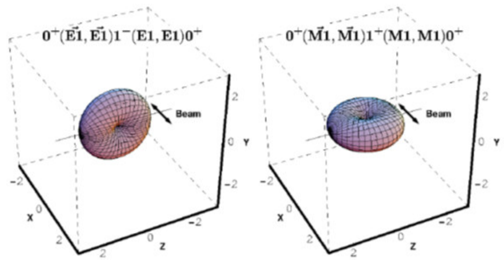
N.Pietralla, H.R. Weller et al., NIM A 483 (2002) 556.

Elastic scattering distribution not isotropic about incident polarization plane.

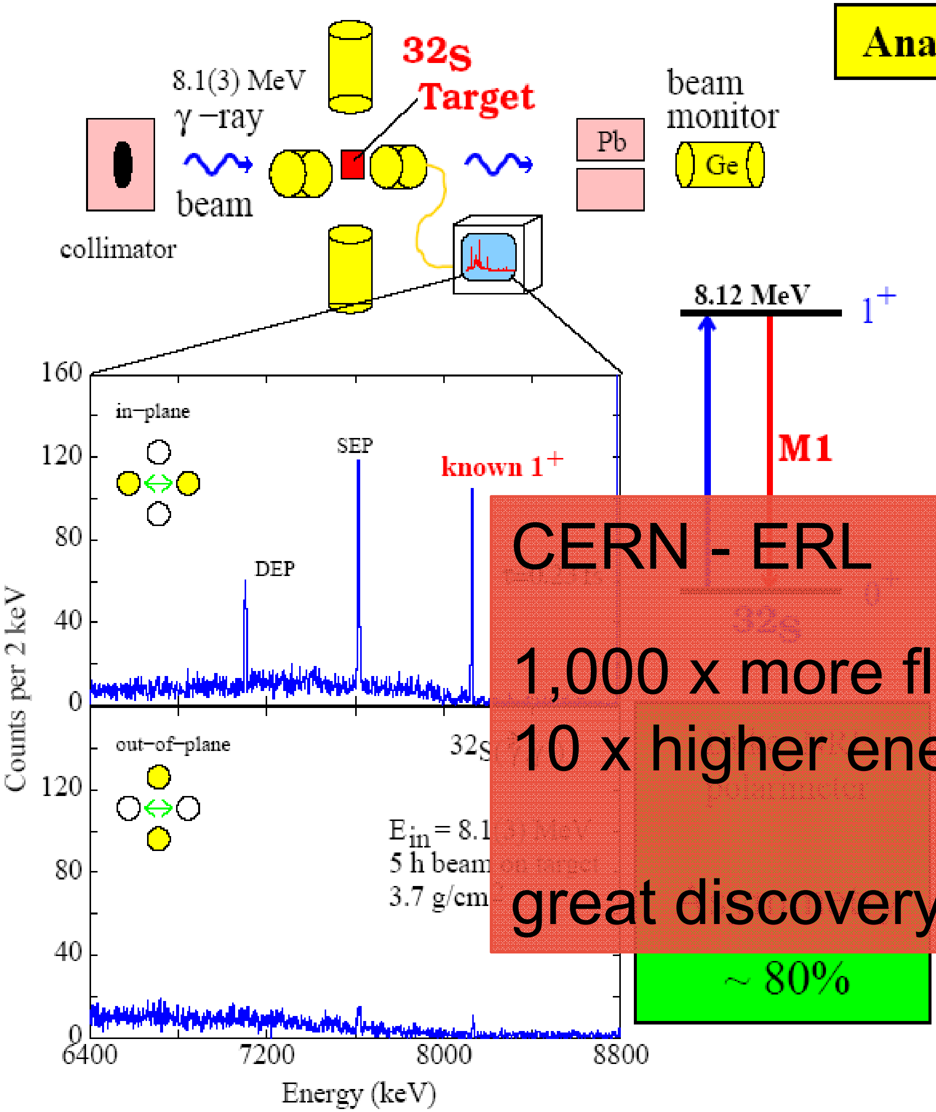
No intensity along oscillating dipole vector

Azimuthal rotation by 90° for M1 and E1 distributions

Observable only for linearly polarized beam

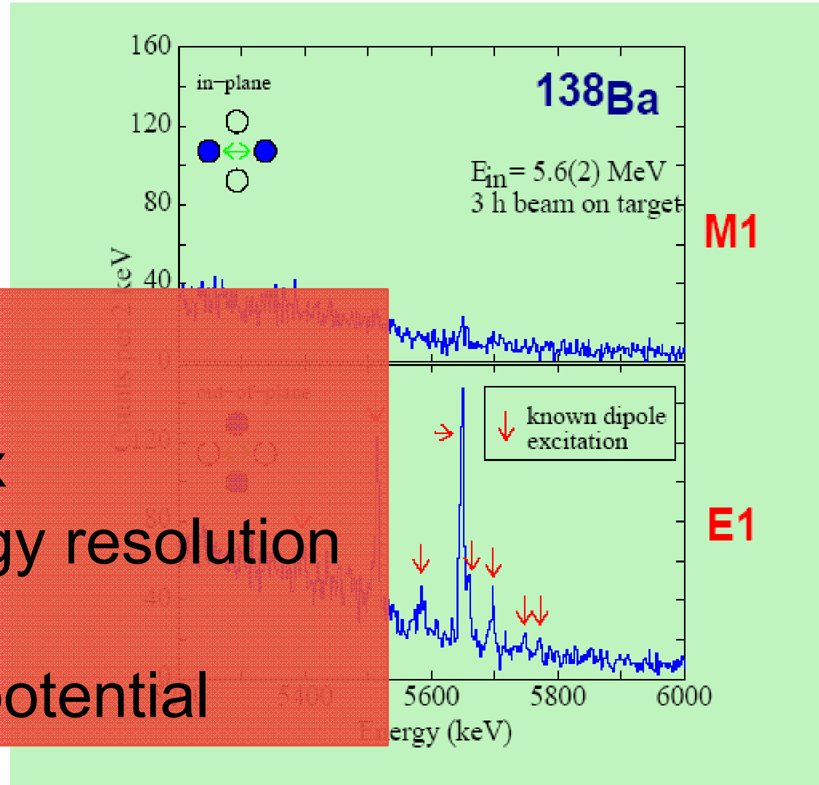


Analyzing Power for the Pygmy Resonance



N.Pietralla et al., Nucl.Instrum.Methods A483, 556 (2002).

"pygmy resonance": all E1 !



N.Pietralla et al., Phys.Rev.Lett.88, 012502 (2002).

CERN - ERL

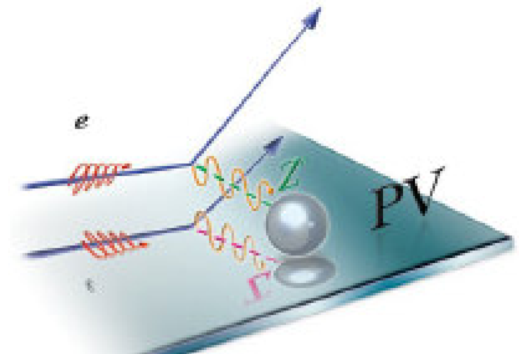
1,000 x more flux

10 x higher energy resolution

great discovery potential

established international community
(not only NRF!)

Parity Violation in Nuclear Structure?



http://irfu.cea.fr/Sphn/Parity/

- parity violation (PV) effect postulated in 1956 and experimentally verified in 1957 by Wu *et al.*

- various theoretical and experimental attempts but impact of weak interaction on nuclear structure not well tested, yet

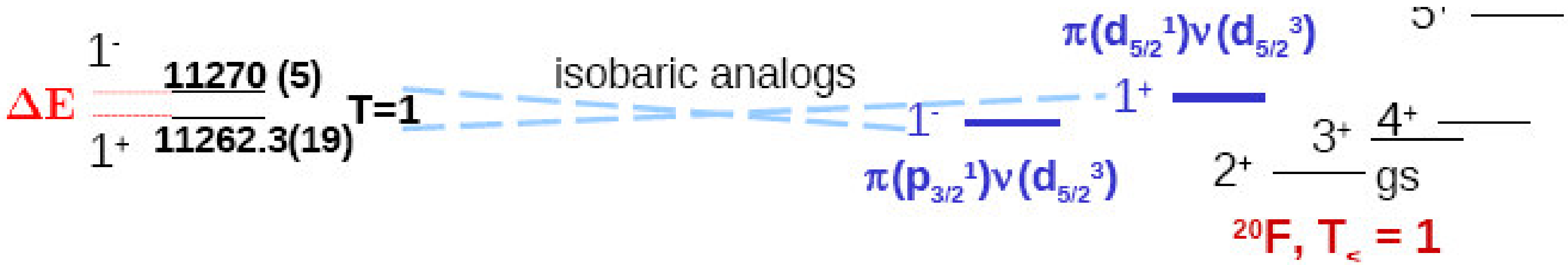
- parity non conservation in nuclear excitation could be tested with circularly photon beams [1]

$$A^a_{RL} = \frac{\sigma^a_R - \sigma^a_L}{\sigma^a_R + \sigma^a_L} \sim \frac{2R}{E_\pi - E_{-\pi}} \langle \phi_{-\pi} | V_{PNC} | \phi_\pi \rangle$$

^{A}Z	Transition $(J_i^\pi; I_i)[E_i] \to (J_f^\pi; I_f)$	$[E_f]$	Admixture $(J_f^{-\pi})[E'_f]$	$\lvert R_N/\Delta E \rvert$
^{14}C	$(0^+,1) \to (2^-,1)$	[7340]	[7010]	31 ± 6
^{14}N	$(1^+,0) \to (1^+,0)$	[6203]	[5691]	7.0 ± 2.0
	$(1^+,0) \to (0^+,1)$	[8624]	[8776]	40 ± 5
	$(1^+,0) \to (2^-,1)$	[9509]	[9172]	45 ± 5
^{15}O	$\left(\frac{1}{2}^-,\frac{1}{2}\right) \to \left(\frac{1}{2}^-,\frac{1}{2}\right)$	[11 025]	[10 938]	37 ± 7
^{16}O	$(0^+,0) \to (2^-,0)$	[8872]	[6917]	18 ± 2
			[11 520]	9.5 ± 0.7
^{18}F	$(1^+,0) \to (1^-,0+1)$	[5605]	[5603]	590 ± 110
^{20}Ne	$(0^+,0) \to (1^-,0)$	[11 270]	[11 262]	670 ± 7000

[1] A.I. Titov *et al.*, *J. Phys. G: Nucl. Part.* Phys. **32** 1097 (2006)

^{20}Ne Parity Doublet



- doublet is isobaric analog of simple shell model states

- high nuclear enhancement factor [1]:
  - overlapping wavefunctions
  - small energy splitting (large uncertainty)

$$|R_N/\Delta E| = (670 \pm 7000) \quad \Delta E = (7.7 \pm 5.3)\ \mathrm{keV}$$

- feasibility of measurement of PV effect on ^{20}Ne?

Experiment on ^{20}Ne at HIγS

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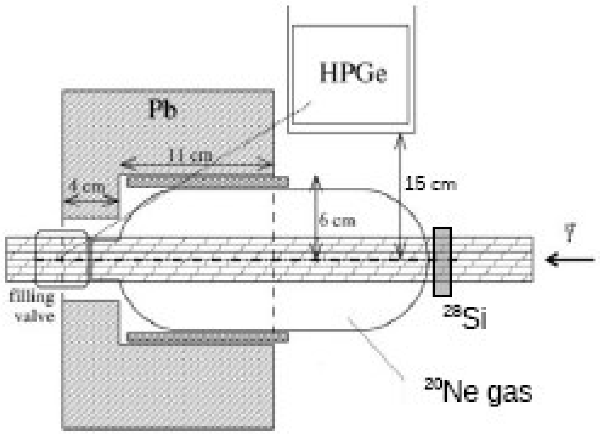
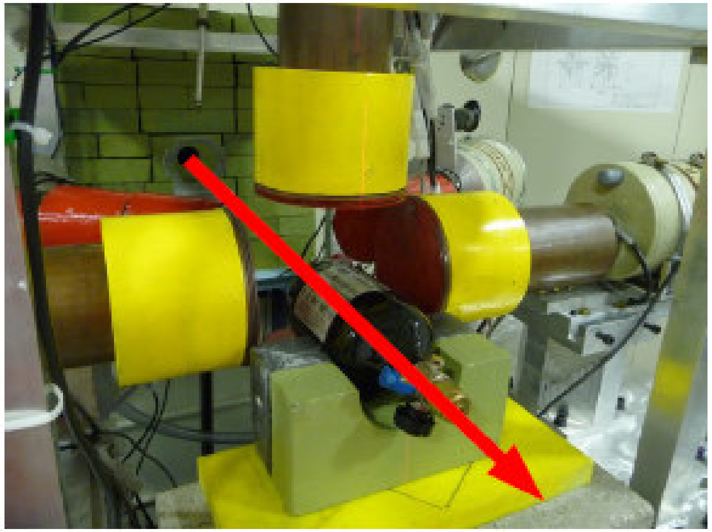


adapted from
T.C. Li *et al.*, Phys. Rev. C **73** 054306 (2006)



- beam energy: 11.26 MeV (ΔE ≈ 350 keV)
- 4 h with circular polarized photons
  (isotropic emission → reference point)
- 20 h with linear polarized photons
  (separation of 1^+ and 1^- state)

Scientific Opportunities at High-Intensity

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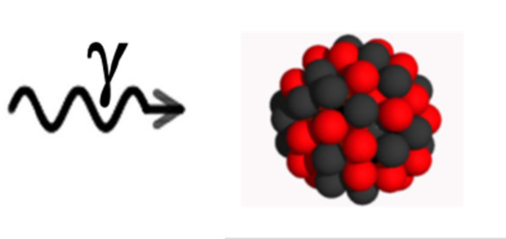
Outline

- Photonuclear Reactions
- Nuclear Resonance Fluorescence
- Some Previous Achievements



- **Intensity Frontier (instrumental challenge)** → **„Discovery Frontier"**

  (scientific opportunities)

  - **„Availability Frontier"** **(NRF on rare isotopes)**
  - **„Sensitivity Frontier"** **(weak channels: strong physics)**
  - **„Precision Frontier"** **(high count rates, new methods)**
- **Conclusion**

Application: ^{6}Li as Benchmark for *ab-initio* Nuclear Structure Theory

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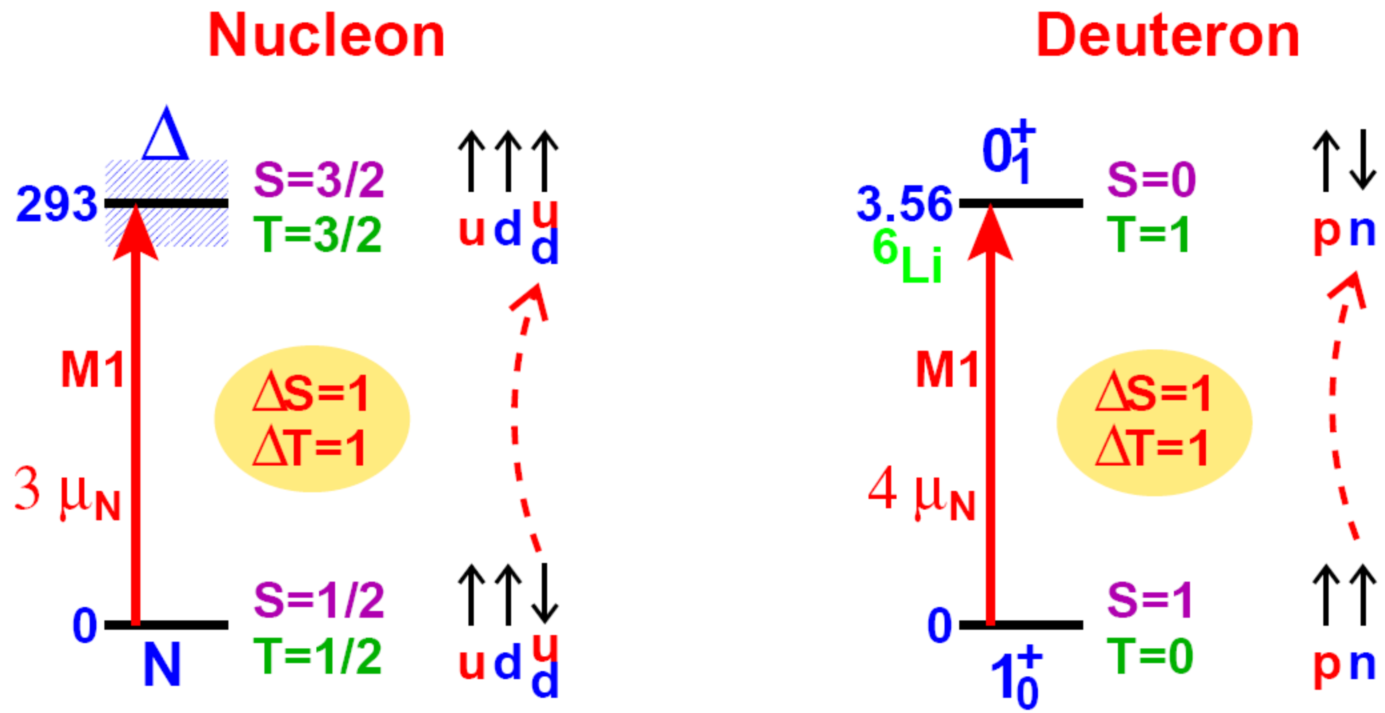
Isospin Excitations of Nucleons and Nuclei



Nuclear Quasideuteron-Configurations: A.F.Lisetskiy et al., Phys. Rev. C **60**, 064310 (1999).