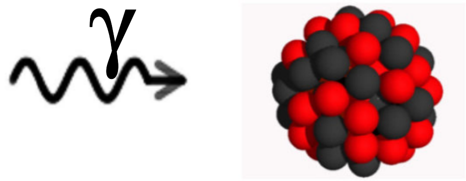
Photonuclear Reactions
with MeV γ-rays from LCB

Norbert Pietralla, TU Darmstadt

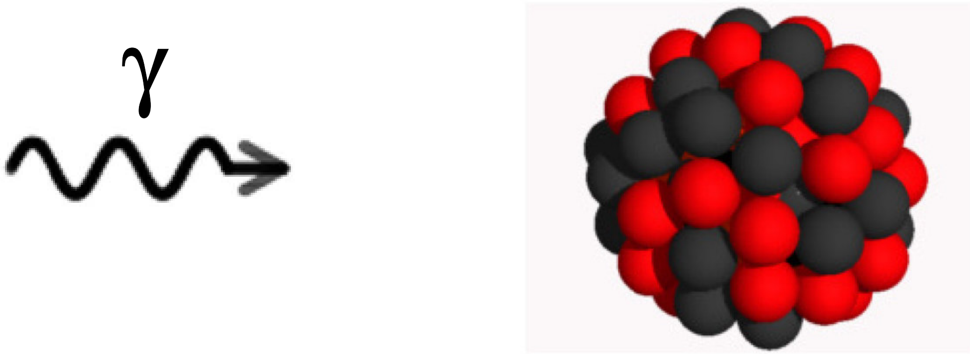
TECHNISCHE UNIVERSITÄT DARMSTADT

Outline



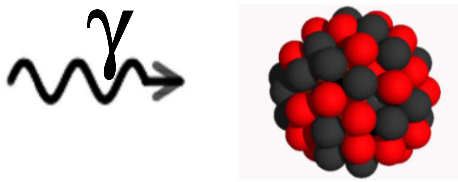
- **Photonuclear Reactions**
- **Nuclear Resonance Fluorescence**
- **Some Previous Achievements**
- **Intensity Frontier** $\rightarrow$ **„Discovery Frontier“**
  - **„Availability Frontier“** **(photonuclear reactions on rare isotopes)**
  - **„Sensitivity Frontier“** **(weak channels: strong physics)**
  - **„Precision Frontier“** **(high count rates, new methods)**
- **Conclusion**

Photonuclear Reactions



What happens?

Nuclear Physics with MeV-range photon beams



Pure EM-interaction

(nuclear-)model independent

“small“ cross sections, intense beams

Minimum projectile mass

min. angular momentum transfer,
spin-selective: low-spin modes [E1,M1,E2,(E3?)]

Polarisation

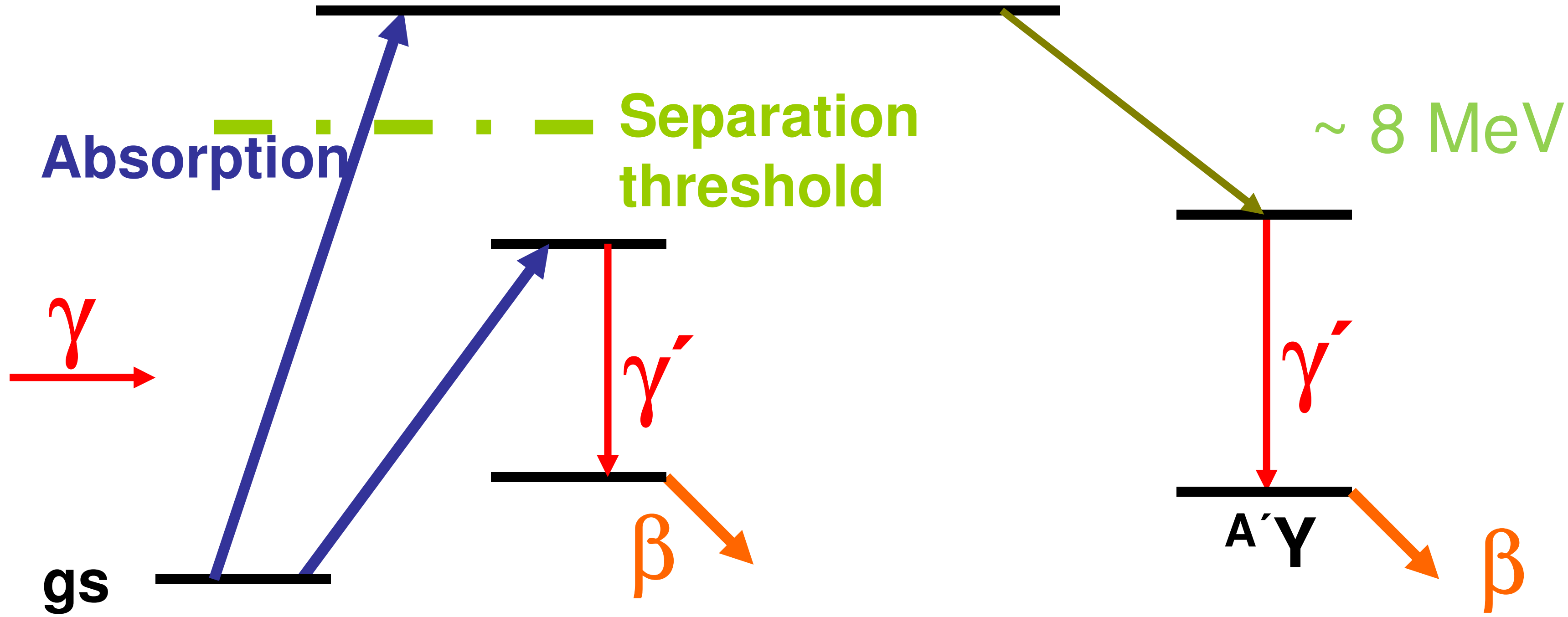
„Parity Physics“, channel selectivity

Narrow Bandwidth (at ELI-NP and CERN-ERL)

Explore specific excitation energy

„Selective Manipulation of Nuclear States“: Nuclear Photonics

Photonuclear Reactions



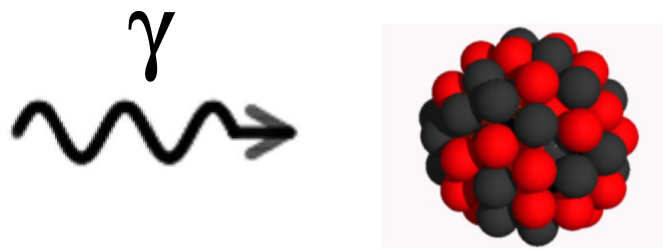
Nuclear Resonance Fluorescence (NRF)

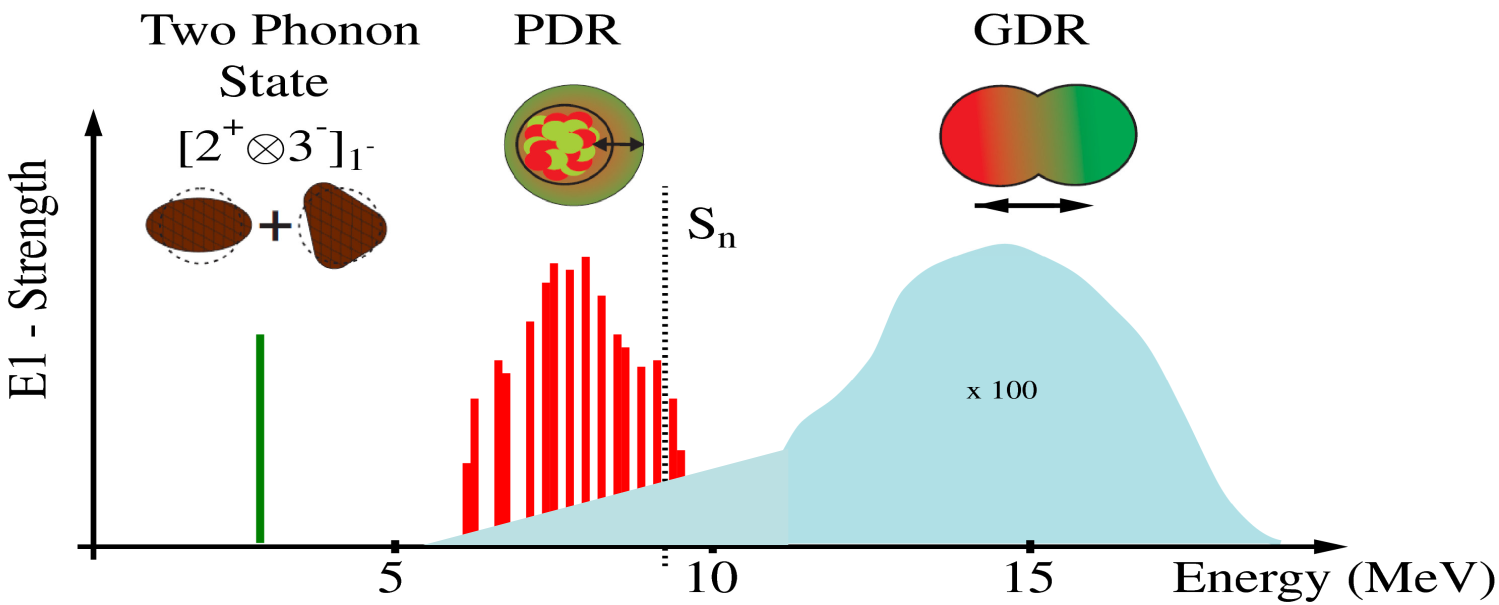
Photoactivation

Photodesintegration (-activation)

Photofission

Electromagnetic dipole-response



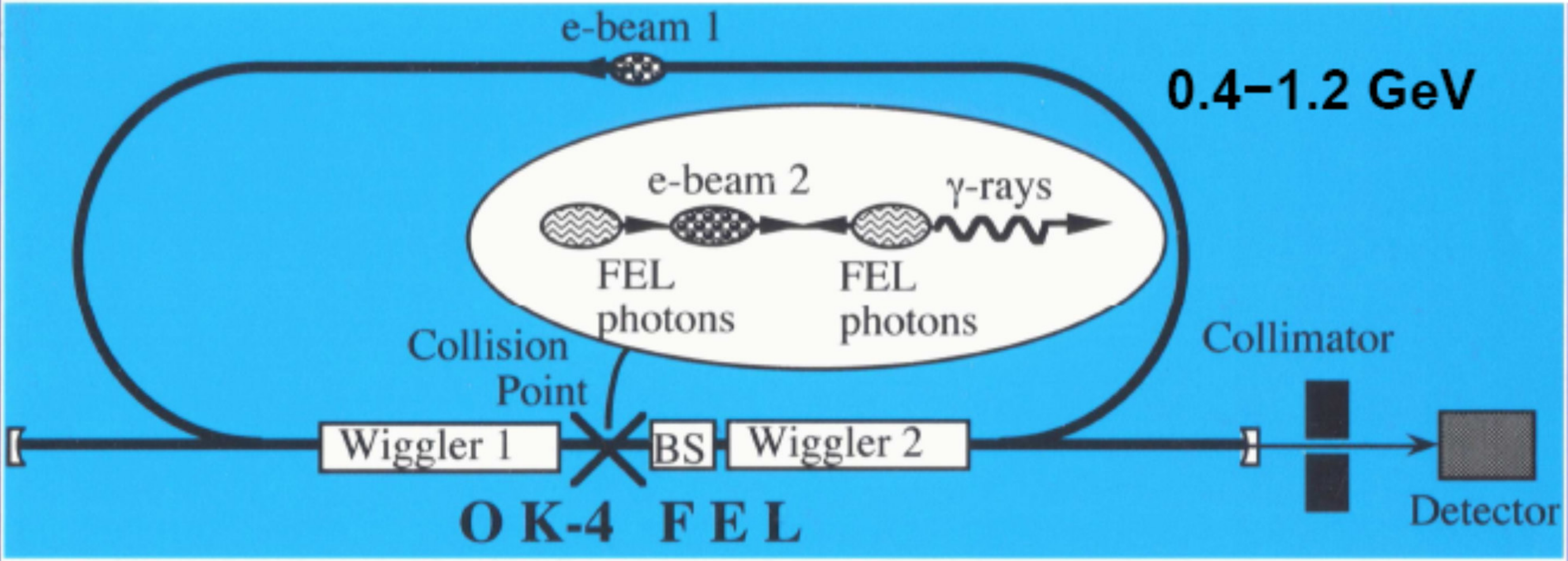


E1 strength distribution

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

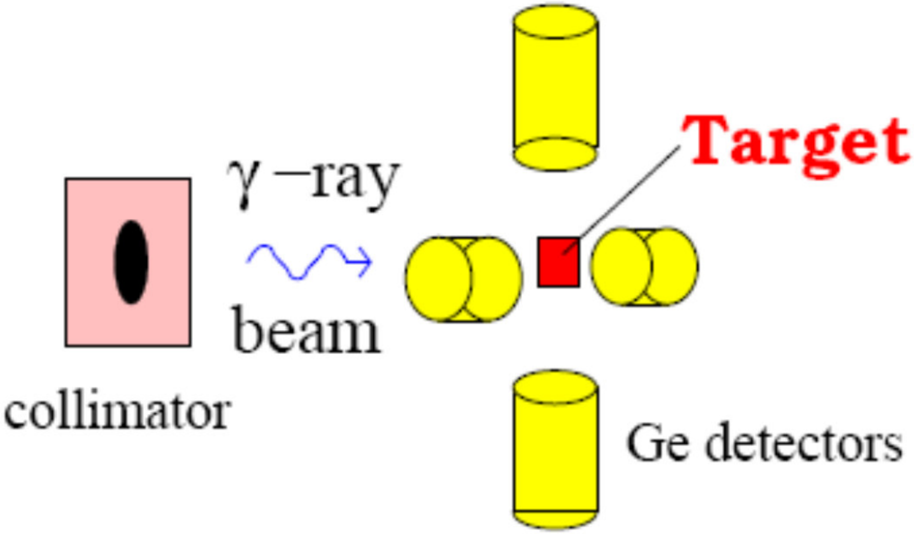


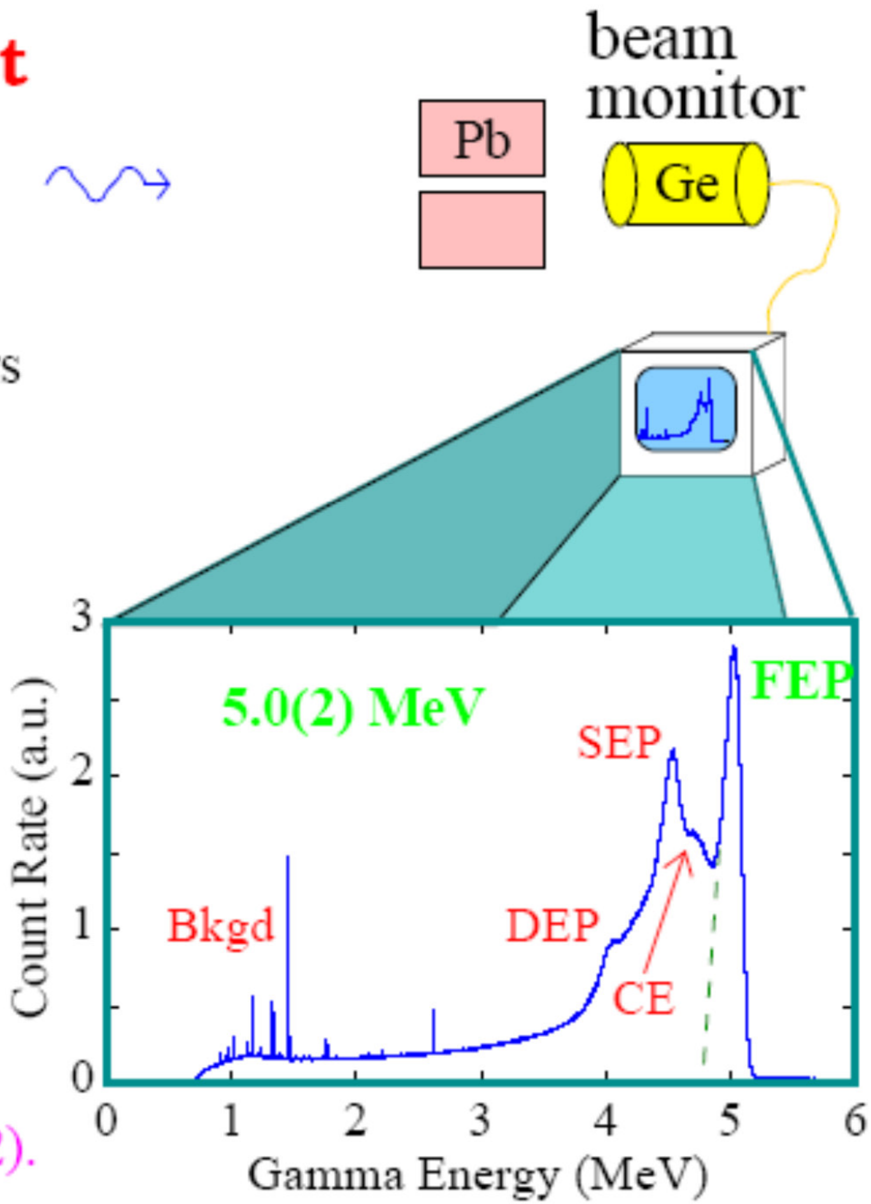
2 − 60 MeV   1.7 − 6.4 eV   ~ 1000

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

nearly monochromatic,   tunable,   completely polarized

Looking at the HIGS Gamma–Ray Beam





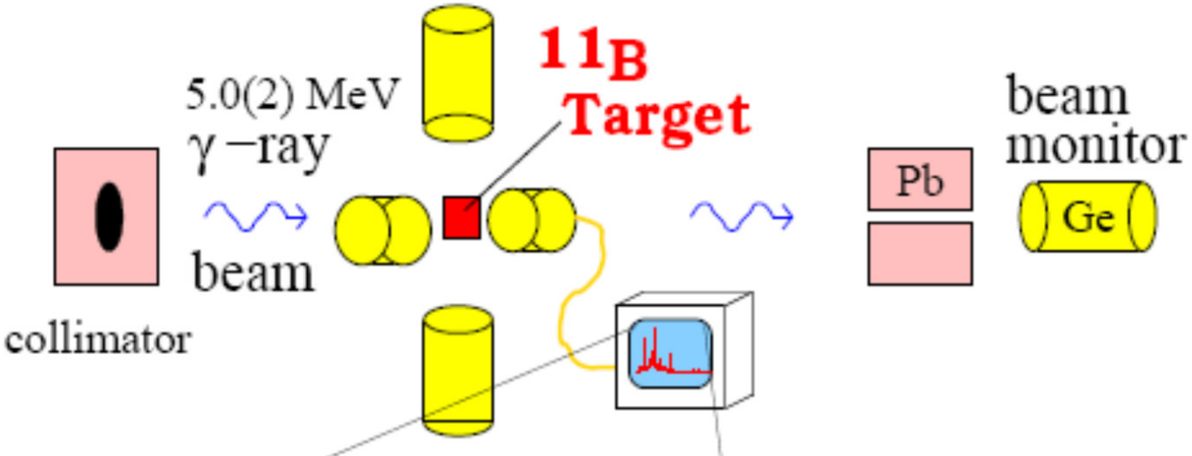
Flux at target: 10^7/s

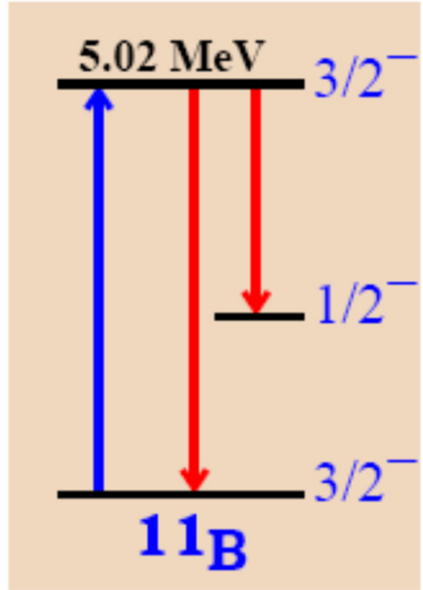
at maximum: 10^5/(s keV)

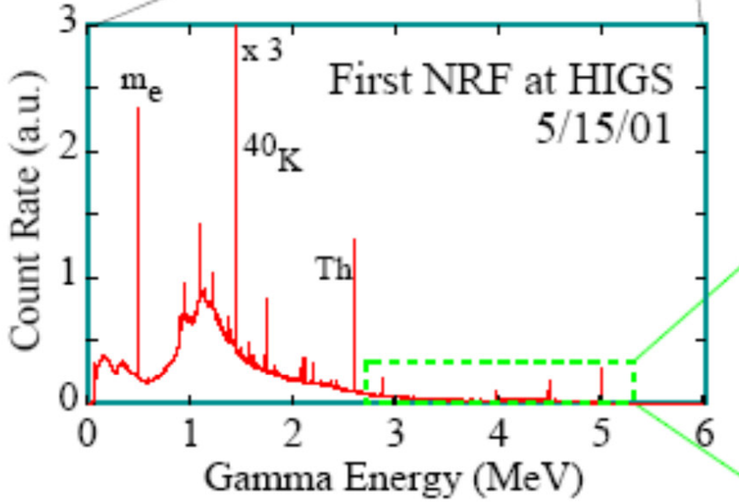
Resolution: 3%
(with 1" collimator)

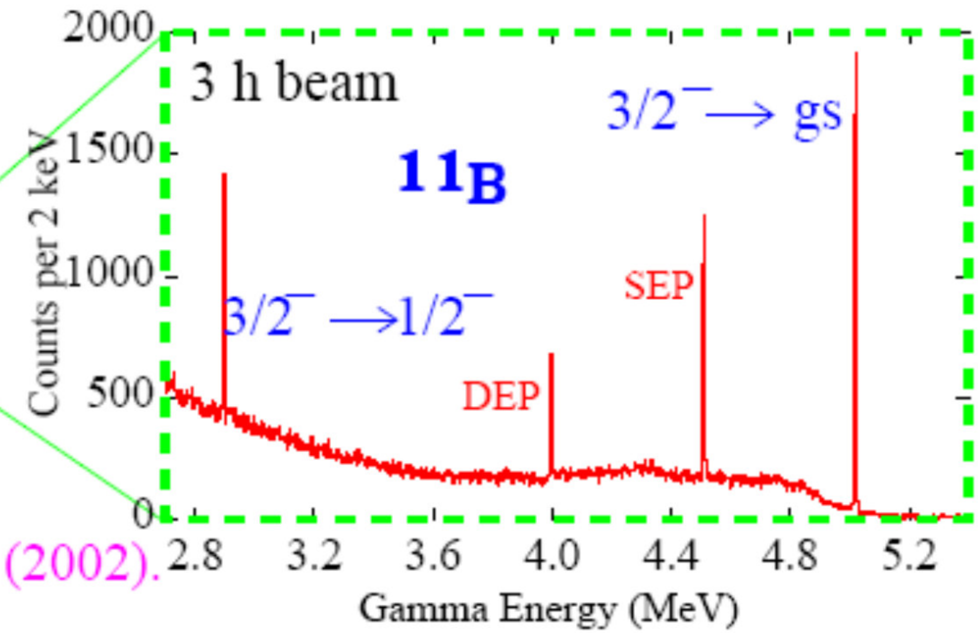
N.Pietralla et al.
Nucl.Instrum.Methods A 483, 556 (2002).

Looking at the Target









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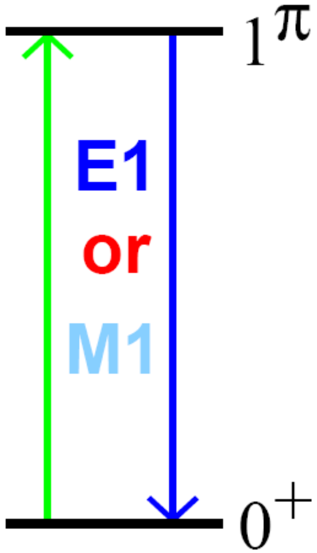
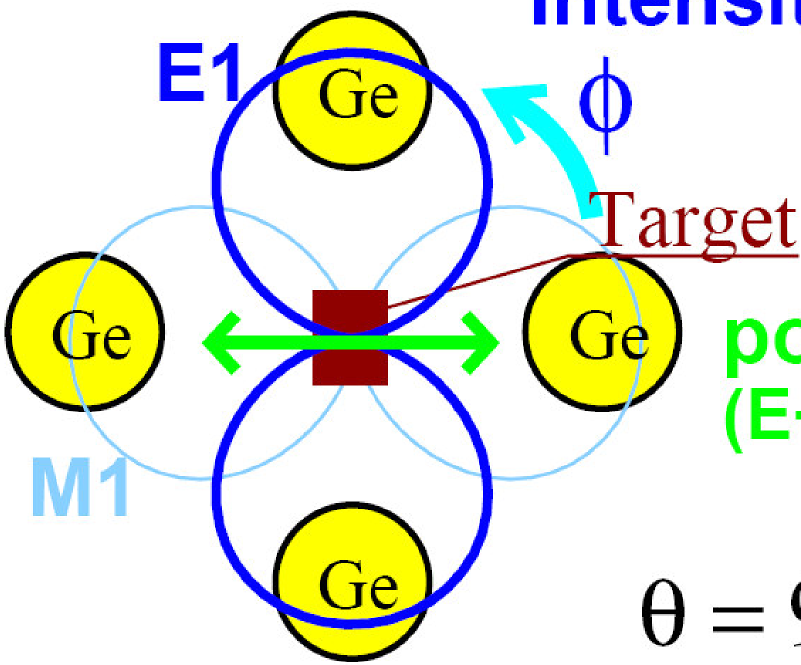
Nucl.Instrum.Methods A483, 556 (2002).

Parity Measurements with Linearly Polarized Photon Beams



Azimuthal Intensity distribution

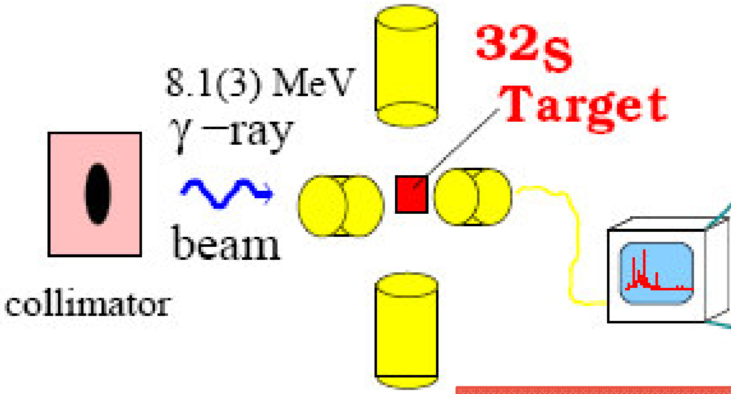


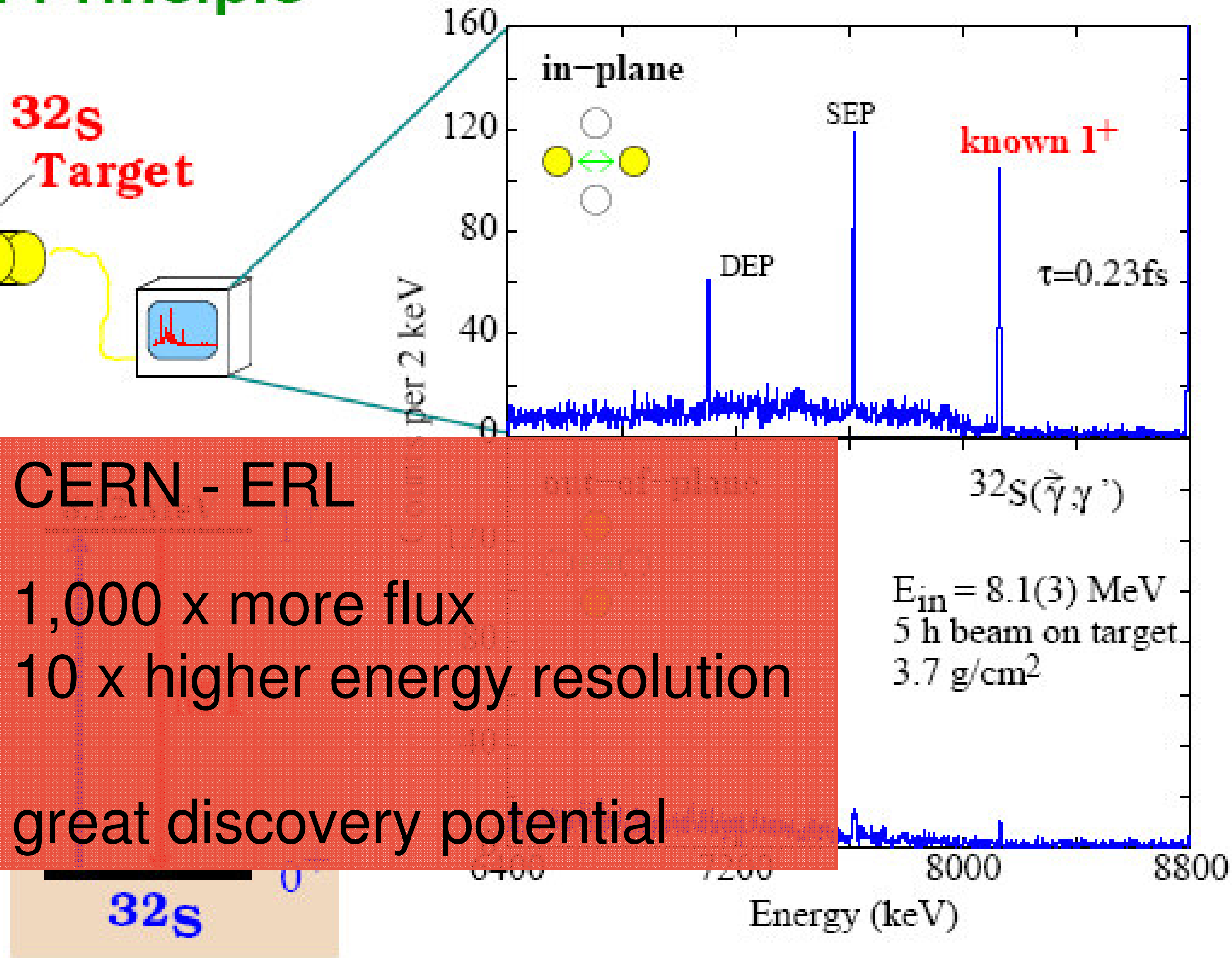
polarization plane (E-vector)

$\theta = 90^{o}$

Azimuthal asymmetry → parity quantum no.

Proof of Principle





DFELL/TUNL polarimeter

Asymmetry

~ 80%

CERN - ERL

1,000 x more flux

10 x higher energy resolution

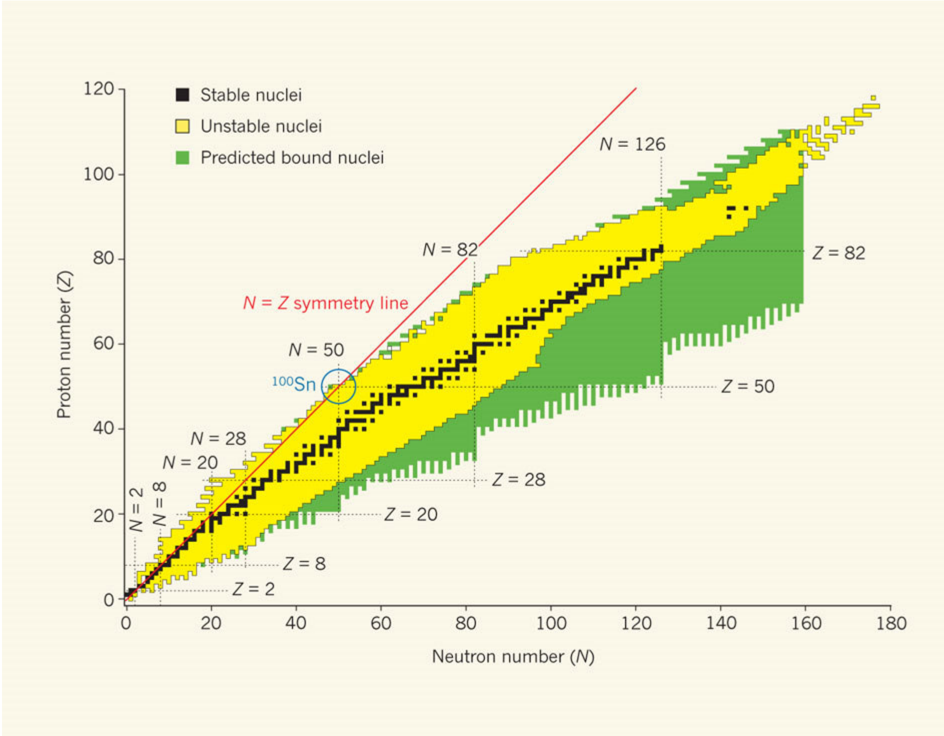
great discovery potential

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

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

Physics with Photon Beams

- Nuclear Structure Physics
  - Nuclear single particle structure
  - Collective nuclear structures
  - Photofission
- Particle-Physics Metrology
  - Neutrino detectors
  - Nuclear matrix elements for ββ-decay
- Nuclear Astrophysics
  - Capture / desintegration reactions
  - Nuclear synthesis
- Applications
  - Radiotomography
  - Nuclear Photonics



ELI – Nuclear Physics, Bucharest, Design

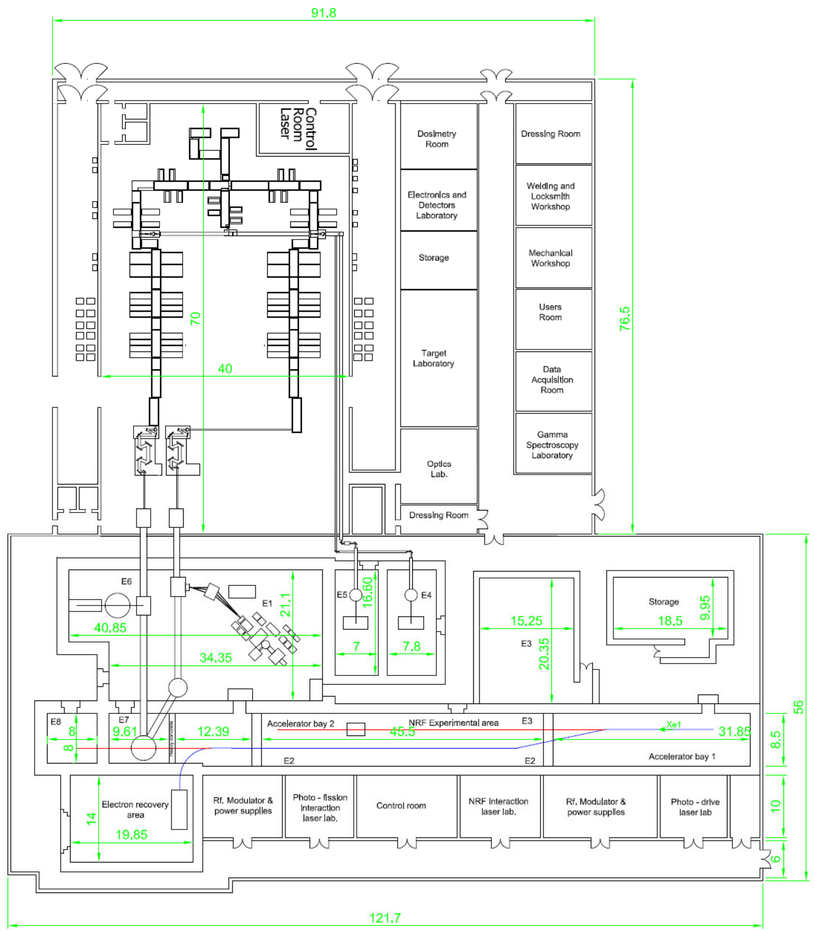
ELI – Nuclear Physics, Floor Plan

TECHNISCHE UNIVERSITÄT DARMSTADT

Equipment

- 2 10-Petawatt-Laser (low-rep., Thales)
- 700 MeV Electron linac (warm)
- external high-rep. high intens. laser
- highest-brillant gamma beams from Lasercompton-backscattering $0.5\ \mathrm{MeV} < E_\gamma < 20\ \mathrm{MeV}$, 10^4 /eV s
- minimale Bandbreite 0.5% - 0.1%

$\rightarrow$ **Photonuclear Reactions**



ELI – NP, Progress

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Civil Conctruction finished: end of 2015

International Scientific Advisory Board
Implementation Phase ELI-NP

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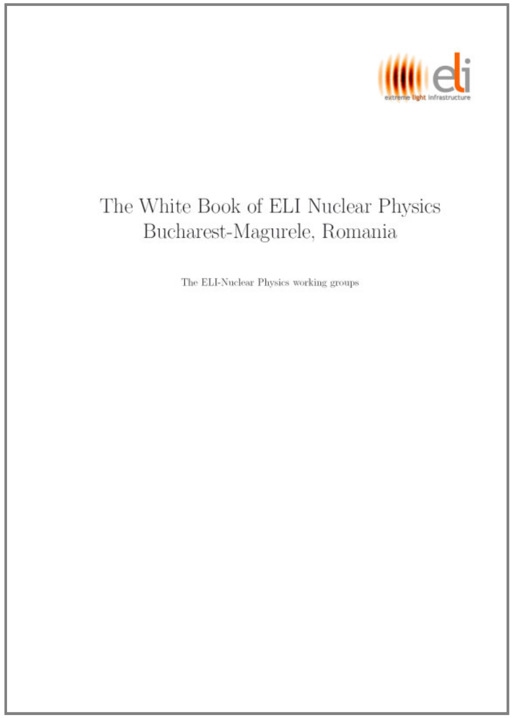
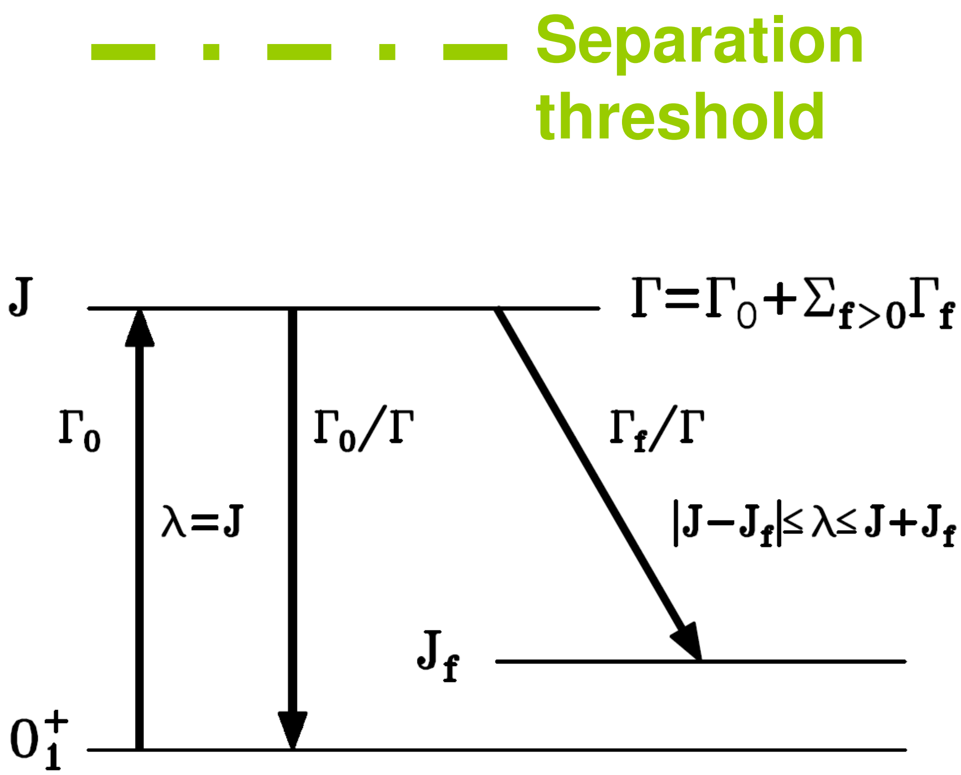

eli

The White Book of ELI Nuclear Physics
Bucharest-Magurele, Romania

The ELI-Nuclear Physics working groups

strong international user community

Nuclear Resonance Fluorescence

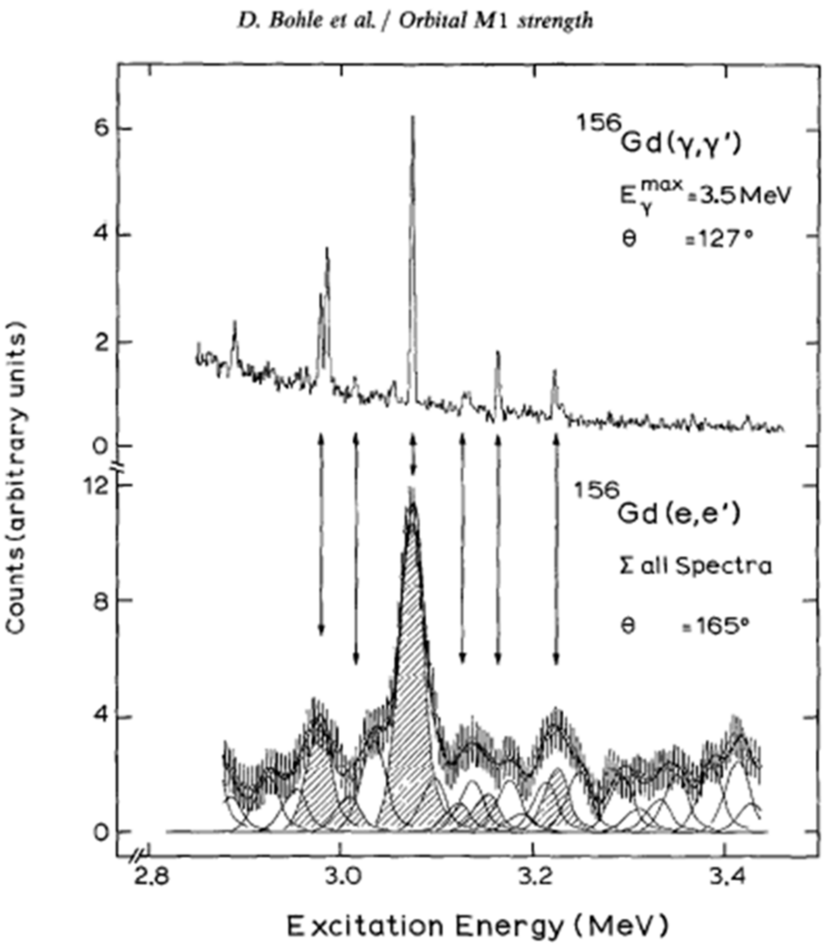


Observables

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

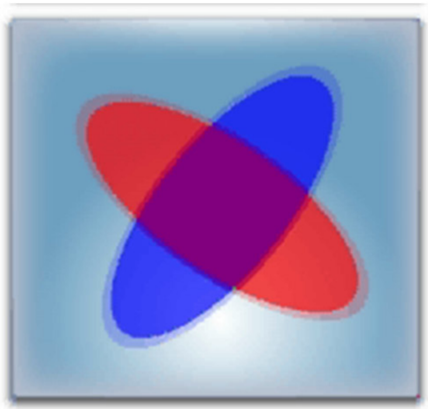
Some Historic Physics Highlights from NRF

(personal selection)



Nuclear Scissors Mode

A.Richter, Darmstadt, 1983



Scissors mode

Classically: current loop

→ magnetic excitation: M1

First example of mixed-symmetry state

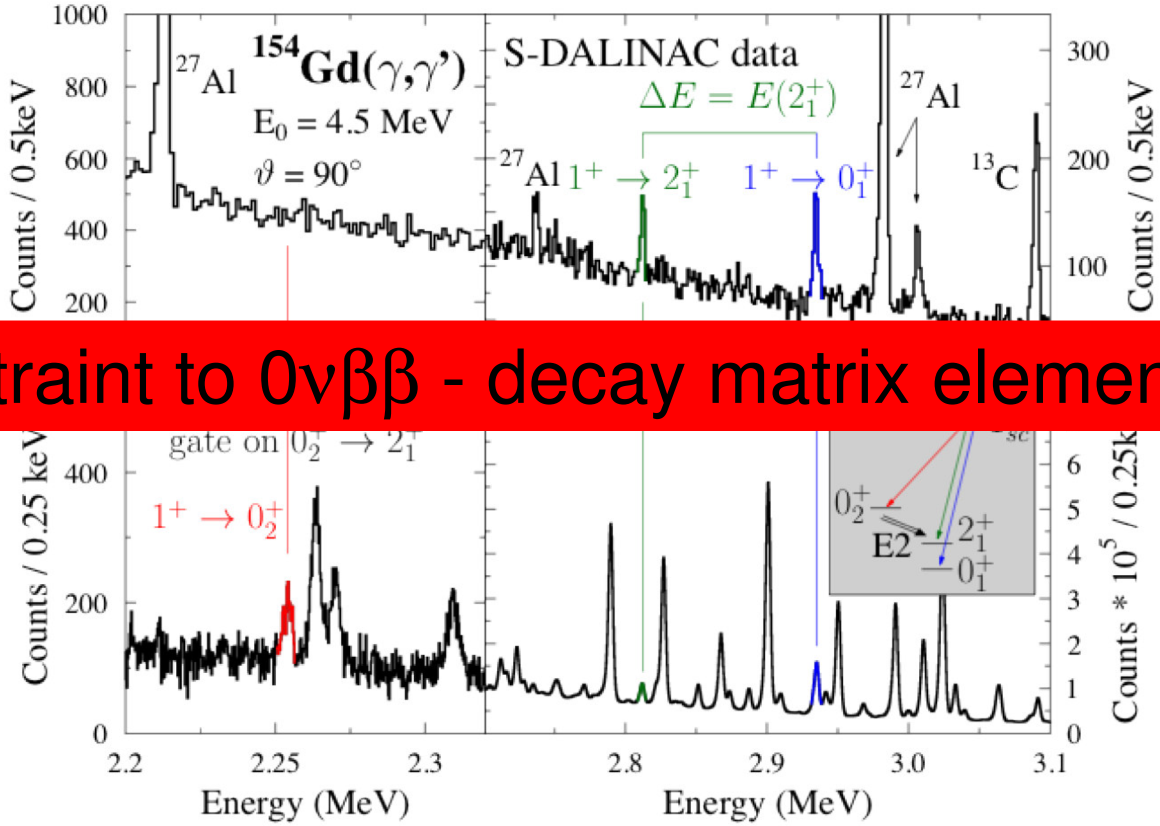
Discovery in electron scattering

Systematics: photon scattering

Scissors Mode: Decay to intrinsic excitations

$1^+_{sc} \rightarrow 0^+_\beta$ first observed in ^{154}Gd (N=90)

- Identification
  @ S-DALINAC



Supplies new constraint to 0νββ - decay matrix element

- Branching
  from γ-spectroscopy
  following EC decay
  (HORUS data)
  with Zilges-group

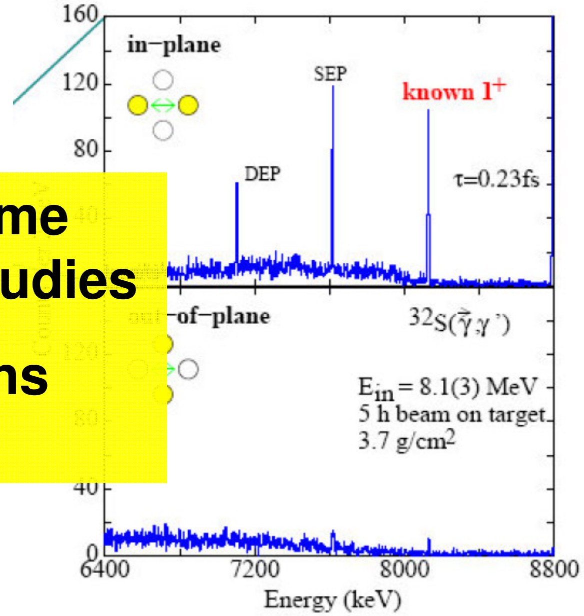
J.Beller, N.P. et al., Phys. Rev. Lett. 111, 172501 (2013).

1. Availability Frontier

- **Current NRF measurements require gramm-size targets (~ 10^{22-21} nuclei)**
- **Required by**
  - **cross sections (~**
  - **detection efficien**
  - **available luminos**
    (number of target nuclei times γ-ray flux)
  - **resonably long beam times (order of days)**
- **Rare p-process nuclei (^{106}Cd,^{130}Ba,^{156}Dy,^{174}Hf)**
  ~ 0.1% ab., enriched material at ~$1,000/mg
- **Long-lived radioactive isotopes(^{10}Be,^{182}Hf,^{250}Cm)**
  $T_{1/2}$ > ~10,000 yrs.

51 more nuclides would become accessible to photonuclear studies

A variety of scientific questions could be answered.

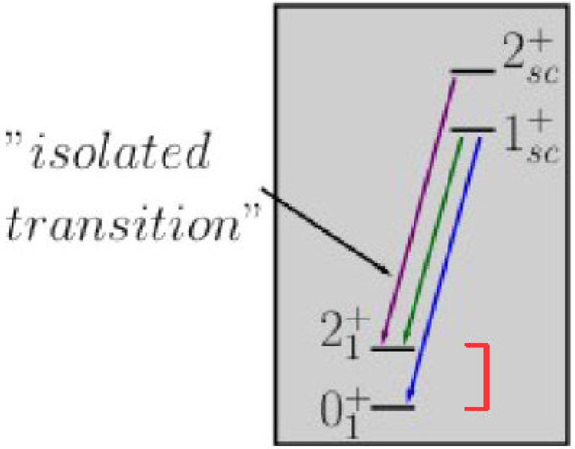


Some Examples for Science Cases on Rare or Long-lived Radioactive Isotopes

- **^{10}Be: What dominates the low-energy E1 strength in light nuclei, 1s – 1p particle-hole transitions or cluster structure?**
  (lifetimes of $1^-/2^+$ doublet at 6 MeV, 2nd/3rd excited state)
- **^{53}Mn: What is the fragmentation of the $\pi(f_{7/2} - f_{5/2})$ spin-flip strength across the Z=28 shell?**
- **^{126}Sn: How does the fine-structure of the PDR evolve with neutron excess?**
- **^{156}Dy: Test of the predicted decay branch of $0\nu\beta\beta$-decay at N=90 from M1 decay branching of the 1^+ scissors mode**
- **$^{248}Cm_{152}$: What are the fission resonances at the N=152 shell?**
- **^{250}Cm: First access to dipole strength above N=152 shell**

2. Sensitivity Frontier

- Search for weak signals sensitive to the physics under study
- One example: Rotational Moment of Inertia of the Scissors Mode



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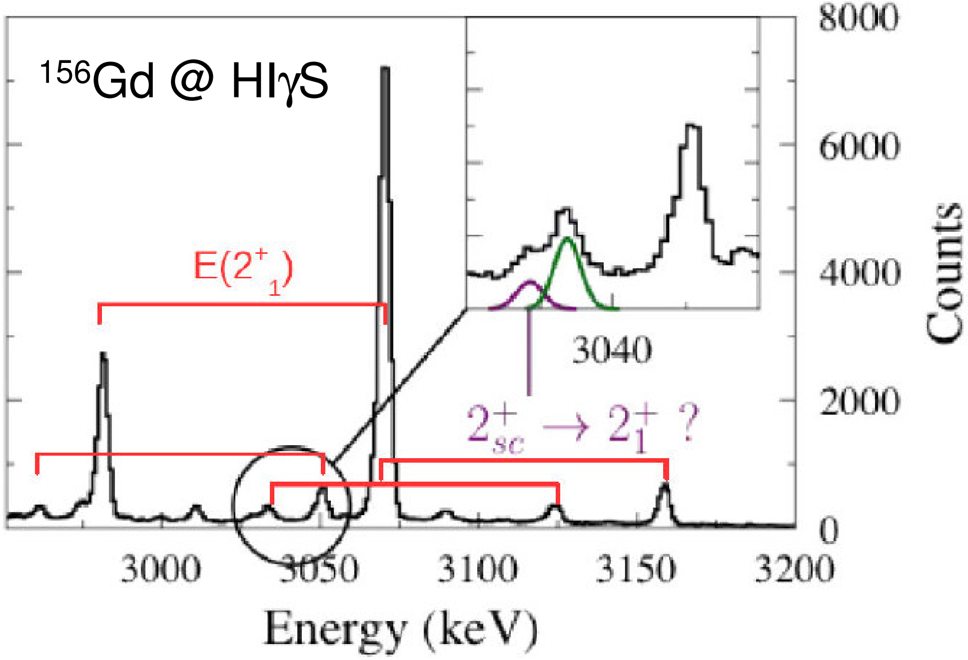


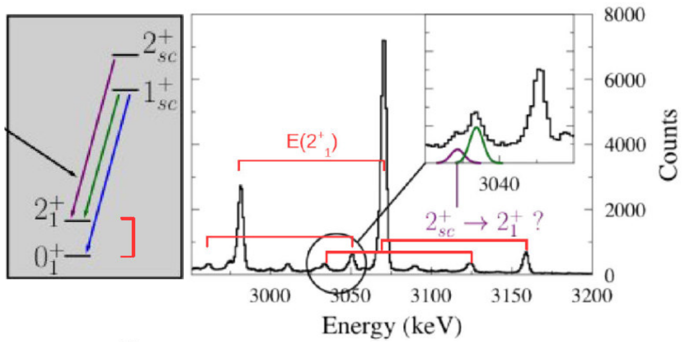
Data: J.Beller, TU Darmstadt

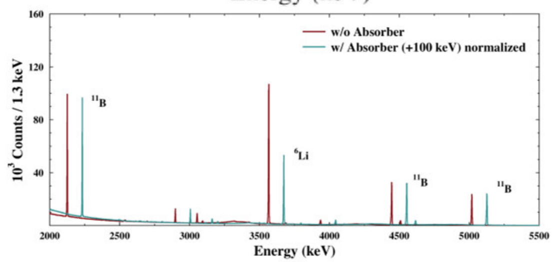
„Discovery Frontier“ for NRF at HIγS-2 / ELI-NP

High-Intensity Frontier = „Discovery Frontier“

(scientific opportunities)

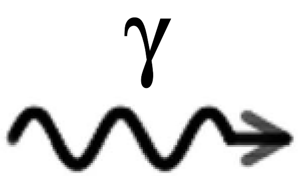
- **„Availability Frontier“**
  (NRF on rare isotopes,
  access to broader „nuclear gene pool“)
- **„Sensitivity Frontier“**
  (weak channels: strong physics)
- **„Precision Frontier“**
  (high count rates, new methods)

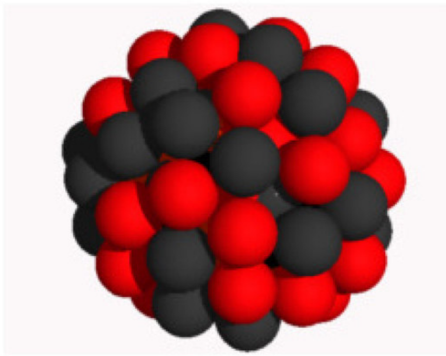




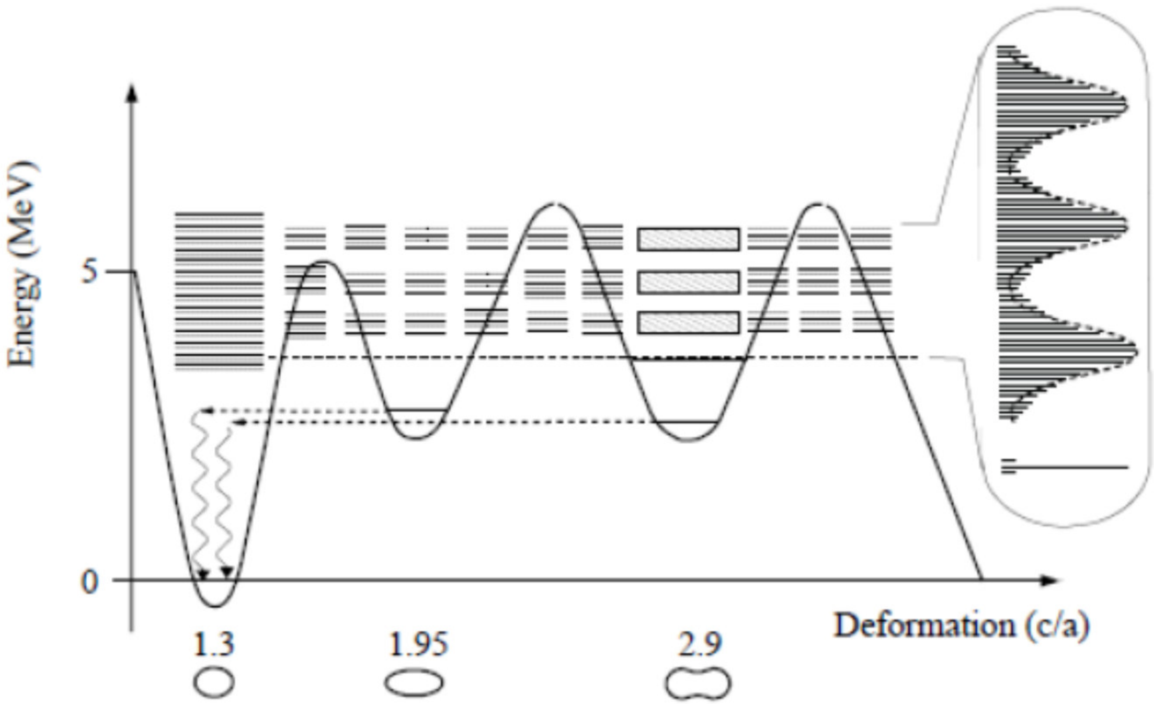
Thank you very much !

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





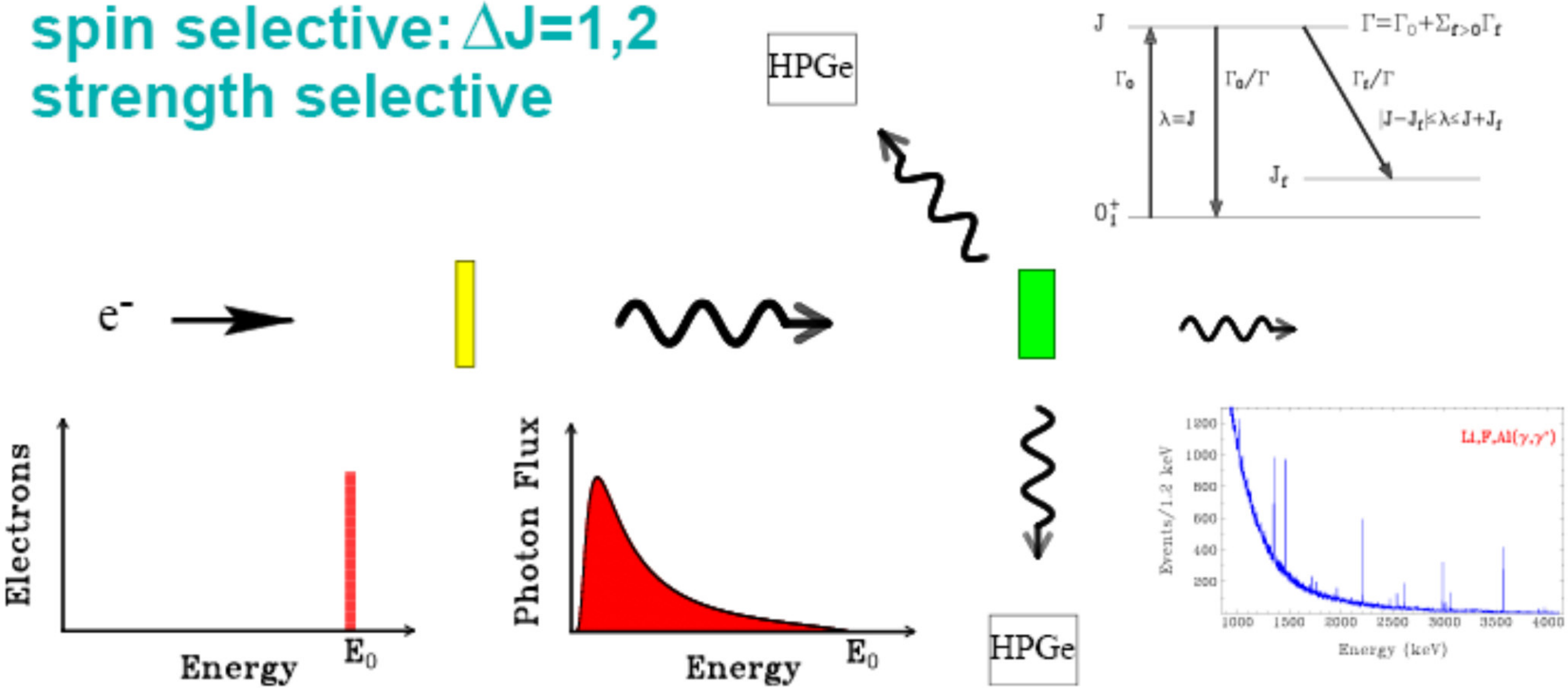
Photofission



Photon Scattering
(Nuclear Resonance Fluorescence)

Traditionally Bremsstrahlung: Kneissl,Pietralla,Zilges, J.Phys.G 32, R217 (2006).

high energy resolution
spin selective: $\Delta J=1,2$
strength selective



NRF Basic Facts

Widths of particle-bound states: $\Gamma \leq 10$ eV

Single-spin level density: $\rho_J \leq 10^4$ MeV^{-1}

→ isolated resonances

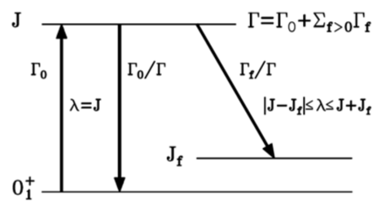
QM:

$$H\Psi = i\hbar\dot{\Psi} \qquad \Psi = \Psi_0\, e^{i\epsilon t/\hbar}, \quad \epsilon = E_0 + i\Gamma/2$$

Decay law:

$$\langle\Psi|\Psi\rangle(t) = e^{-t/\tau} = e^{-\Gamma t/\hbar}, \quad \Gamma\ \tau = \hbar$$

Typical lifetime limit: $\tau \geq 100$ as



Total width:

$$\Gamma = \sum_i \Gamma_i, \qquad \Gamma_i = \sum_{\pi\lambda} \Gamma_{i,\pi\lambda}$$

Transition rates:

$$\Gamma_{i,\pi\lambda} = c_{\pi\lambda} \left(\frac{E_\gamma R}{\hbar c}\right)^{2\lambda+1} B(\pi\lambda; J_i \rightarrow J_f)$$

NRF cross section

Breit-Wigner absorption resonance curve for isolated resonance
[from Fourier transform: $\Psi(t) \rightarrow \Psi(E)$]

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

On resonance cross sect.s are very large: $\sigma_0 \cong 200$ b (for $\Gamma_0=\Gamma$, 5 MeV)
However, resonances are very narrow

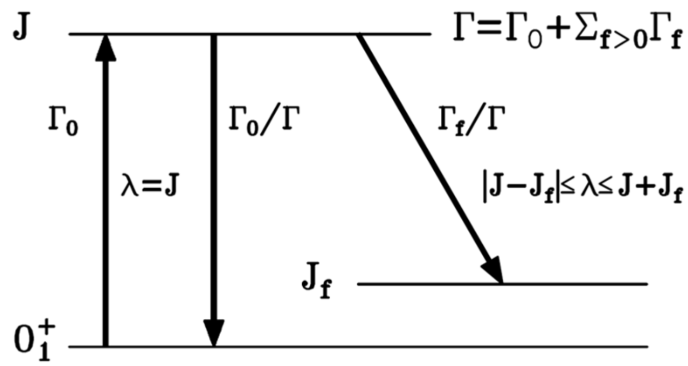
Thermal motion of target nuclei lead to Gaussian Doppler-broadening of resonance (typical Doppler width $\Delta \approx$ few eV >> $\Gamma \approx$ 10s of meV)

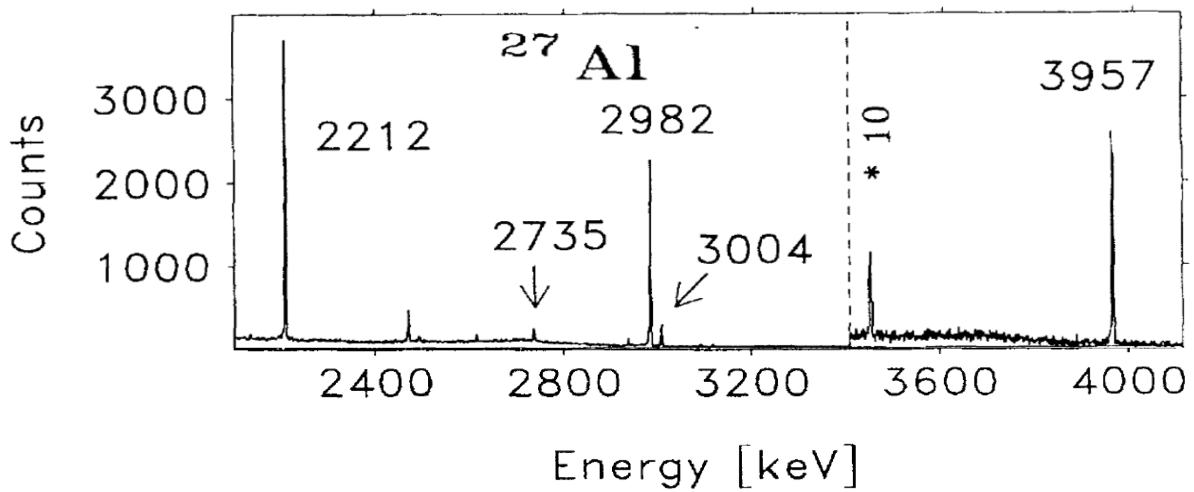
$$\sigma_a^D(E) = \frac{\sqrt{\pi}}{2} \sigma_0 \frac{\Gamma}{\Delta} e^{-\left(\frac{E-E_r}{\Delta}\right)^2}$$

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

Scattering cross section

$$I_{sc,0} = I_a \, \Gamma_0/\Gamma \sim \Gamma_0^2/\Gamma$$





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

Angular Distribution, Spin Quantum Number J

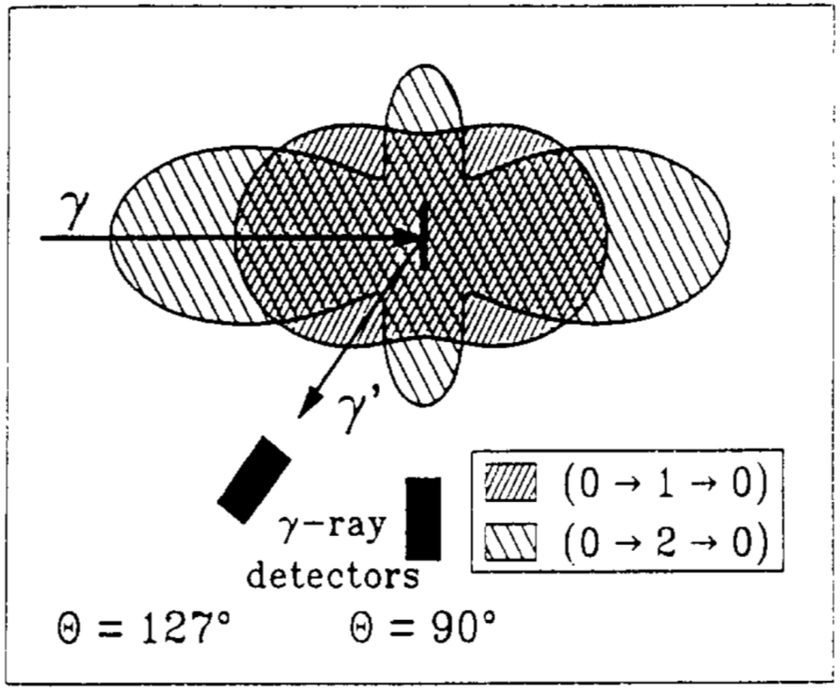
$$\left\langle \frac{d\sigma}{d\Omega} \right\rangle_f (\theta) = g \left(\frac{\pi \hbar c}{E_r} \right)^2 \Gamma_0 \frac{\Gamma_f}{\Gamma} \frac{W(\theta)}{4\pi} \equiv I_{s,f} \frac{W(\theta)}{4\pi} \ .$$

Photon helicity 1, m = ±1
→ non-isotropically alignment of photo-excited state (even oriented for circularly polarized beam)

Pronounced angular correlations when involving spin-0 states (ee-nuclei)

Angular distribution functions W(ϑ) from angular correlation theory

→ Spin quantum numbers J (easiest in even-even nuclei).



90°/127° – intensity ratios: 2.0 (J=2) vs 0.8 (J=1)

Observables in NRF

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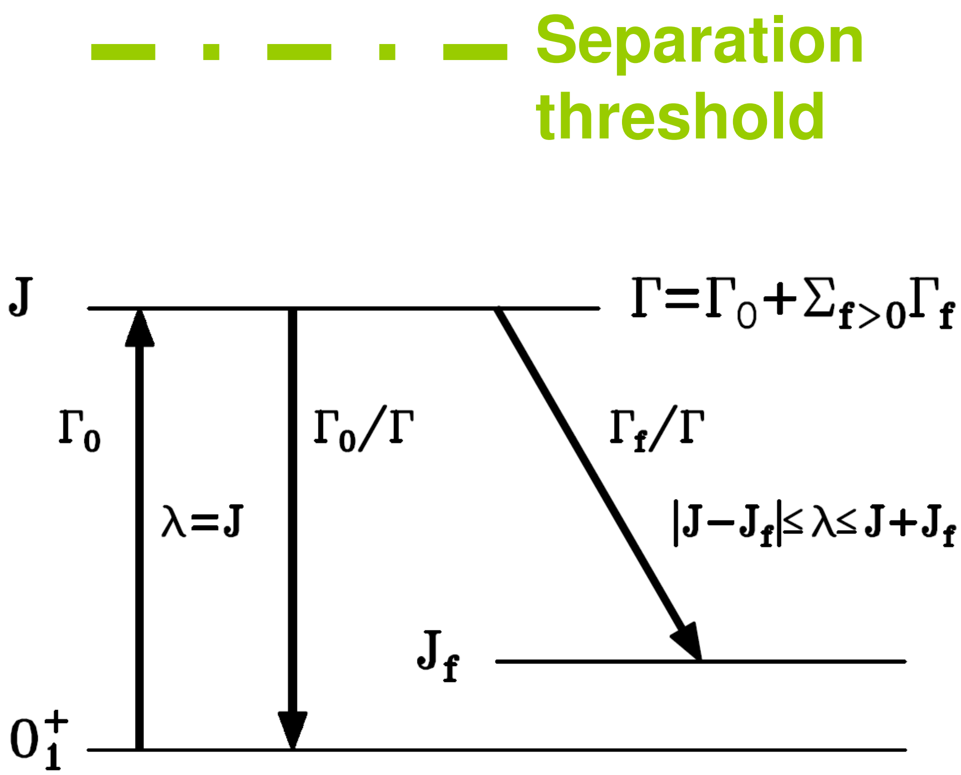

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S-DALINAC at TU Darmstadt

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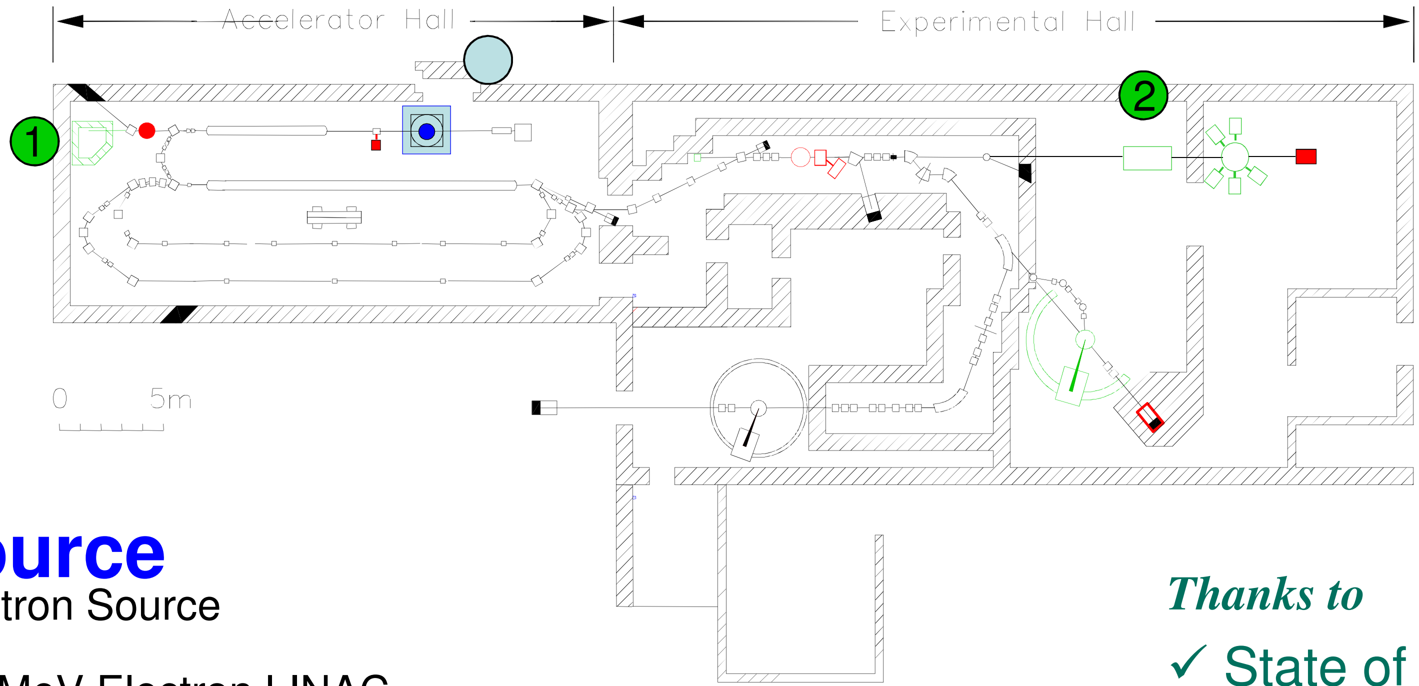


Source

- Electron Source
- 130 MeV Electron LINAC

Photon Experiments

1. 10 MeV Injector: Photon Scattering / Photofission
2. < 30 MeV Tagger: Photodesintegration / Photon Scattering

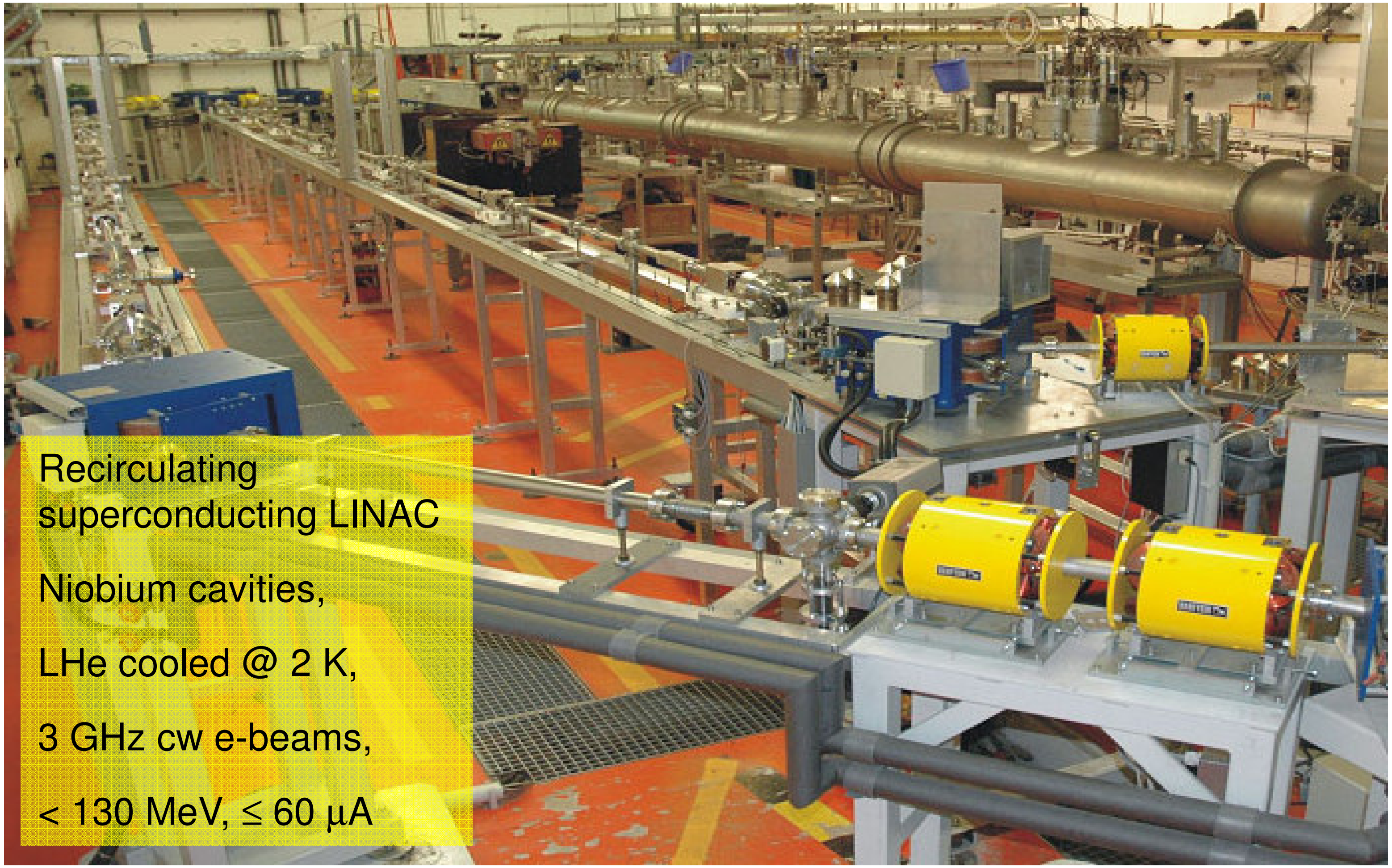
Thanks to

✓ State of Hesse

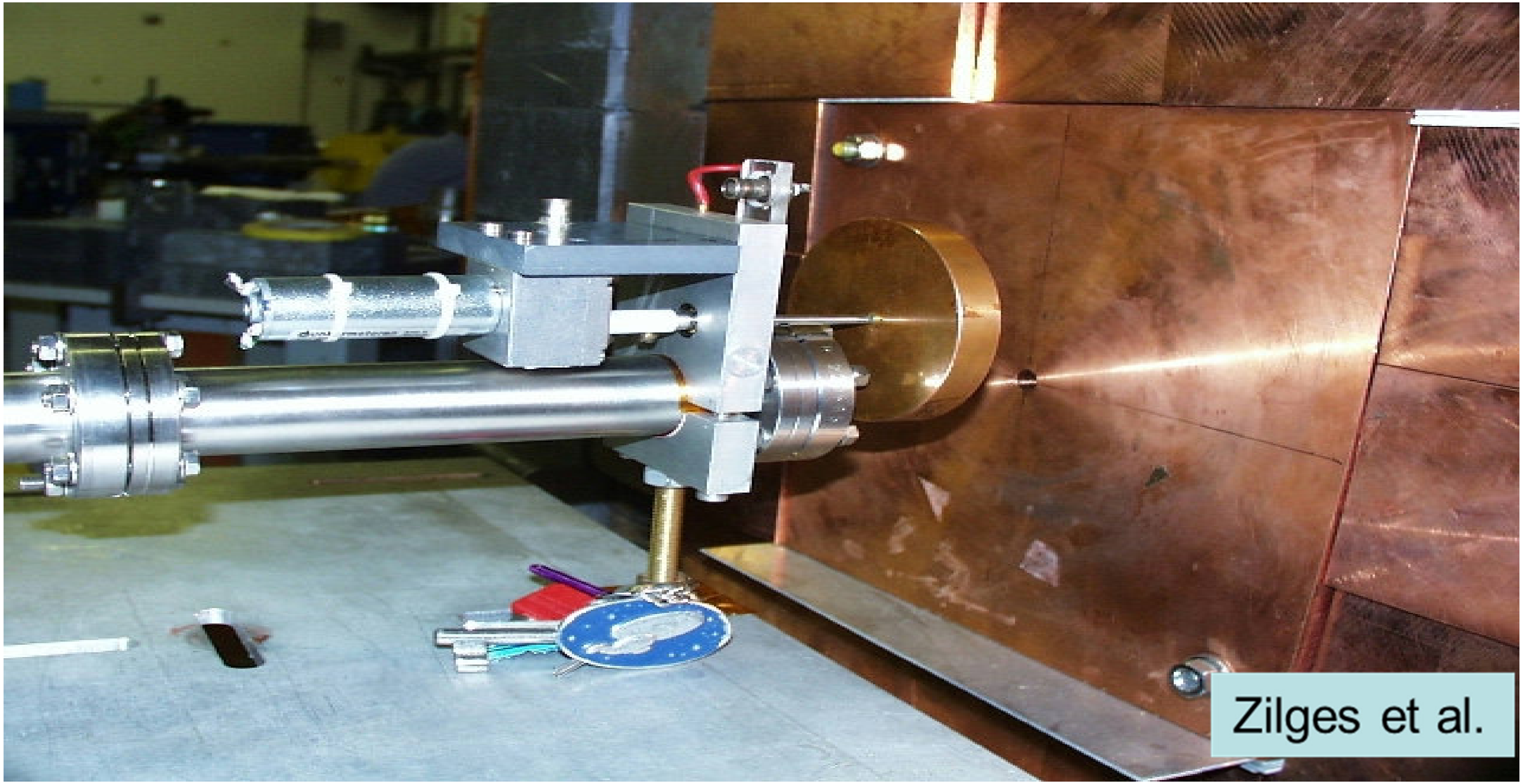
✓ TU Darmstadt

✓ DFG

S-DALINAC at TU Darmstadt

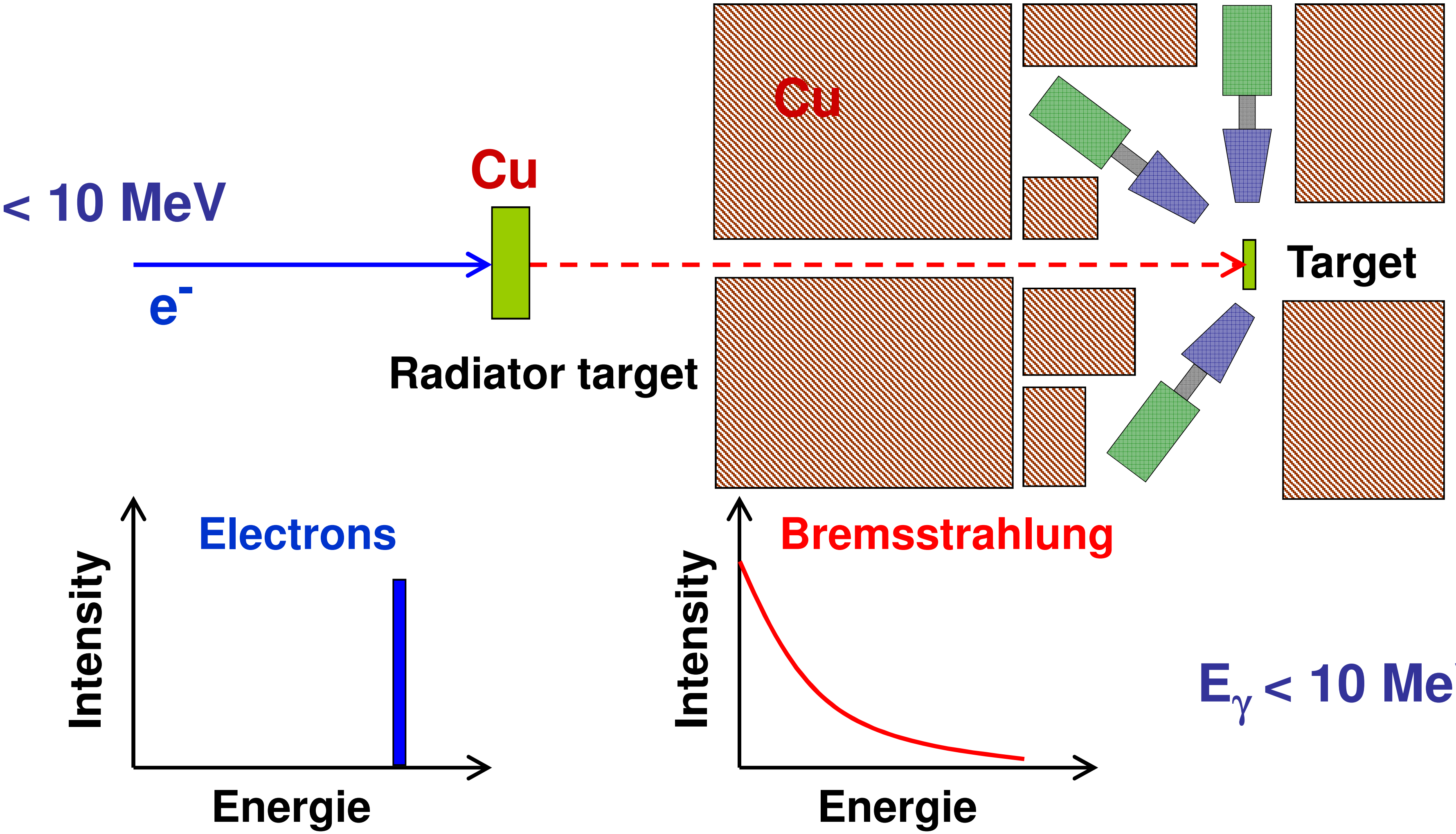


Bremsstrahlung-Site



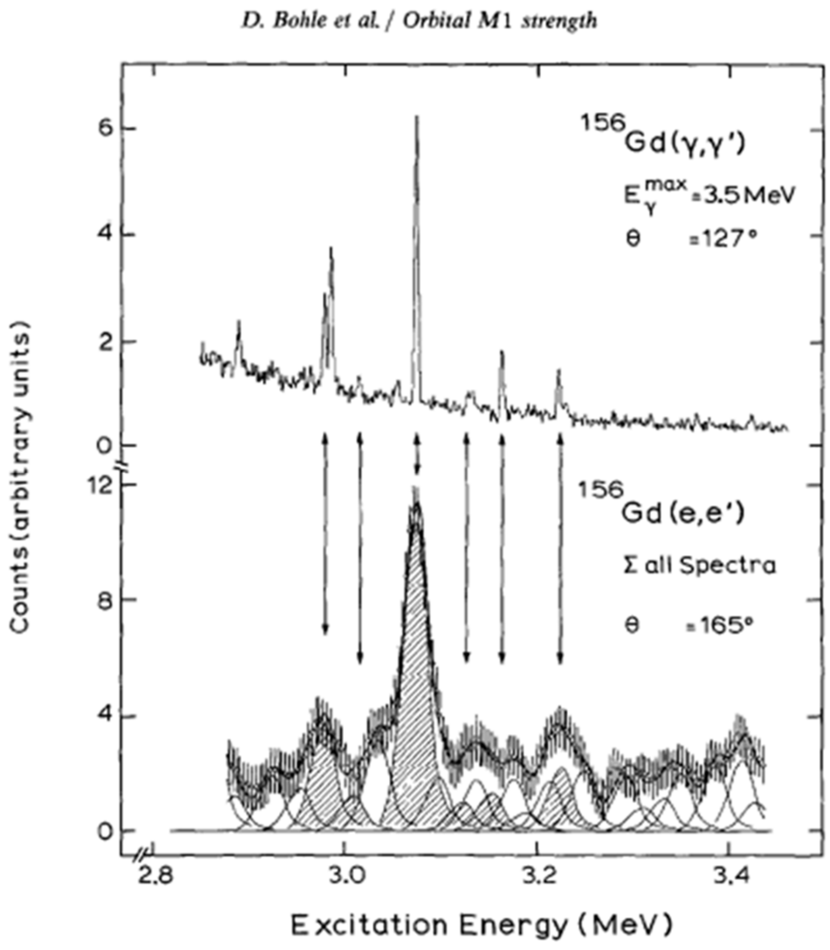
Darmstadt Low-Energy Photon Scattering Site at S-DALINAC

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

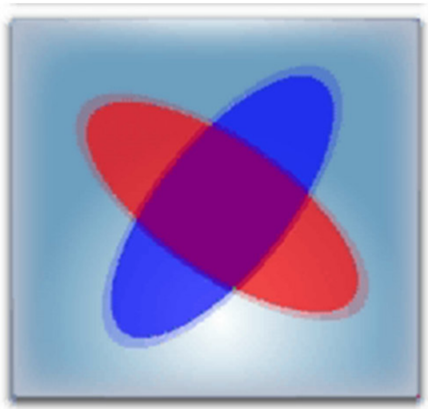


$E_\gamma < 10$ MeV

Some Historic Physics Highlights from NRF
(personal selection)



Nuclear Scissors Mode
A.Richter, Darmstadt, 1983



Scissors mode

Classically: current loop

→ magnetic excitation: M1

First example of mixed-symmetry state

Discovery in electron scattering

Systematics: photon scattering

Systematics of scissors mode in rare earth's

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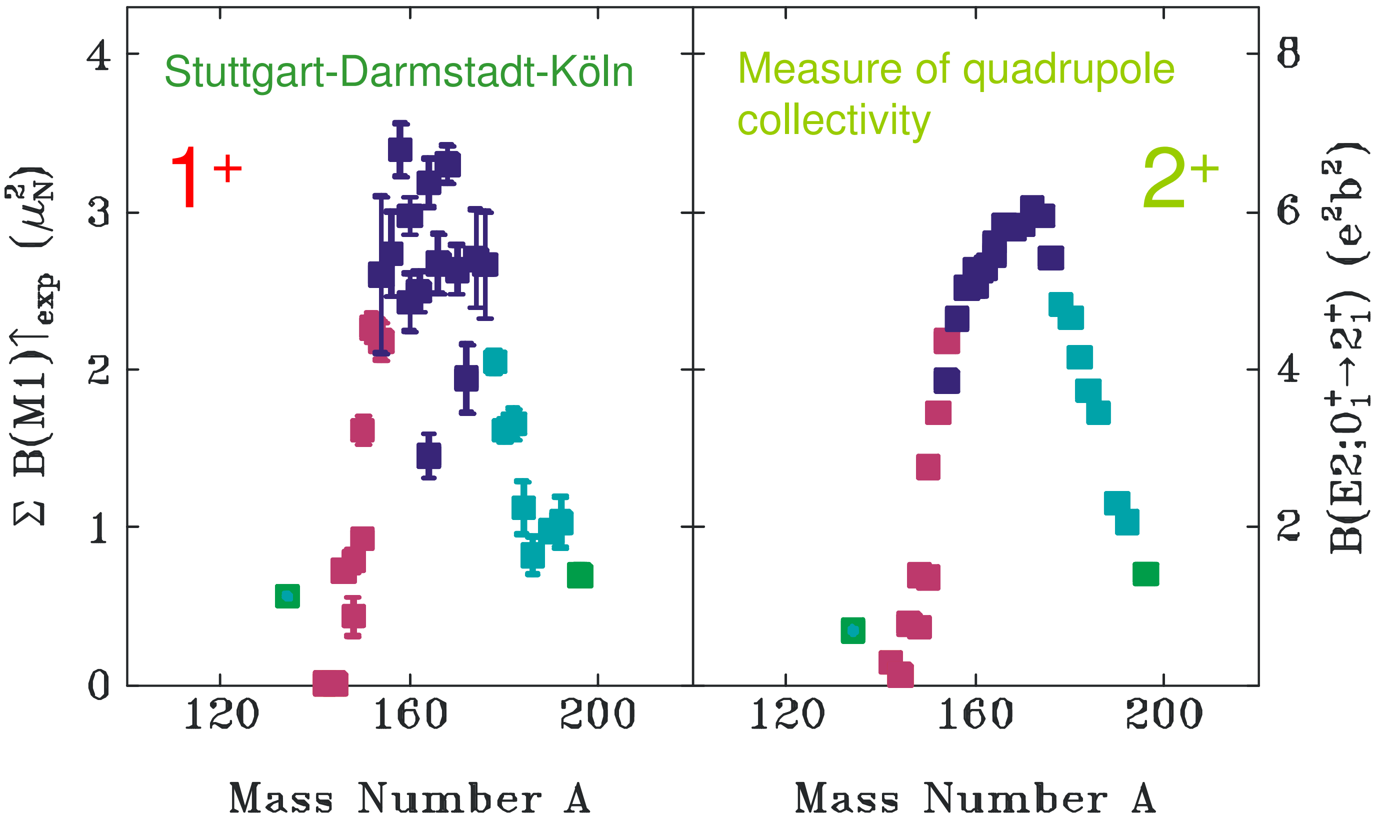
Collectivity of the Scissors Mode

Richter, Kneissl, von Brentano et al.

M1



E2

N. Pietralla et al., PRC 58, 184 (1998)

Nuclear Structures with Mixed pn-Symmetry

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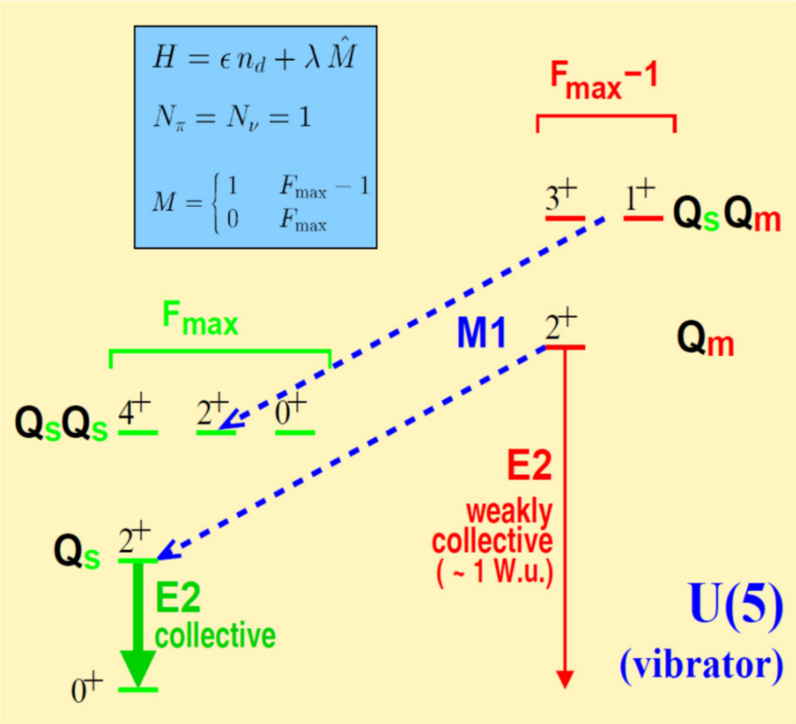
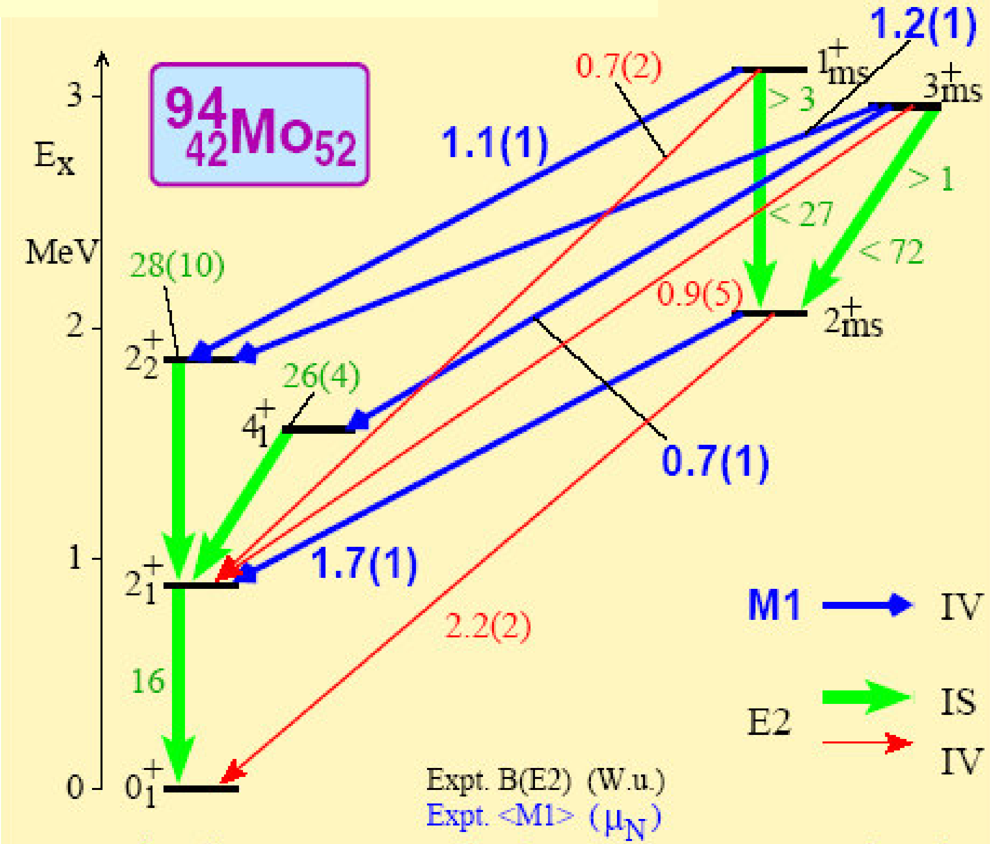
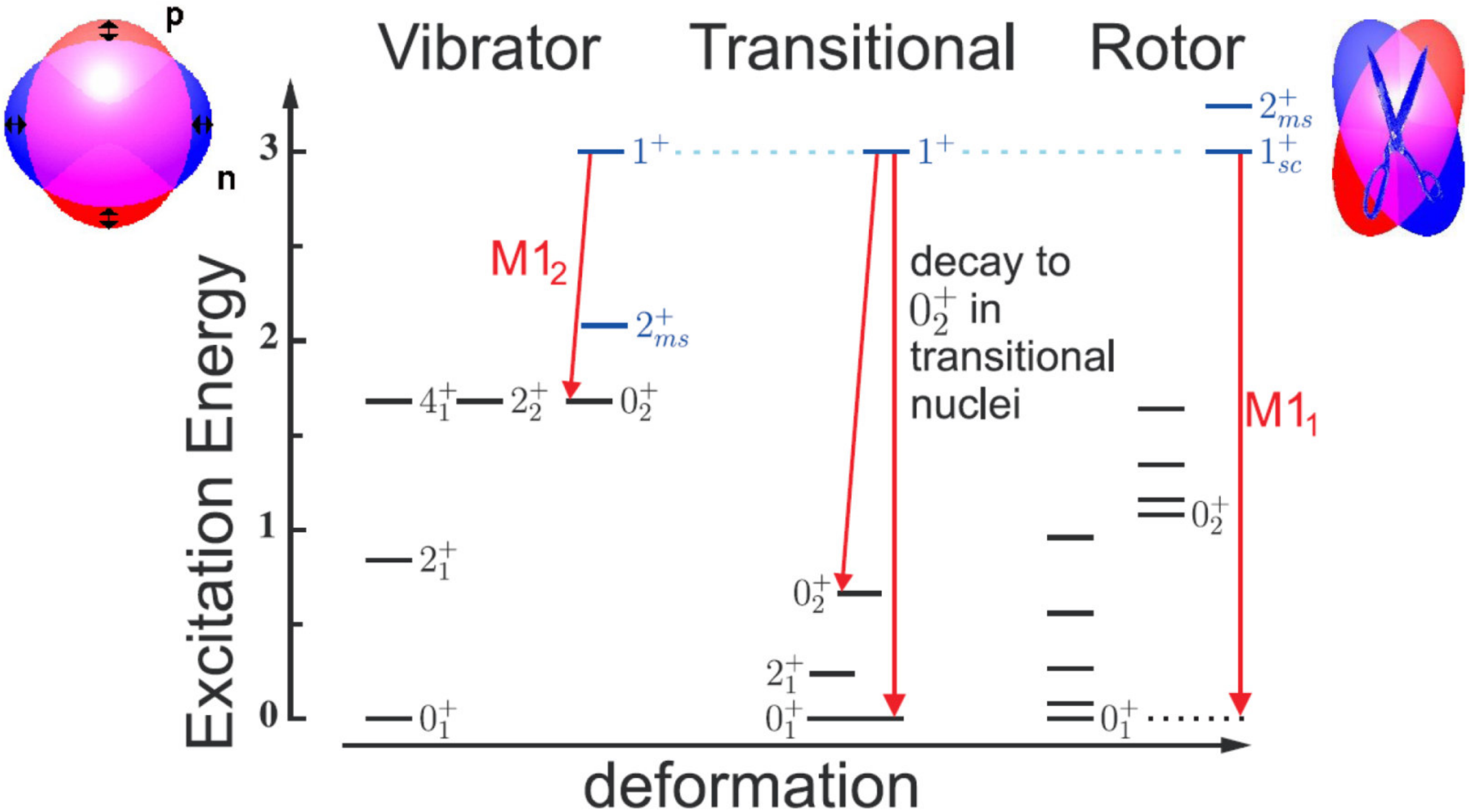
M1 as unique signature for mixed-symmetry states





N.Pietralla, C.Fransen et al., Phys.Rev.Lett. 83, 1303 (1999).
N.Pietralla, C.Fransen et al., Phys.Rev.Lett. 84, 3775 (2000).
C.Fransen, N.Pietralla et al., Phys.Rev.C 67, 024307 (2003).

M1 Scissors mode: Decay to intrinsic excitations



‚Application‘: Dipole strength and 0νββ-decays

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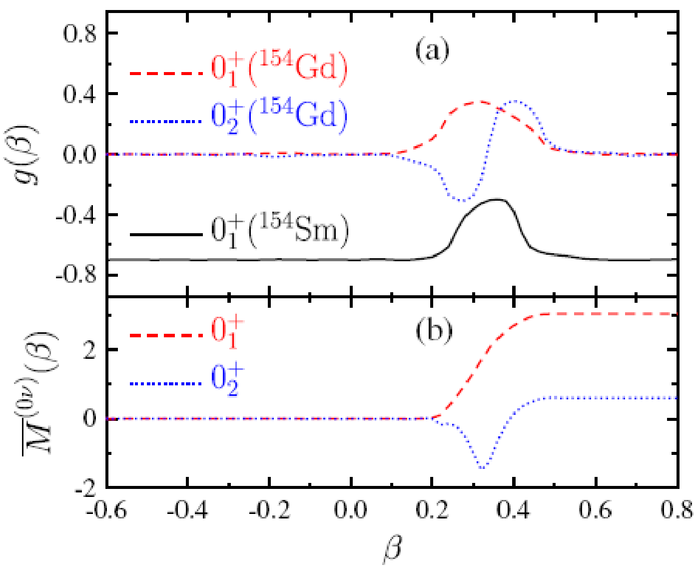
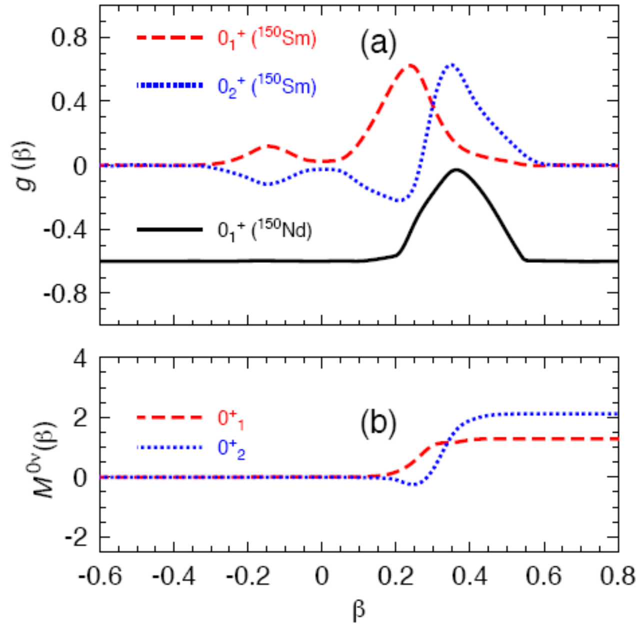
PRL **111,** 172501 (2013) PHYSICAL REVIEW LETTERS week ending 25 OCTOBER 2013

Constraint on $0\nu\beta\beta$ Matrix Elements from a Novel Decay Channel of the Scissors Mode: The Case of ^{154}Gd

J. Beller,[1,*] N. Pietralla,[1] J. Barea,[2] M. Elvers,[3,†] J. Endres,[3,‡] C. Fransen,[3] J. Kotila,[4] O. Möller,[1] A. Richter,[1] T. R. Rodríguez,[1] C. Romig,[1] D. Savran,[5,6] M. Scheck,[1,7] L. Schnorrenberger,[1] K. Sonnabend,[8] V. Werner,[9] A. Zilges,[3] and M. Zweidinger[1]



^{150}Nd: larger **0νββ-decay branch to 0^+_2 state** than to gs due to QSPT at N=90.



Pygmy Dipole Resonance

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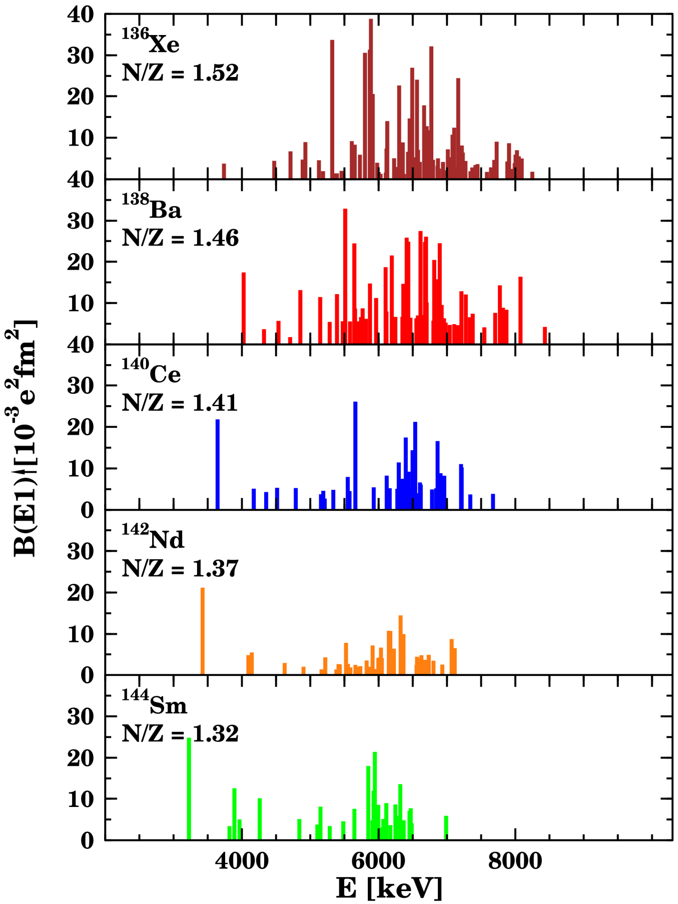
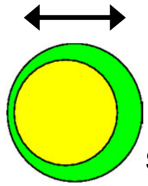


- **Concentration around 5-7 MeV**

- **Fragmented strength**

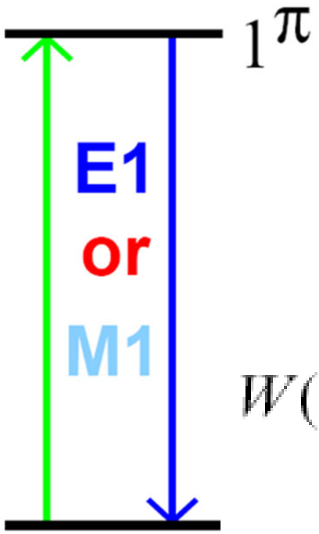
- **Summed strength: Scaling with N/Z ?**

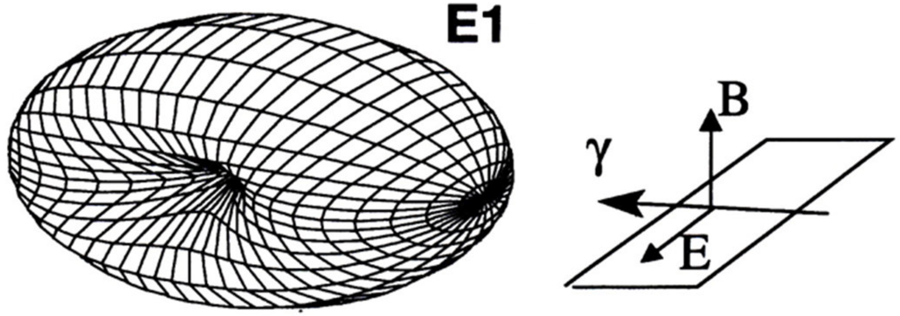


*R.-D. Herzberg et al., PLB **390**, 49 (1997).*
*A. Zilges et al., PLB **542**, 43 (2002).*
*D. Savran et al., PRC **84**, 024326 (2011).*

*U. Kneissl et al., J.Phys.G **32**, R217 (2006).*

Parity quantum number π for J=1 states





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

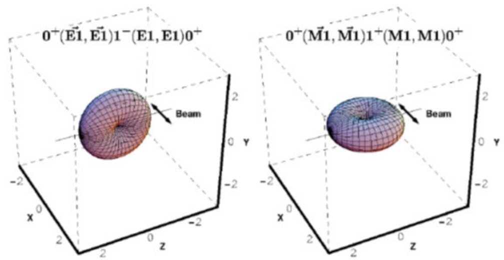
N.Pietralla, H.R. Weller et al., NIM A 483 (2002) 556.

Elastic scattering distribution not isotropic about incident polarization plane.

No intensity along oscillating dipole vector

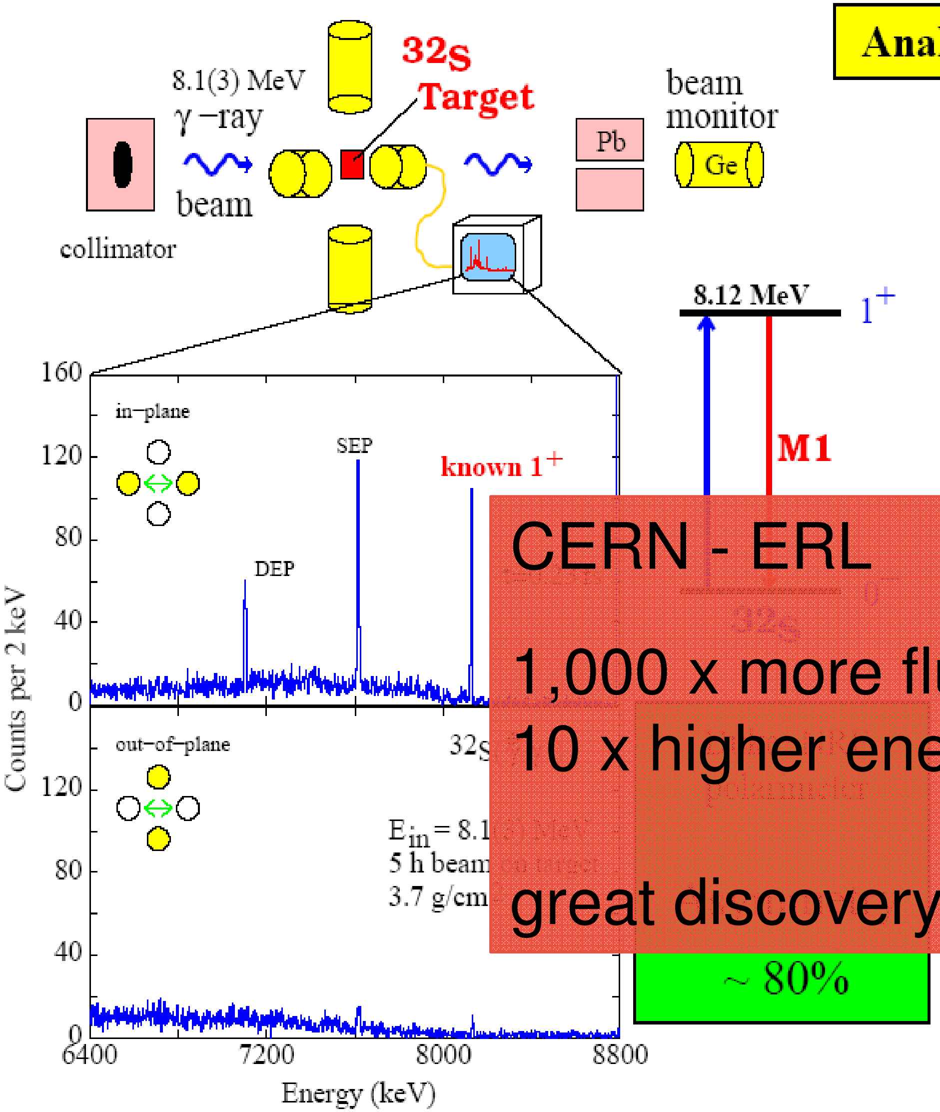
Azimuthal rotation by 90^{o} for M1 and E1 distributions

Observable only for linearly polarized beam

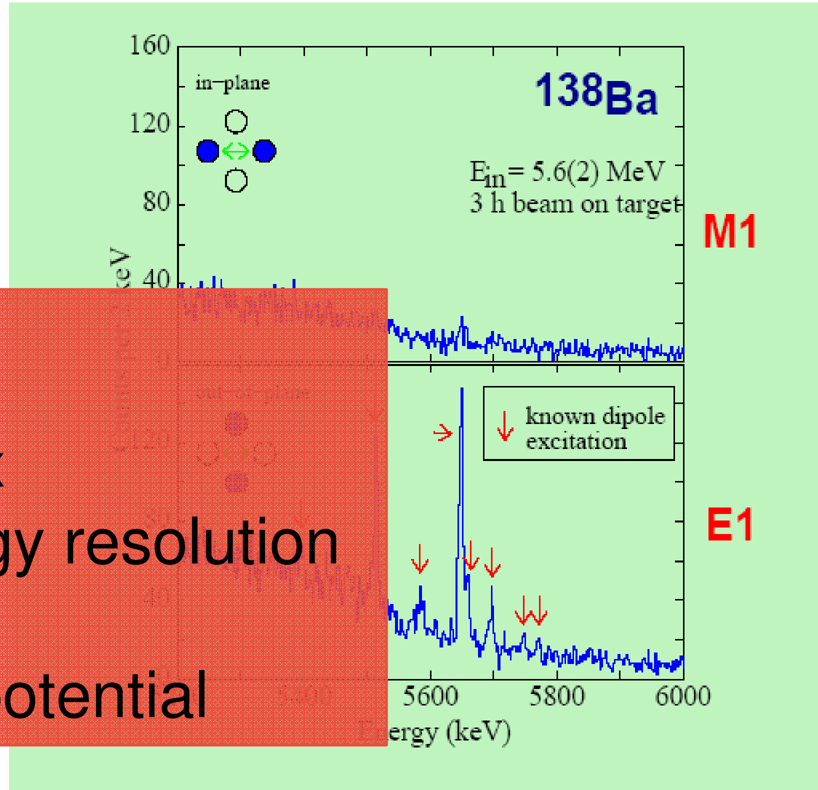


Analyzing Power for the Pygmy Resonance

"pygmy resonance": all E1 !



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



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!)

Advanced set-up: γ^3 at HIγS

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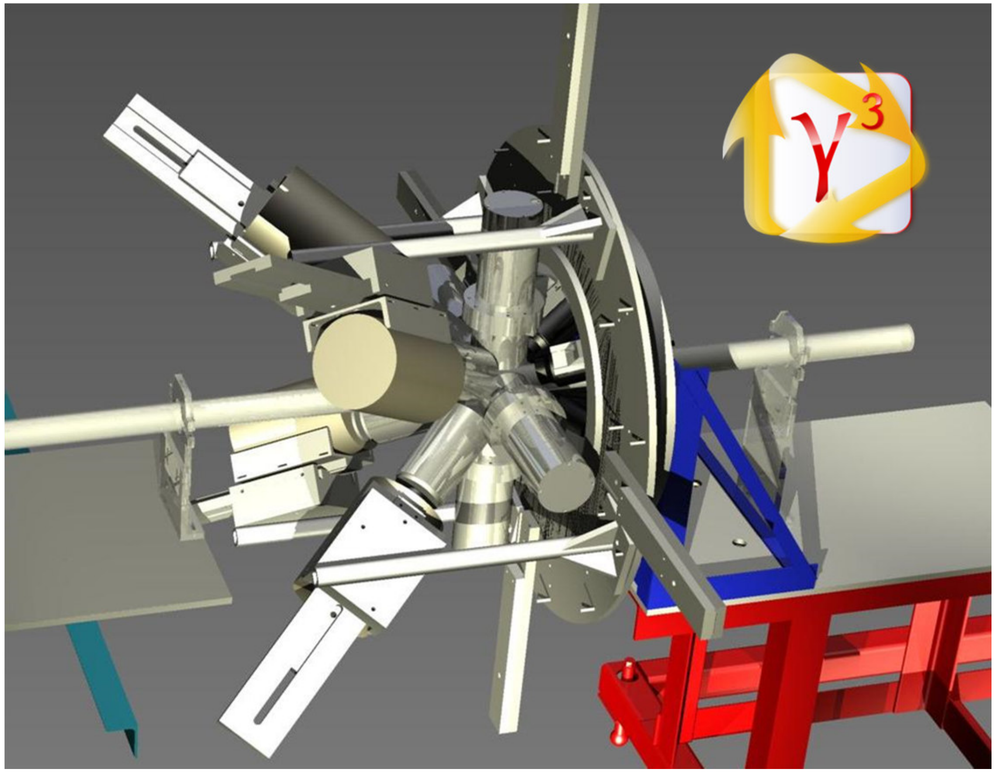
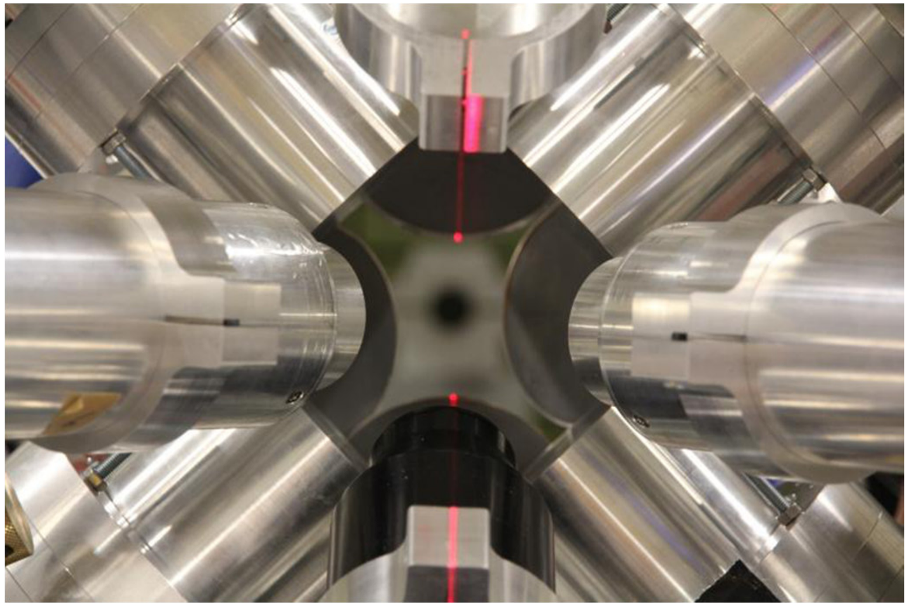
B. Löher et al., Nucl. Instruments Methods Phys. Res. Sect. A **723**, 136–142 (2013).





First γγ-coincidences in a γ-beam: γ^3 @ HIγS

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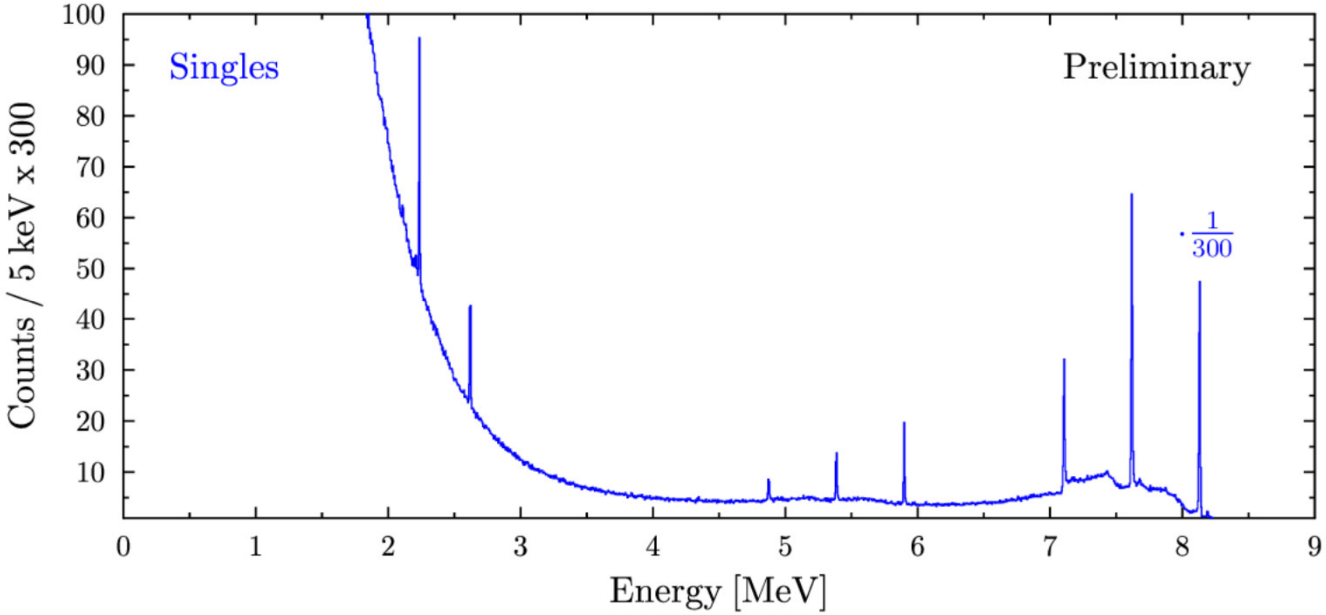
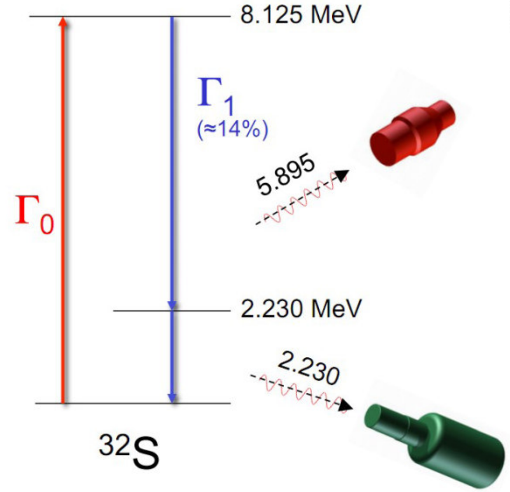


B. Löher et al., Nucl. Instruments Methods Phys. Res. Sect. A **723**, 136–142 (2013).



First $\gamma\gamma$-coincidences in a γ-beam: γ^3 @ HIγS

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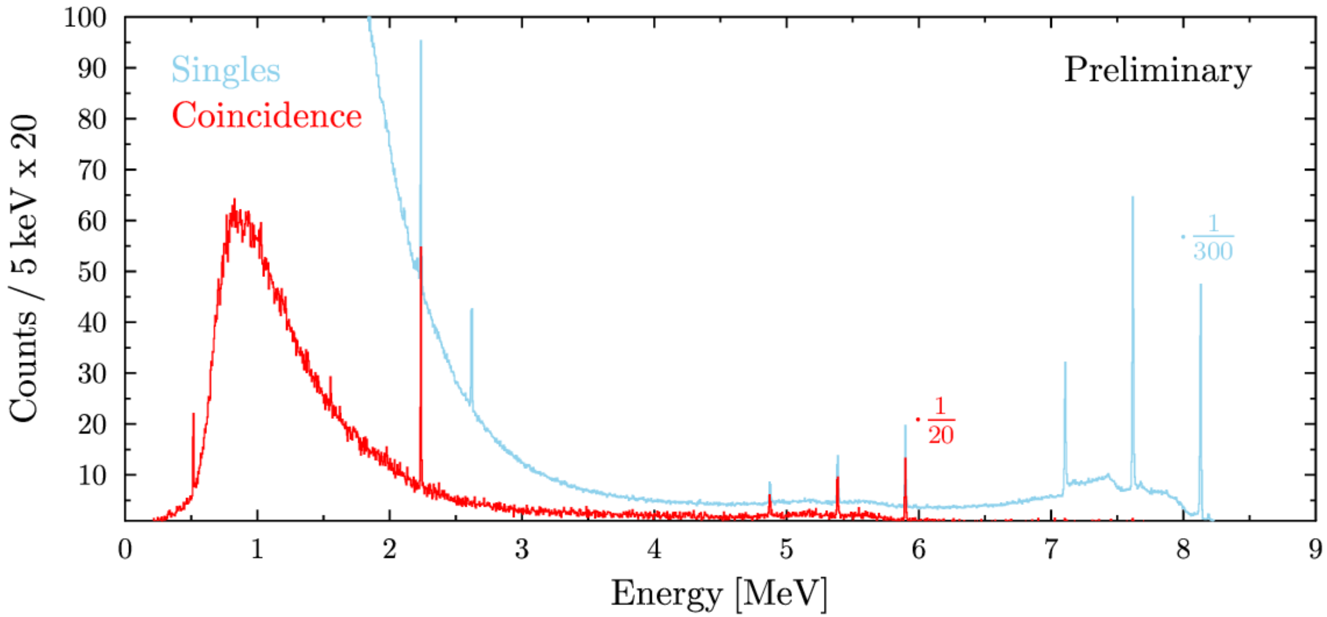
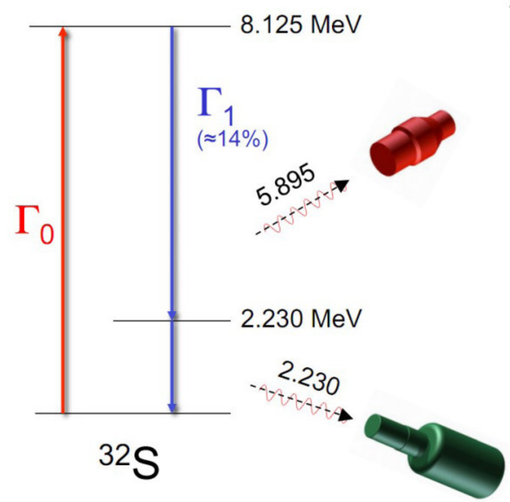
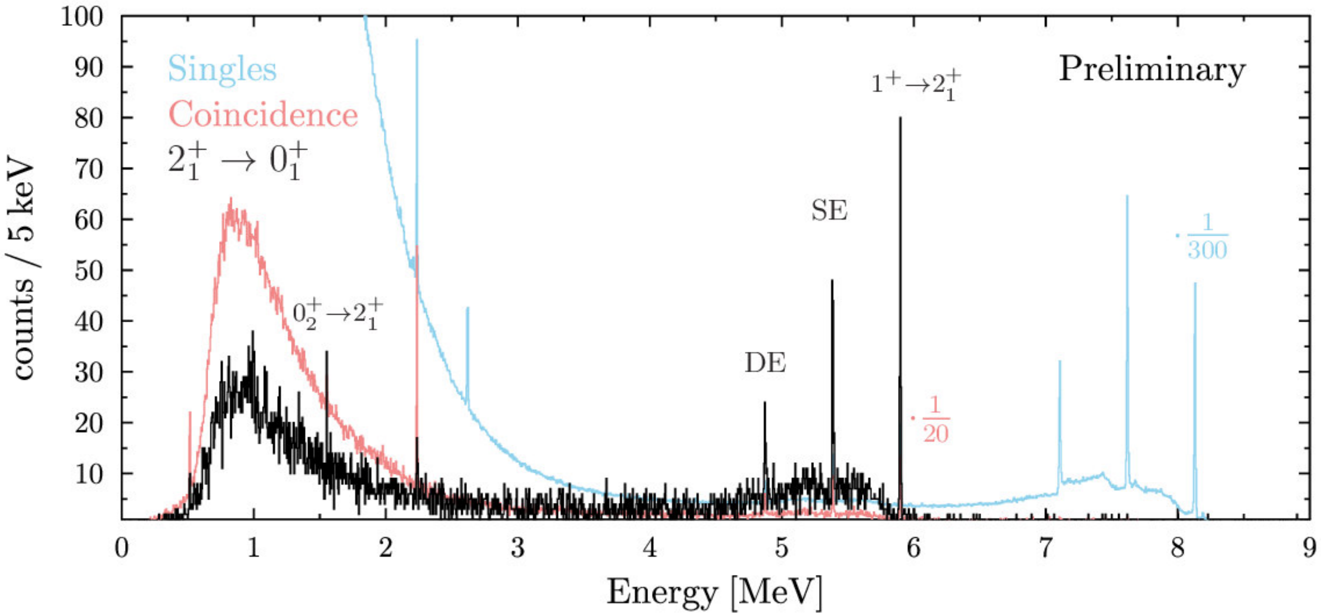
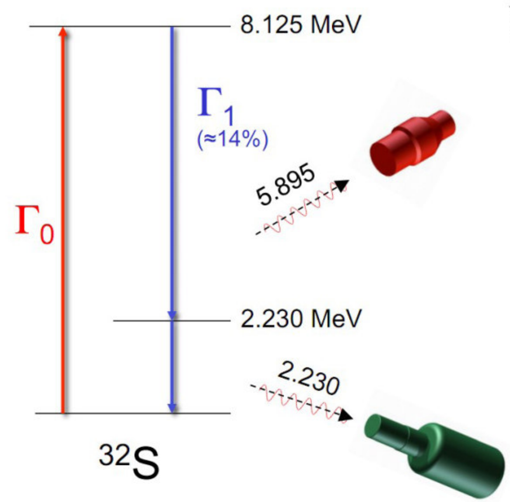




B. Löher et al., Nucl. Instruments Methods Phys. Res. Sect. A **723**, 136–142 (2013).

First γγ-coincidences in a γ-beam: γ^3 @ HIγS





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

Parity Violation in Nuclear Structure?

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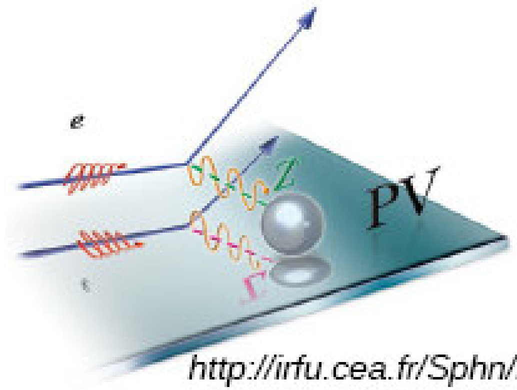


http://irfu.cea.fr/Sphn/Parity/

- 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

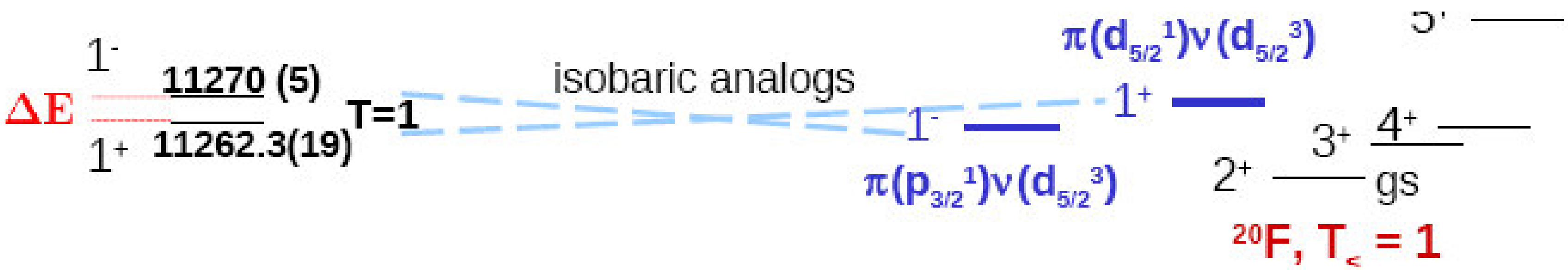
- parity non conservation in nuclear excitation could be tested with circularly photon beams [1]

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

^{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



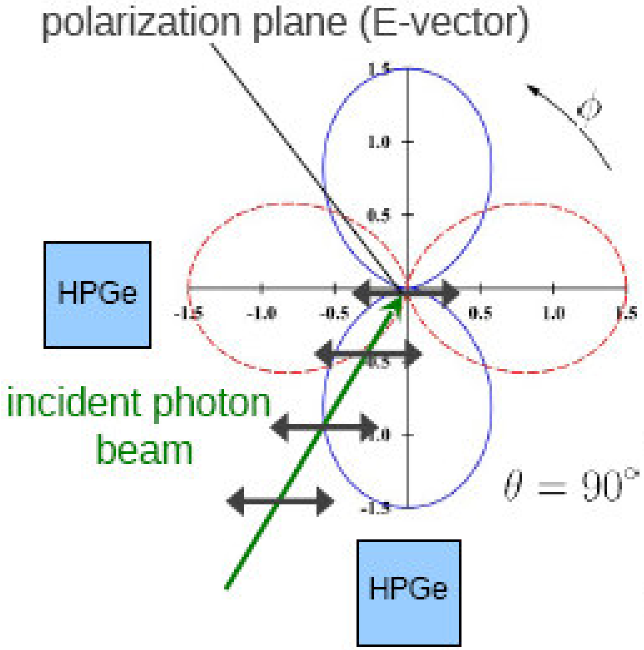
- doublet is isobaric analog of simple shell model states
- high nuclear enhancement factor [1]:
  - overlapping wavefunctions
  - small energy splitting (large uncertainty)

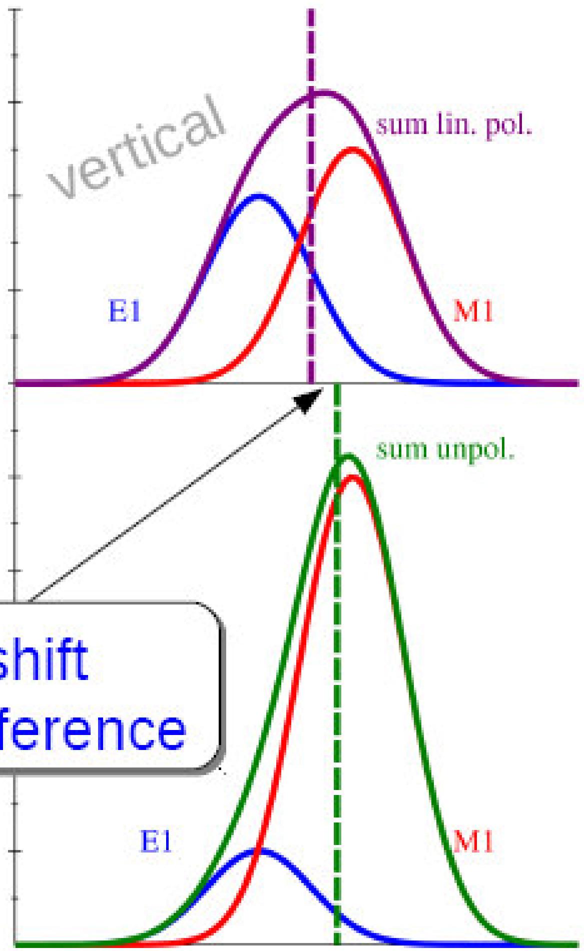
$$|R_N/\Delta E| = (670 \pm 7000) \quad \Delta E = (7.7 \pm 5.3)\ \mathrm{keV}$$

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

Energy Splitting of ^{20}Ne Parity Doublet

E1 transition
M1 transition

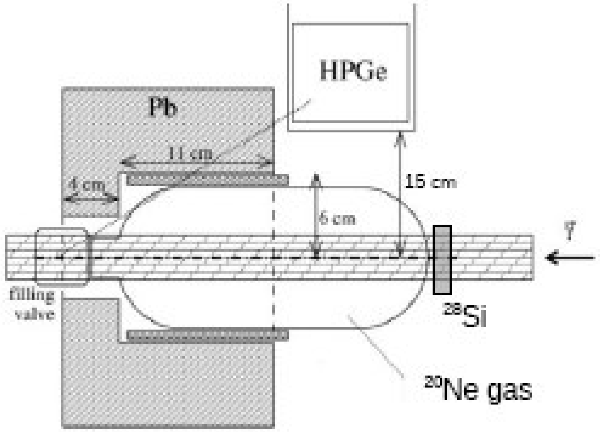




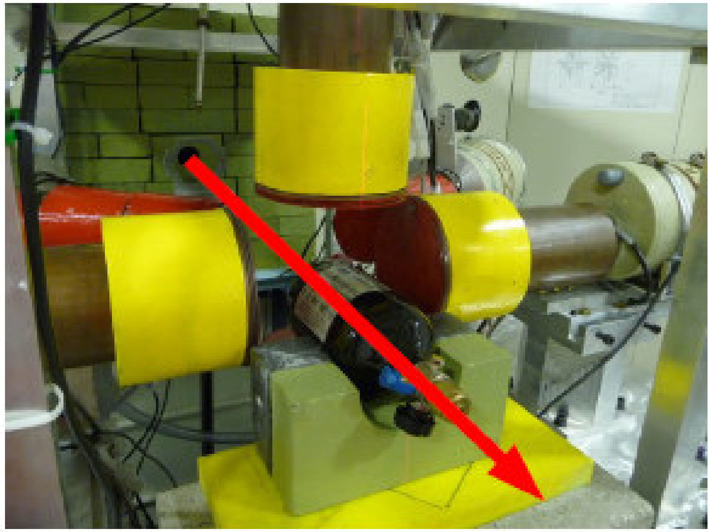
Centroid shift
→ energy difference

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

Experiment on ^{20}Ne at HIγS



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



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

Energy Splitting of ^{20}Ne Parity Doublet

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- before:

  1^-
  1^+

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

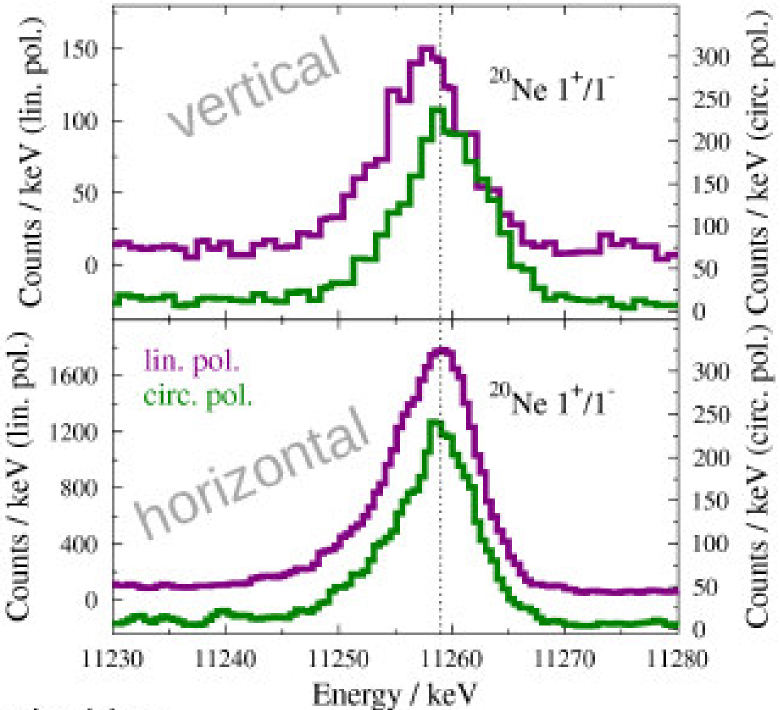
  $$\frac{R_N}{\Delta E} = 670 \pm 700$$

- now:

  1^+
  1^-

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

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



HIγS data J.Beller et al., TU Darmstadt, to be publ. (2014)

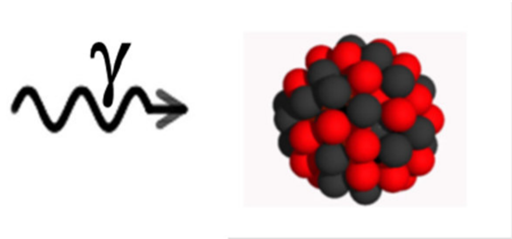
- ^{20}Ne doublet:
  - strong M1: $\Gamma_{0,\ 1^+} = 11.2(20)$ eV [2]
  - weak E1: $\Gamma_{0,\ 1^-} = 0.39(5)$ eV [2]

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

Scientific Opportunities at High-Intensity

Outline

- Photonuclear Reactions
- Nuclear Resonance Fluorescence
- Some Previous Achievements

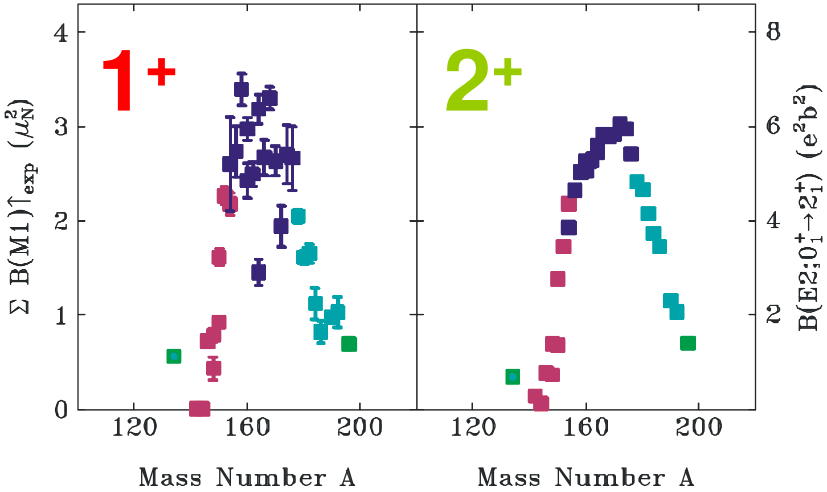


- **Intensity Frontier (instrumental challenge)** → **„Discovery Frontier“**
  (scientific opportunities)
  - **„Availability Frontier“** **(NRF on rare isotopes)**
  - **„Sensitivity Frontier“** **(weak channels: strong physics)**
  - **„Precision Frontier“** **(high count rates, new methods)**
- **Conclusion**

3. Precision Frontier

- **High Intensity = High count rates → small statistical uncertainties**
  - **address unresolved questions that cannot be answered today because of uncertainties**
    - **e.g., scaling of scissors mode with deformation**
    - **evolution of K-mixing in octupole-vibrational bands of deformed nuclei**
    - **the „unknown unknown“…**

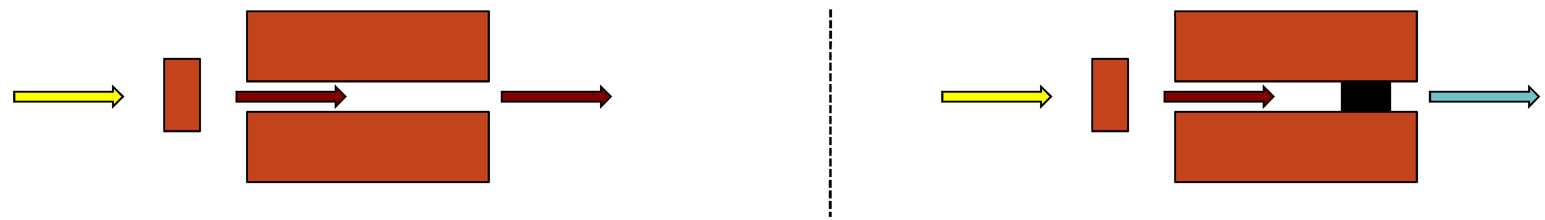
N. Pietralla et al., PRC **58**, 184 (1998)

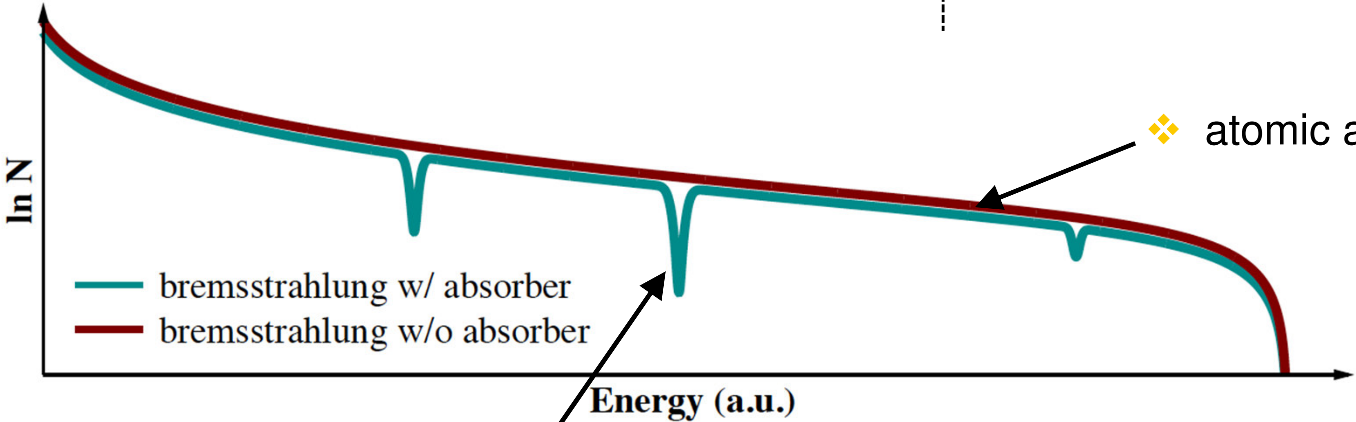


- **High Intensity enables new approaches**
  - **e.g. → Nuclear Self Absorption**

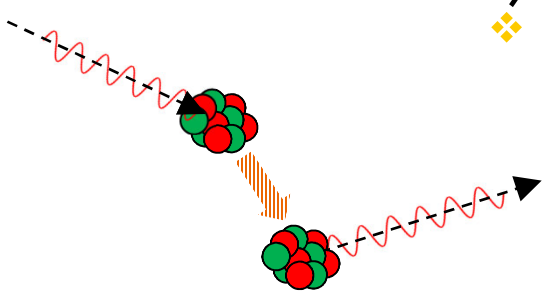
Absorption Processes

Absorption lines only a few eV wide!



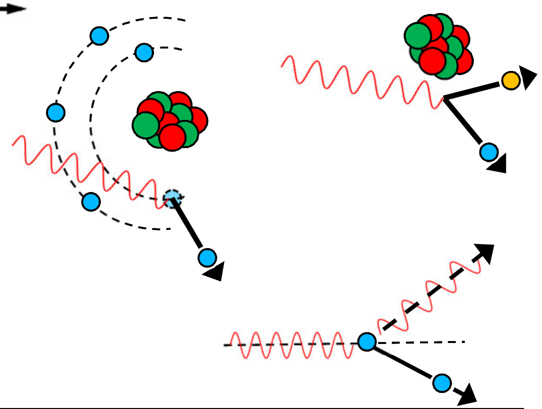


- atomic attenuation
  - several processes
  - contributes at each energy
  - independent of Γ_0



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

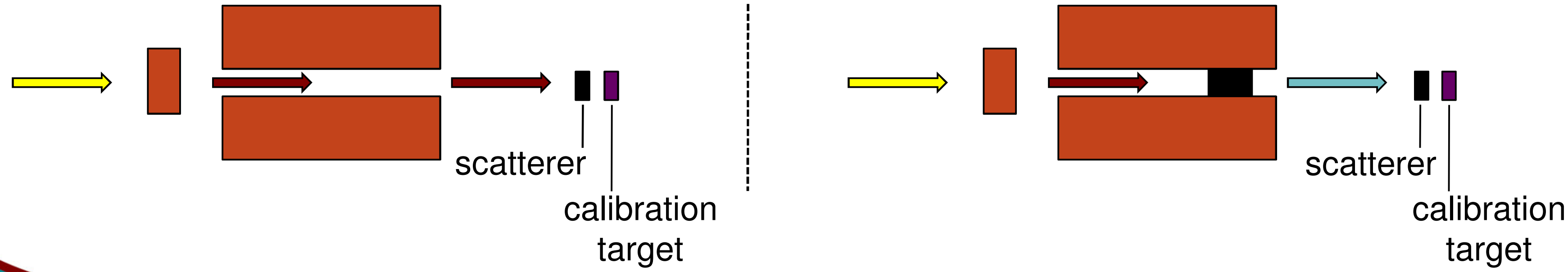
$$\sigma_a \propto \Gamma_0 \cdot e^{-\left(\frac{E-E_r}{\Delta}\right)^2}$$

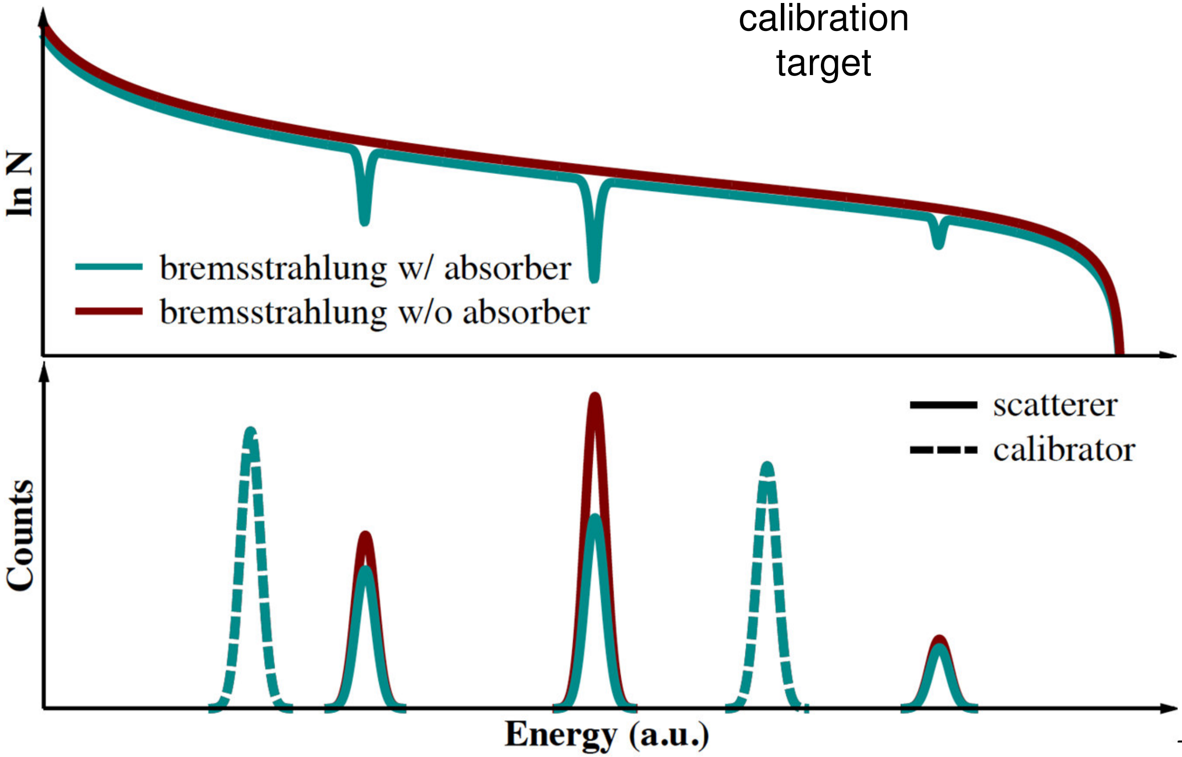


Principle of Measurement and Self Absorption[1]

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

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





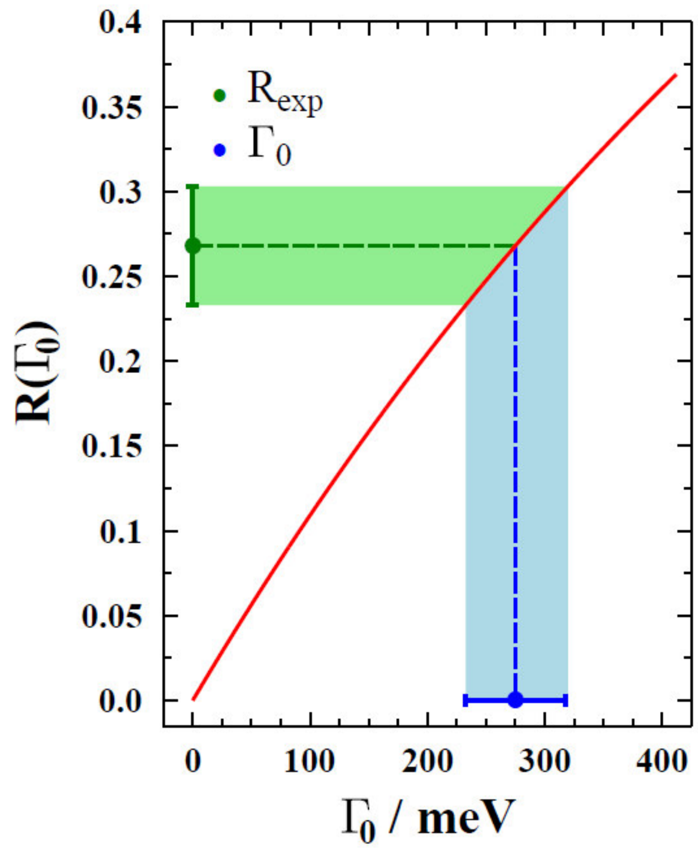
Self Absorption:
Decrease of Scattered Photons because of Resonant Absorption

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

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

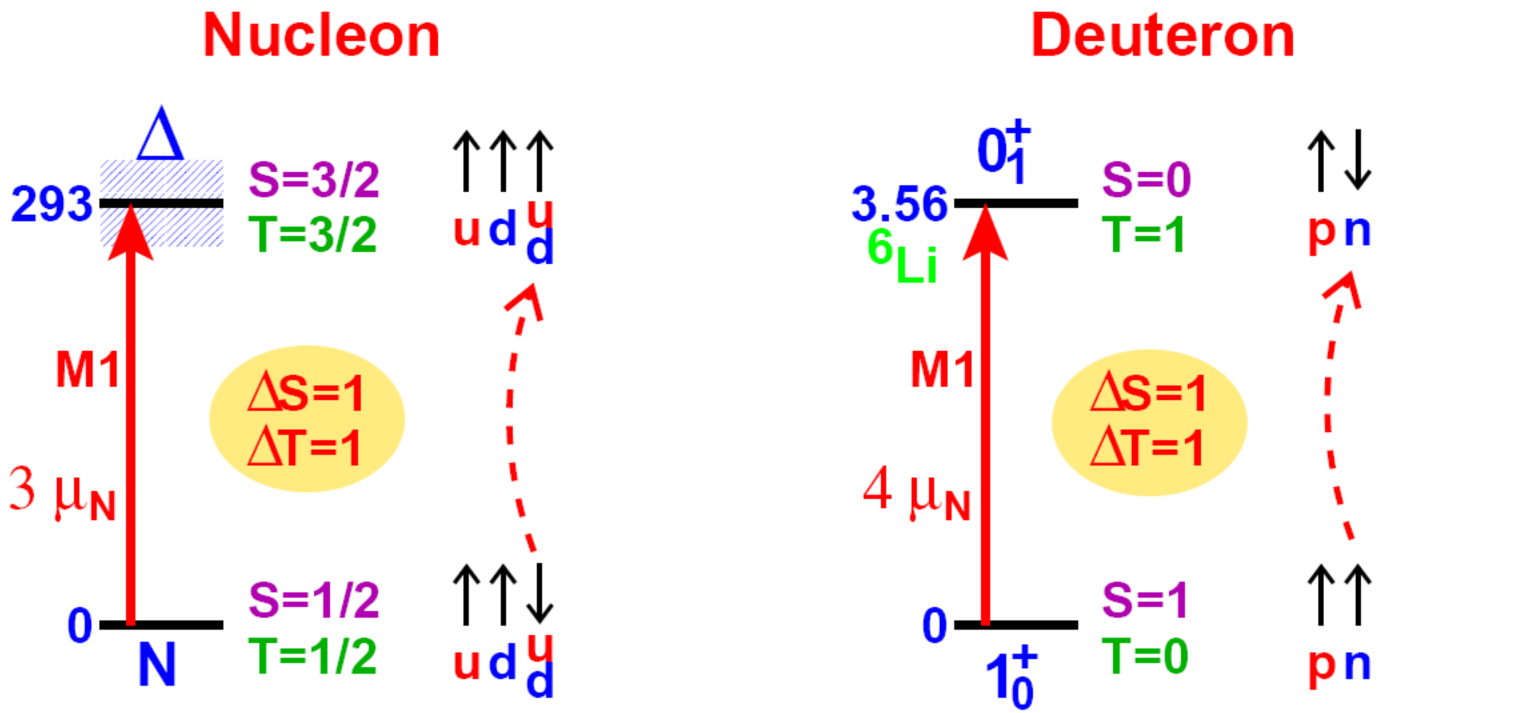
Determination of Ground-State Transition Width and Branching Ratio to the Ground State

- 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 transition width Γ and branching ratio Γ_0/Γ to ground state can be determined



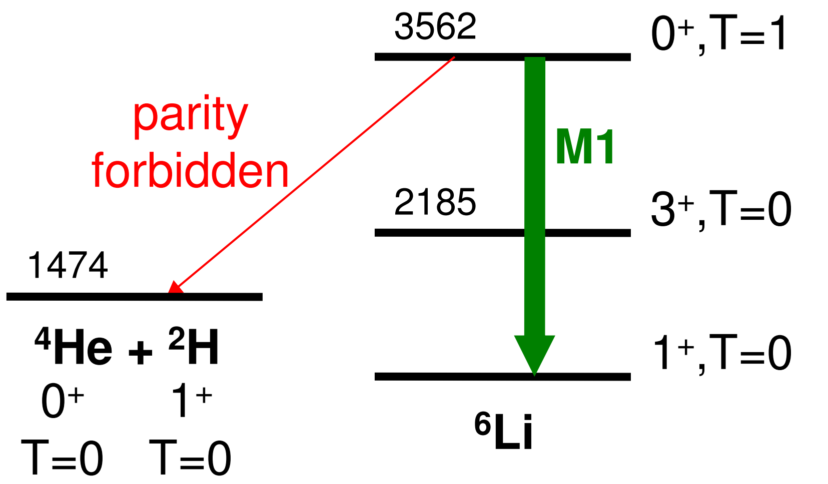
Application: ^{6}Li as Benchmark for *ab-initio* Nuclear Structure Theory

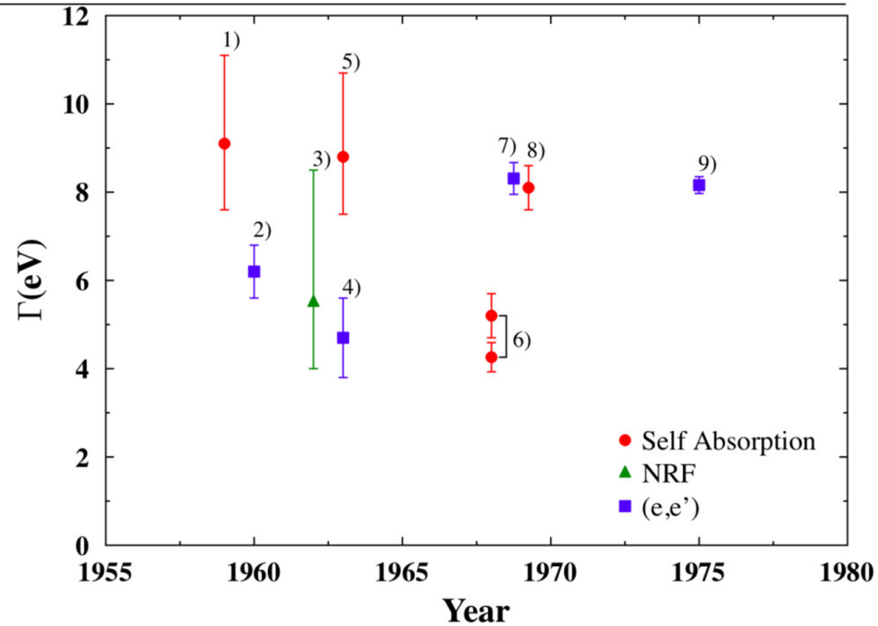
Isospin Excitations of Nucleons and Nuclei

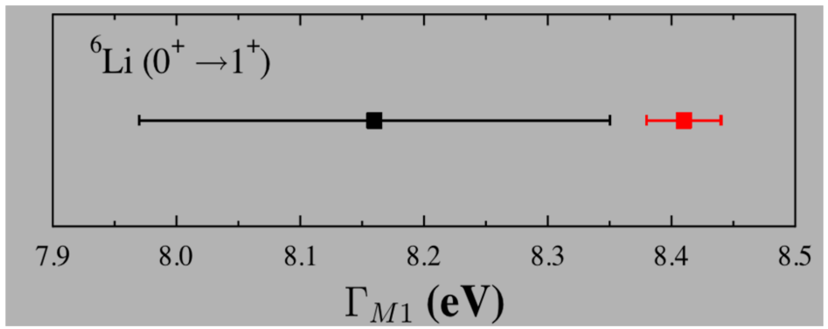


Nuclear Quasideuteron-Configurations: A.F.Lisetskiy et al., Phys. Rev. C **60**, 064310 (1999).

^{6}Li as Benchmark for *ab-initio* Theory







- Exp.: Γ_{M1}=**8.16(19) eV** (from (e,e'))
- S. Pastore *et al.*, PRC **87** (2013): chiral currents contribute significantly to Γ_{M1}
- GFMC with one-body EM current operator at leading order (impulse approximation): **6.90(2) eV**
- GFMC with additional two-body meson-exchange currents up to N^{3}LO (χEFT): **8.41(3) eV**

Self Absorption Measurement on ^{6}Li

(Ch.Romig, TU Darmstadt, PhD thesis, 2014 in preparation)

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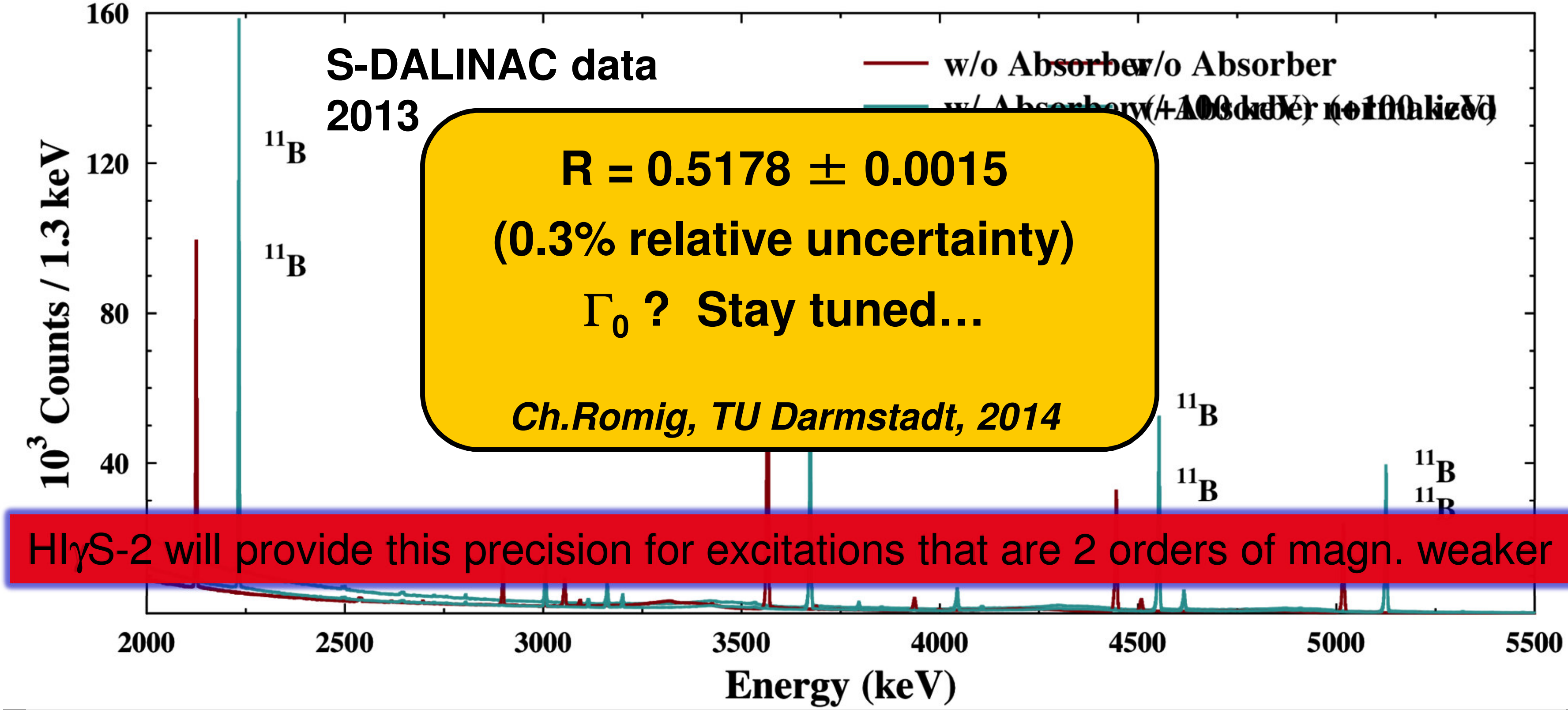
- scatterer: 5 g Li_2CO_3 (enriched to 95% in ^{6}Li)
- calibration target: 4.2 g ^{11}B (sandwiched)
- absorber: 10 g Li_2CO_3 (enriched to 95% in ^{6}Li)
- endpoint energy: 7.1 MeV
- 7 days w/o absorber
- 8 days w/ absorber



R = 0.5178 ± 0.0015

(0.3% relative uncertainty)

Γ_0 ? Stay tuned…

Ch.Romig, TU Darmstadt, 2014

HIγS-2 will provide this precision for excitations that are 2 orders of magn. weaker !