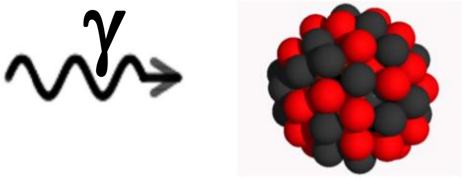
Photonuclear Reactions

with MeV γ-rays from LCB

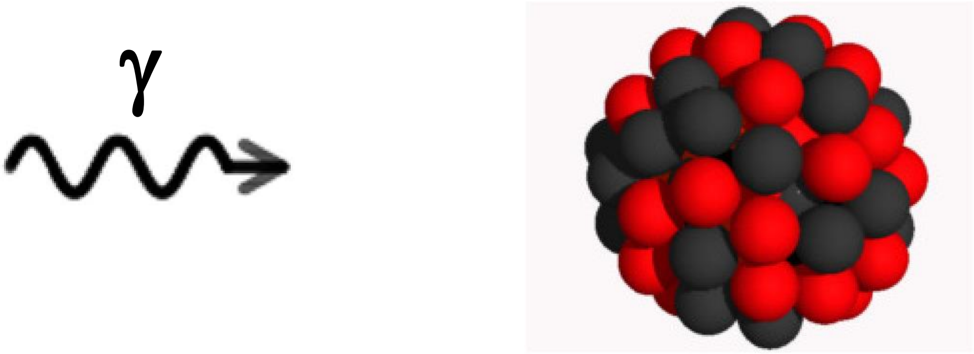
Norbert Pietralla, TU Darmstadt

Outline



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

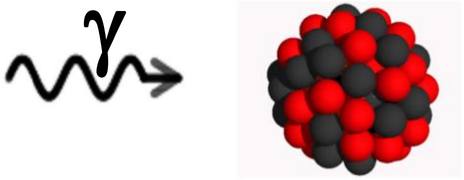
Photonuclear Reactions



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

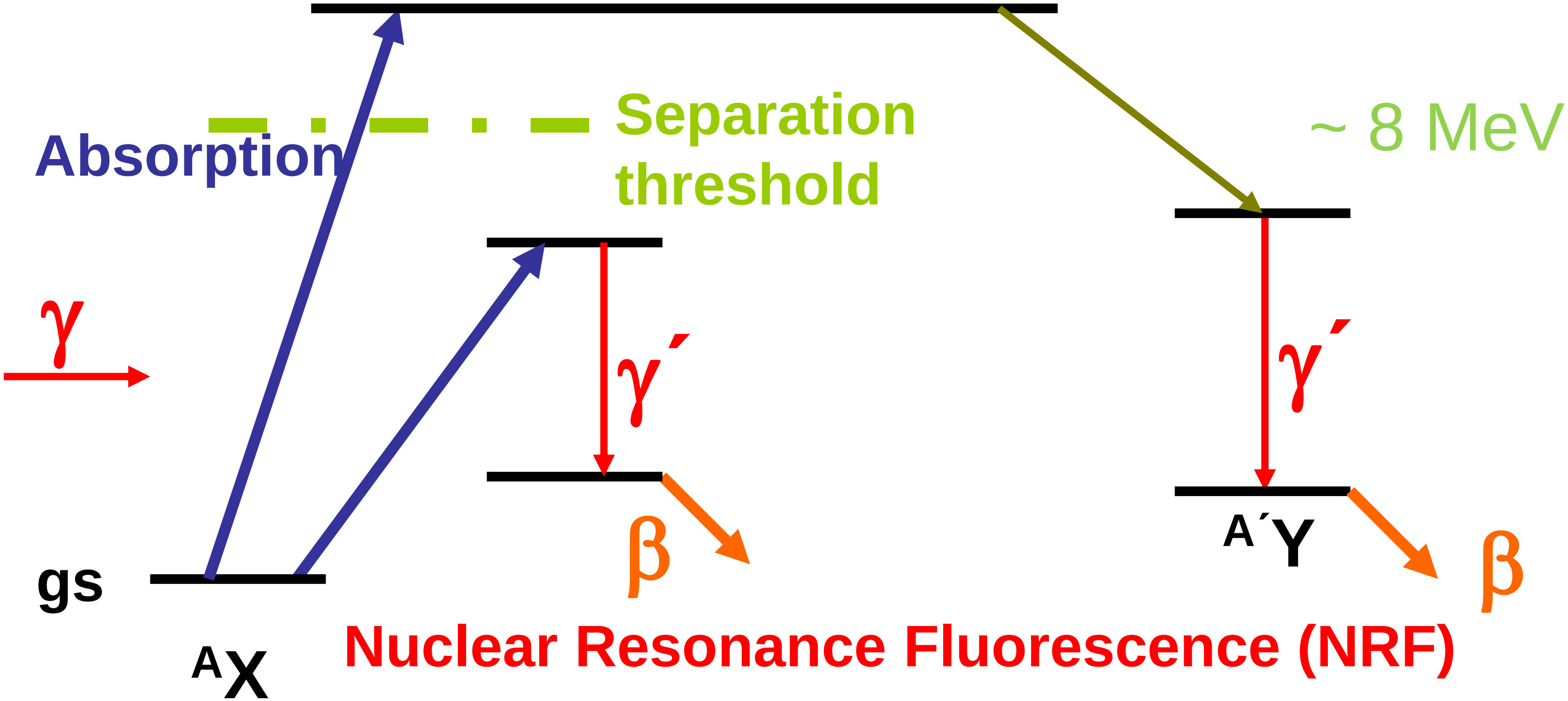
„Parity Physics“, channel selectivity

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

Explore specific excitation energy

„Selective Manipulation of Nuclear States“: Nuclear Photonics

Photonuclear Reactions



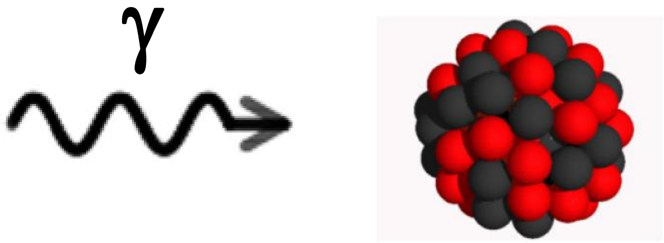
Nuclear Resonance Fluorescence (NRF)

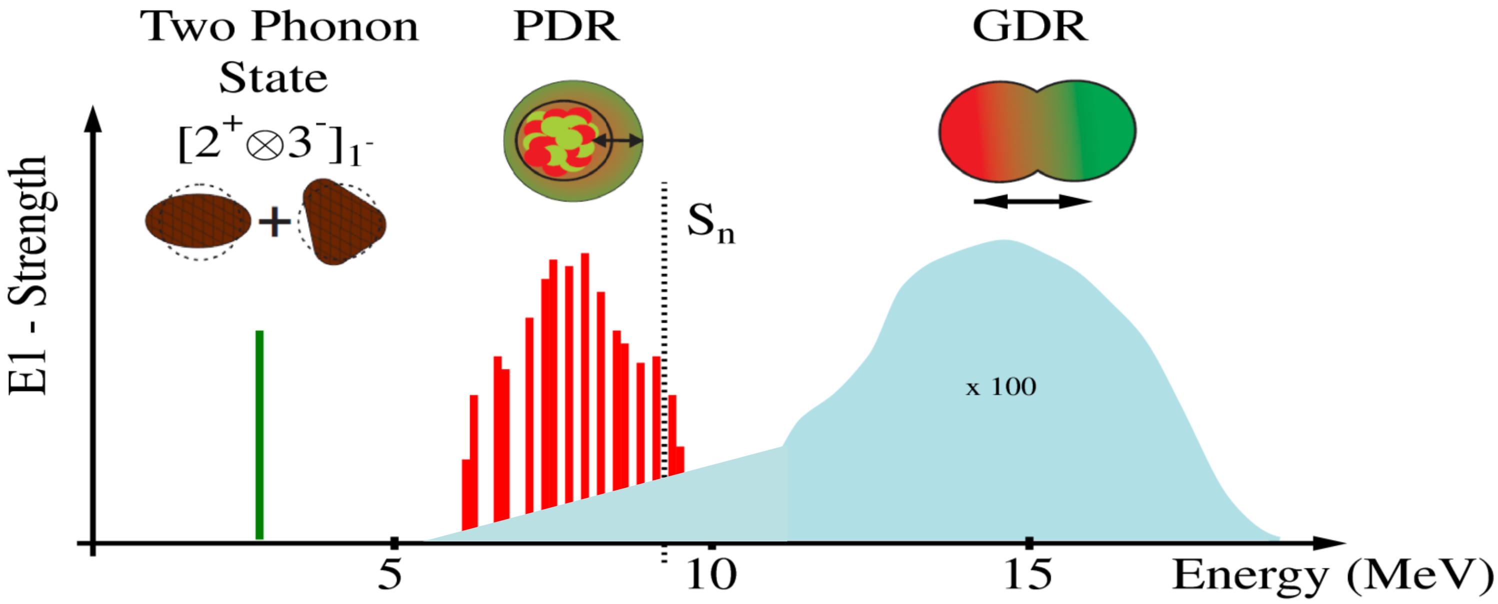
Photoactivation

Photodesintegration (-activation)

Photofission

Electromagnetic dipole-response



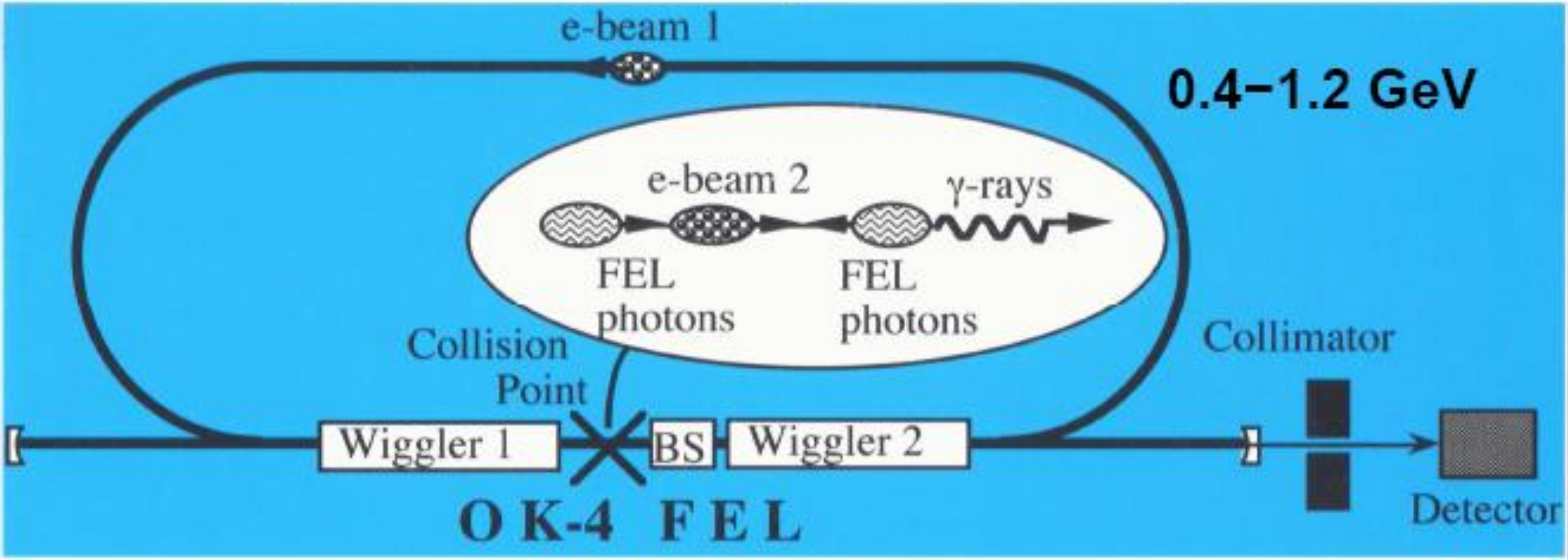


E1 strength distribution

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

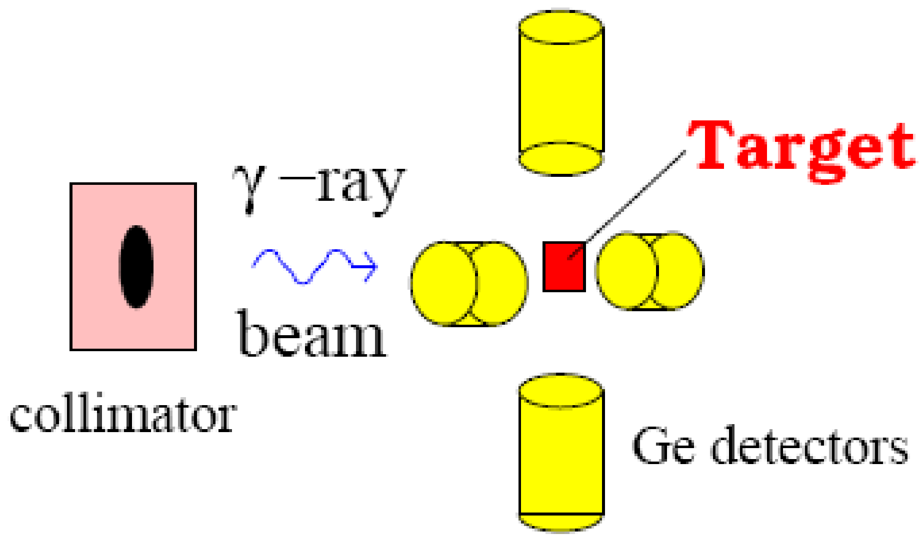


2 − 60 MeV **1.7 − 6.4 eV** **~ 1000**

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

nearly monochromatic, tunable, completely polarized

Looking at the HIGS Gamma-Ray Beam

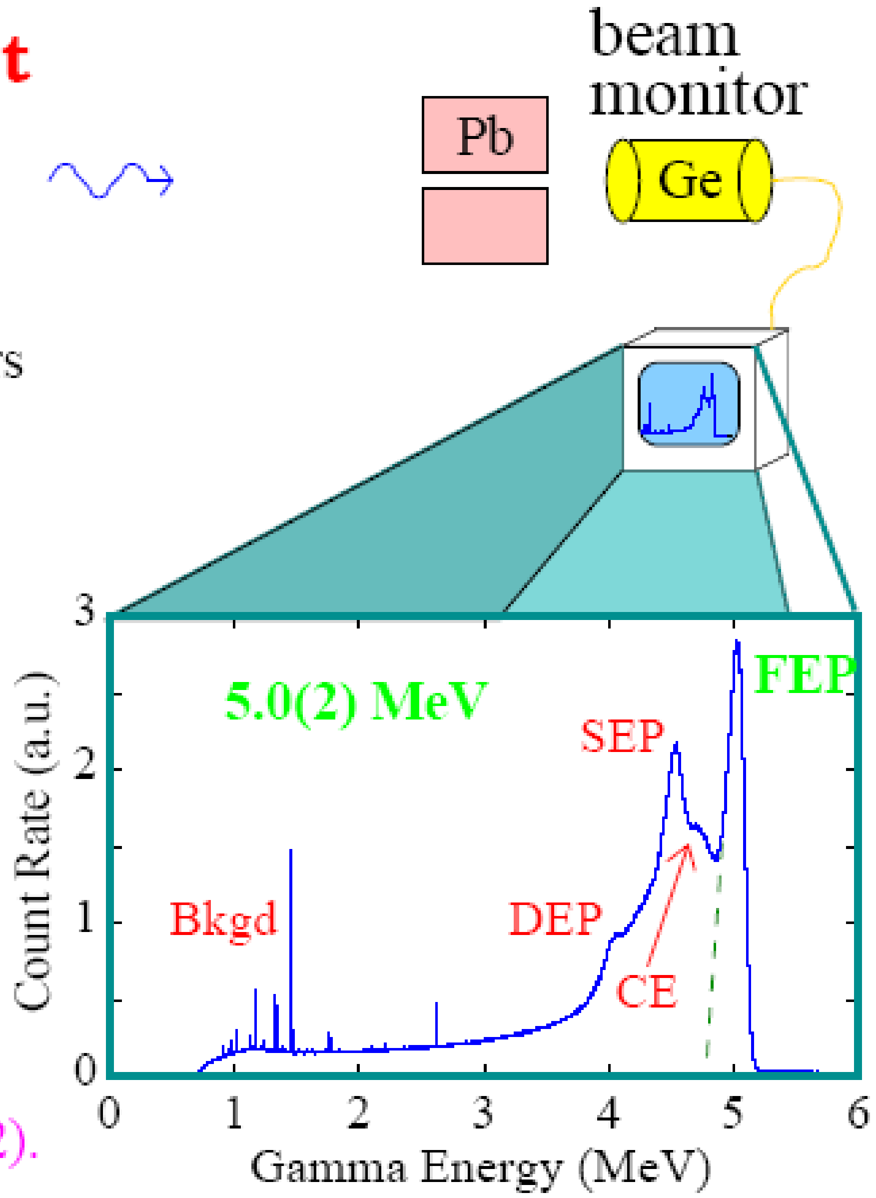


Flux at target: 10^7/s

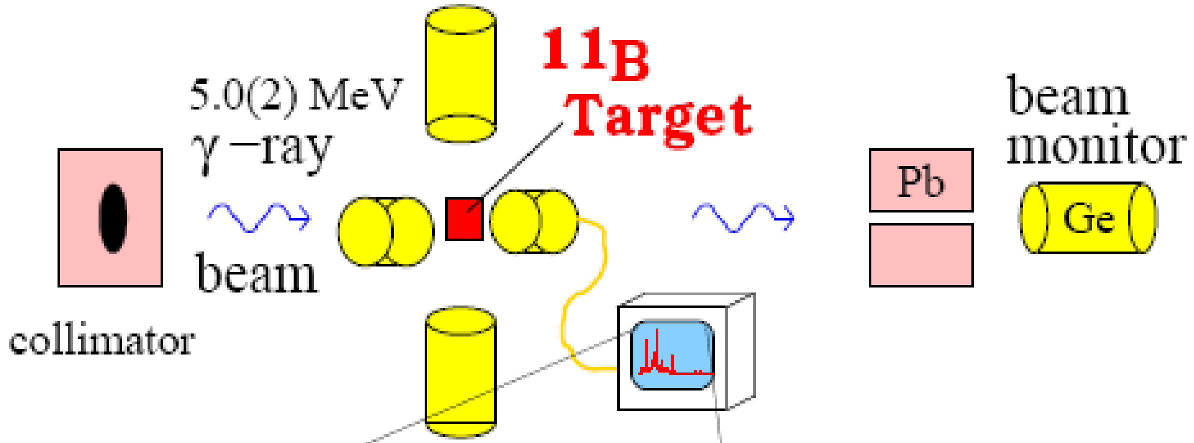
at maximum: 10^5/(s keV)

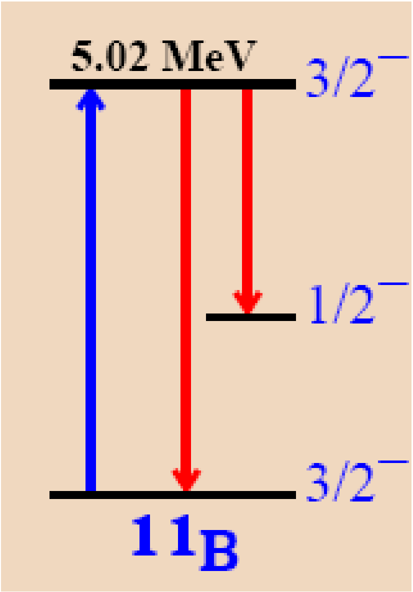
Resolution: 3%
(with 1" collimator)

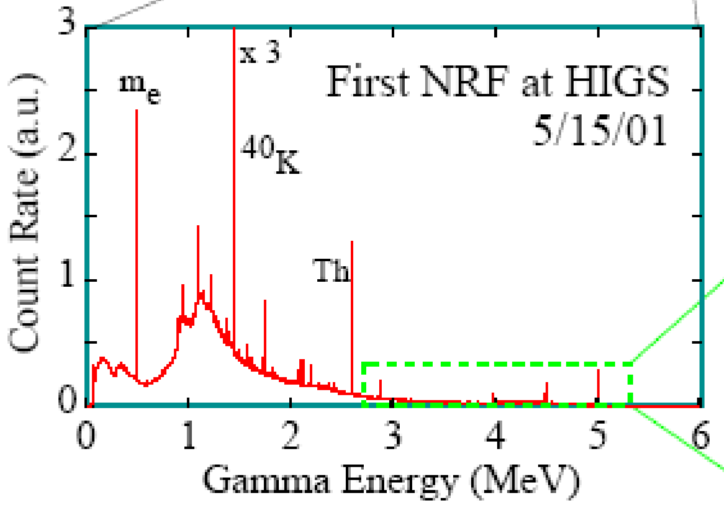
N.Pietralla et al.
Nucl.Instrum.Methods A 483, 556 (2002).

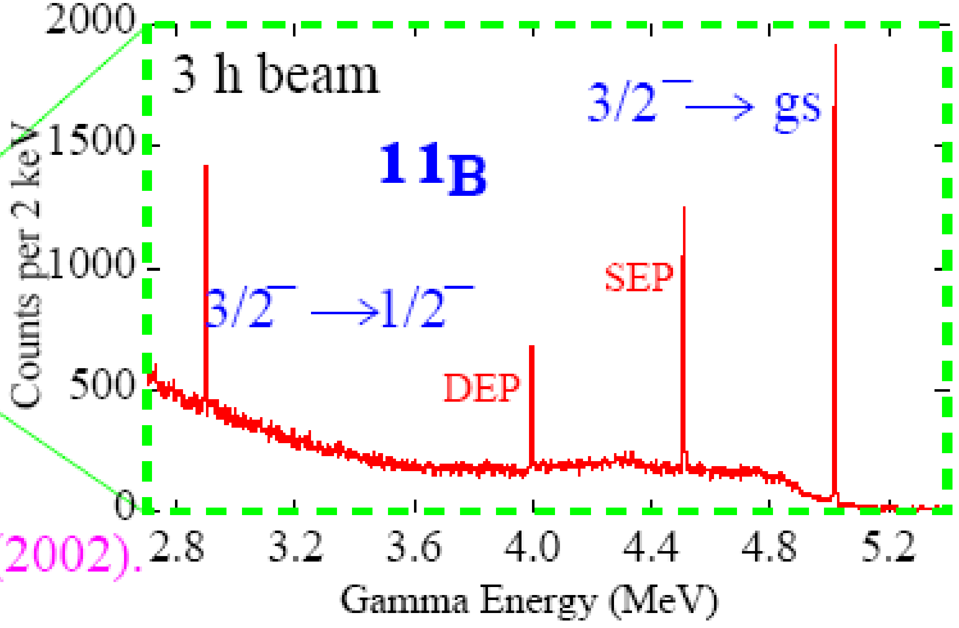


Looking at the Target



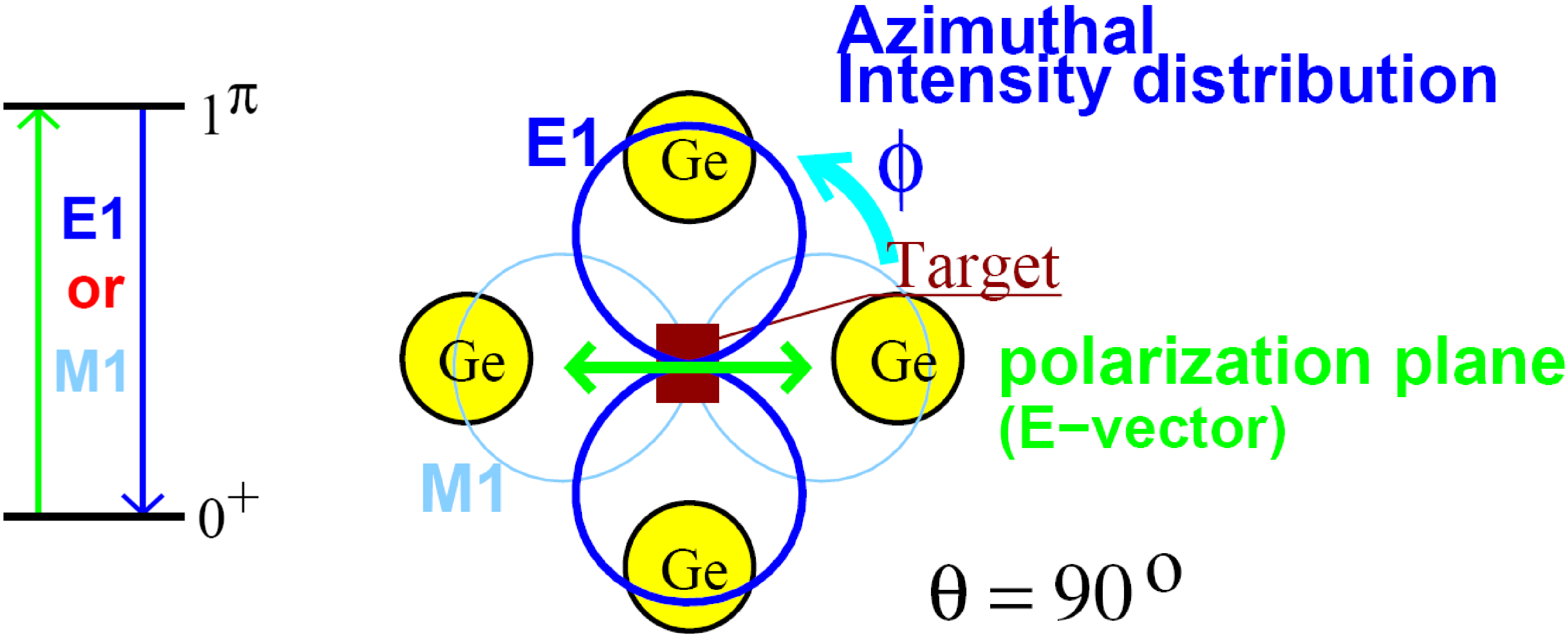






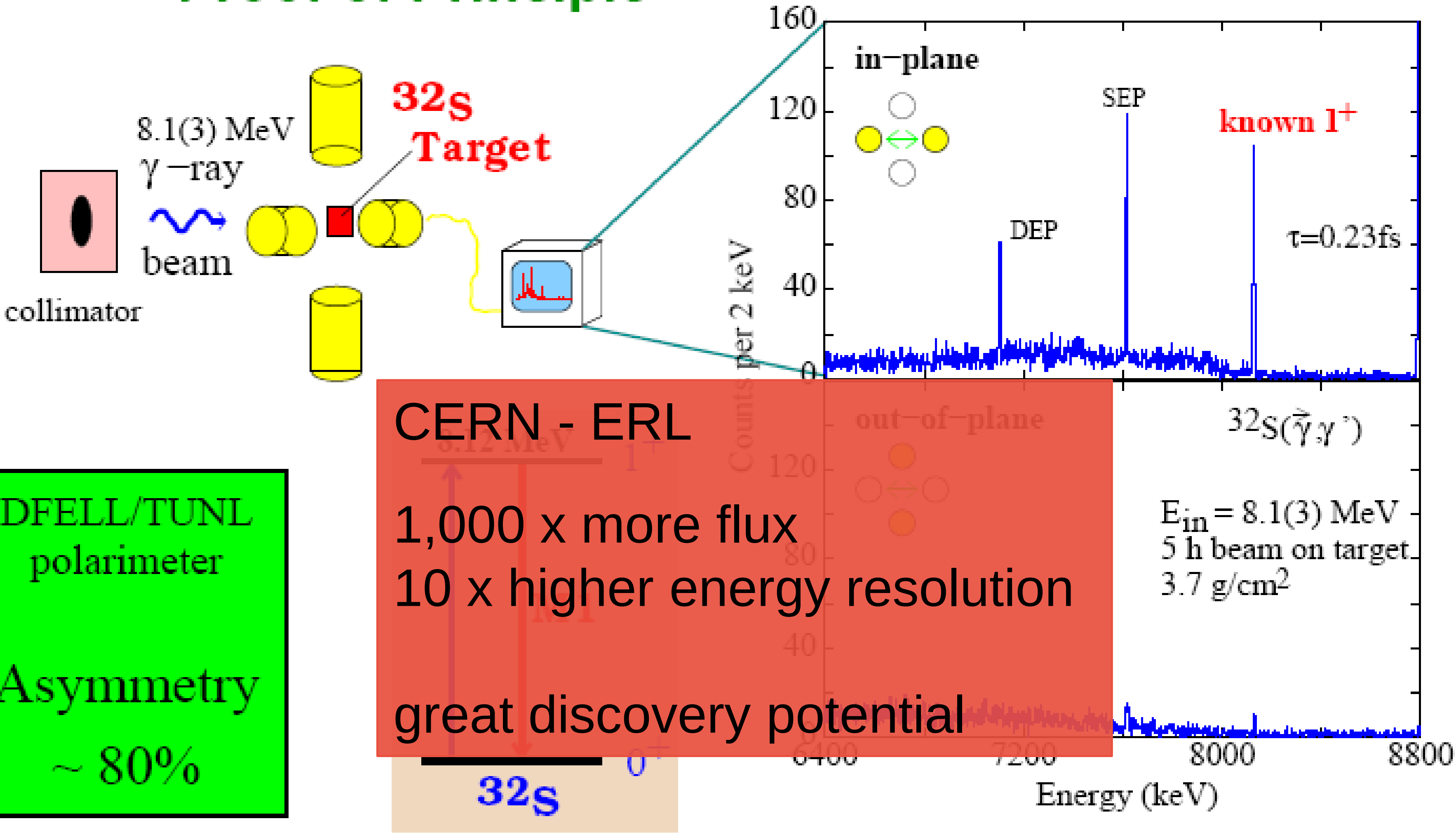
N.Pietralla et al.
Nucl.Instrum.Methods A483, 556 (2002).

Parity Measurements with Linearly Polarized Photon Beams



Azimuthal asymmetry → parity quantum no.

Proof of Principle



CERN - ERL

1,000 x more flux
10 x higher energy resolution

great discovery potential

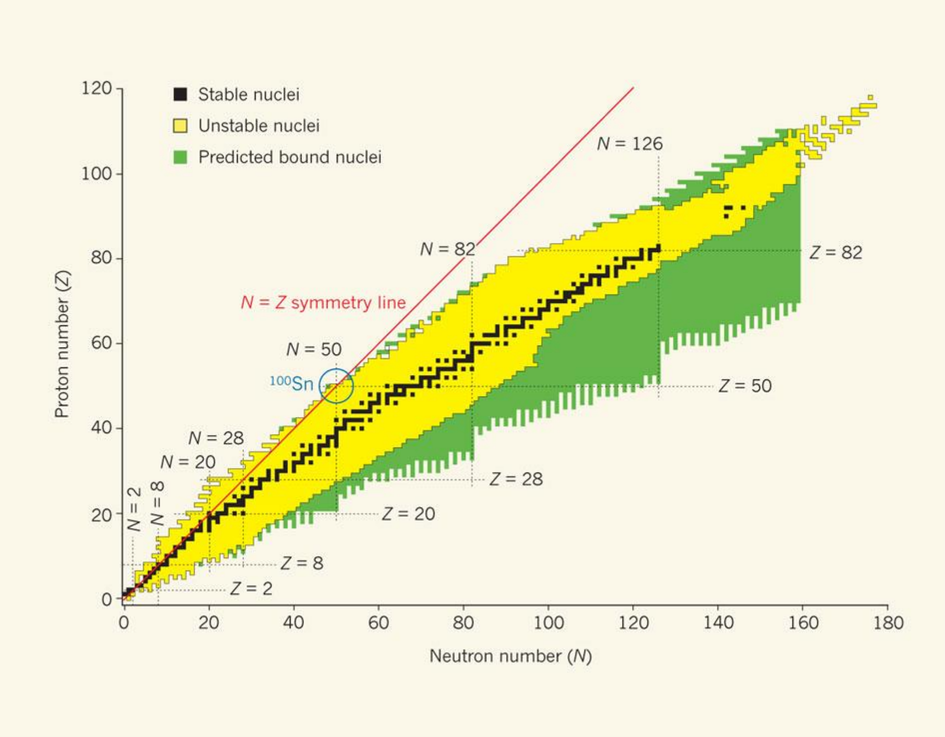
DFELL/TUNL polarimeter

Asymmetry
~ 80%

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



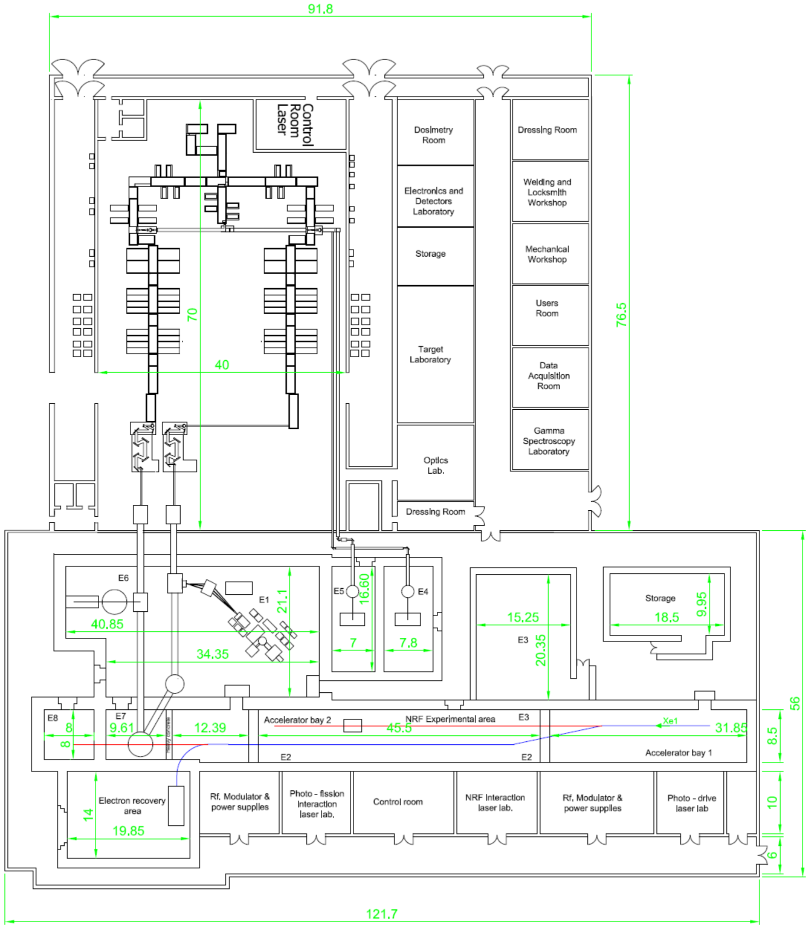
ELI – Nuclear Physics, Bucharest, Design

ELI – Nuclear Physics, Floor Plan

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%

→ **Photonuclear Reactions**



ELI – NP, Progress

01.10.2014

Civil Conctruction finished: end of 2015

International Scientific Advisory Board

Implementation Phase ELI-NP

Faiçal AZAIEZ - Institut de Physique Nucléaire d'Orsay, France

Christopher BARTY - Lawrence Livermore National Laboratory, USA

Paul BOLTON - Kansai Photon Science Institute, JAEA, Japan

Angela BRACCO - Istituto Nazionale di Fisica Nucleare, Milano, Italy

Richard CASTEN - Yale University, New Haven, Connecticut, USA

John COLLIER - STFC Rutherford Appleton Laboratory, Oxfordshire, United Kingdom

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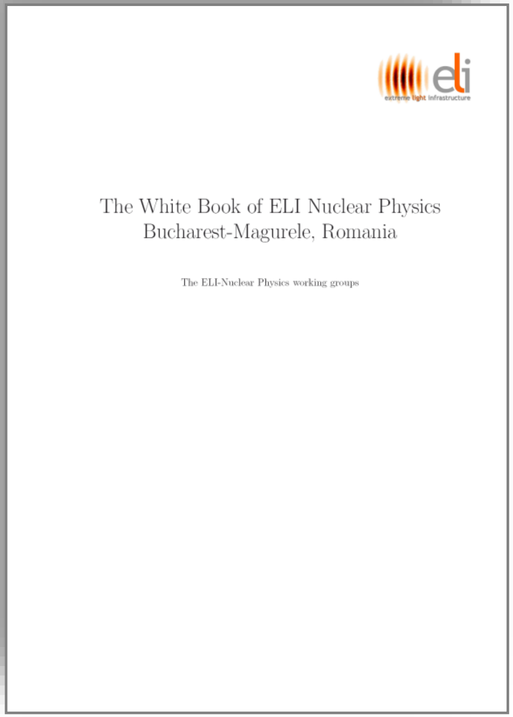
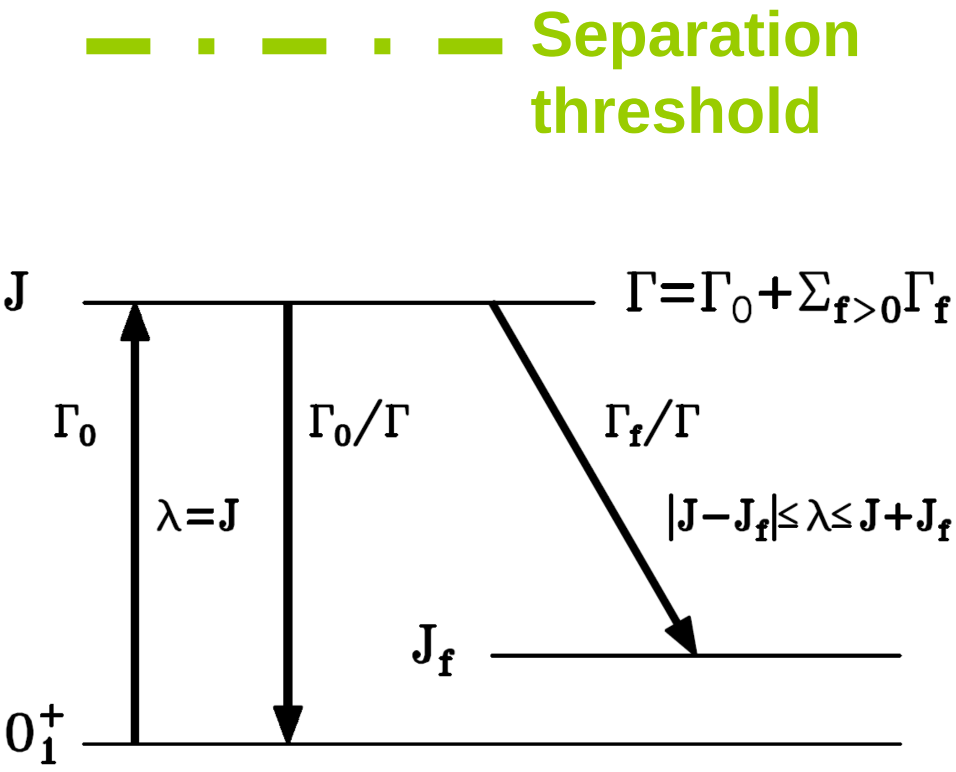


The White Book of ELI Nuclear Physics
Bucharest-Magurele, Romania

The ELI-Nuclear Physics working groups

strong international user community

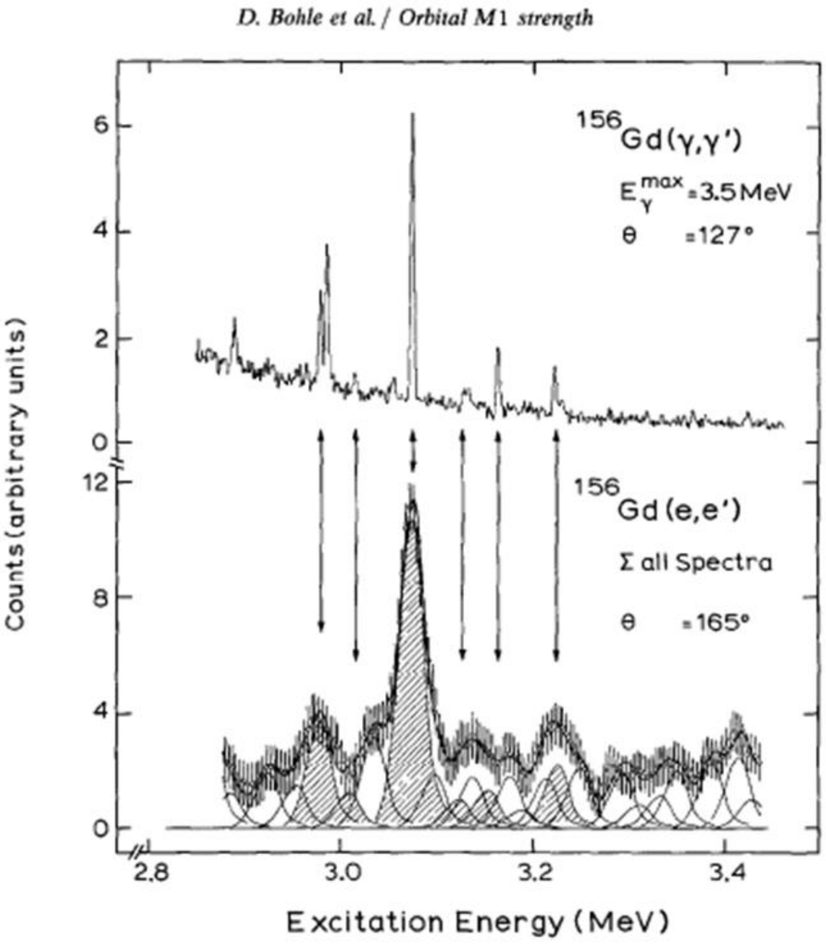
Nuclear Resonance Fluorescence



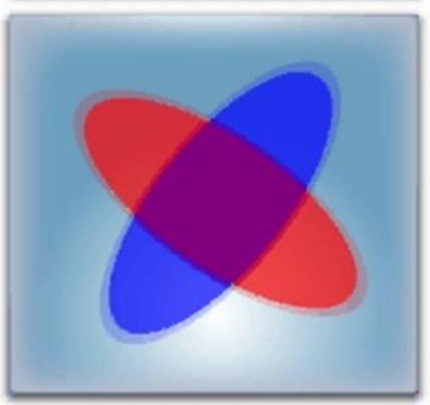
Observables

- 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

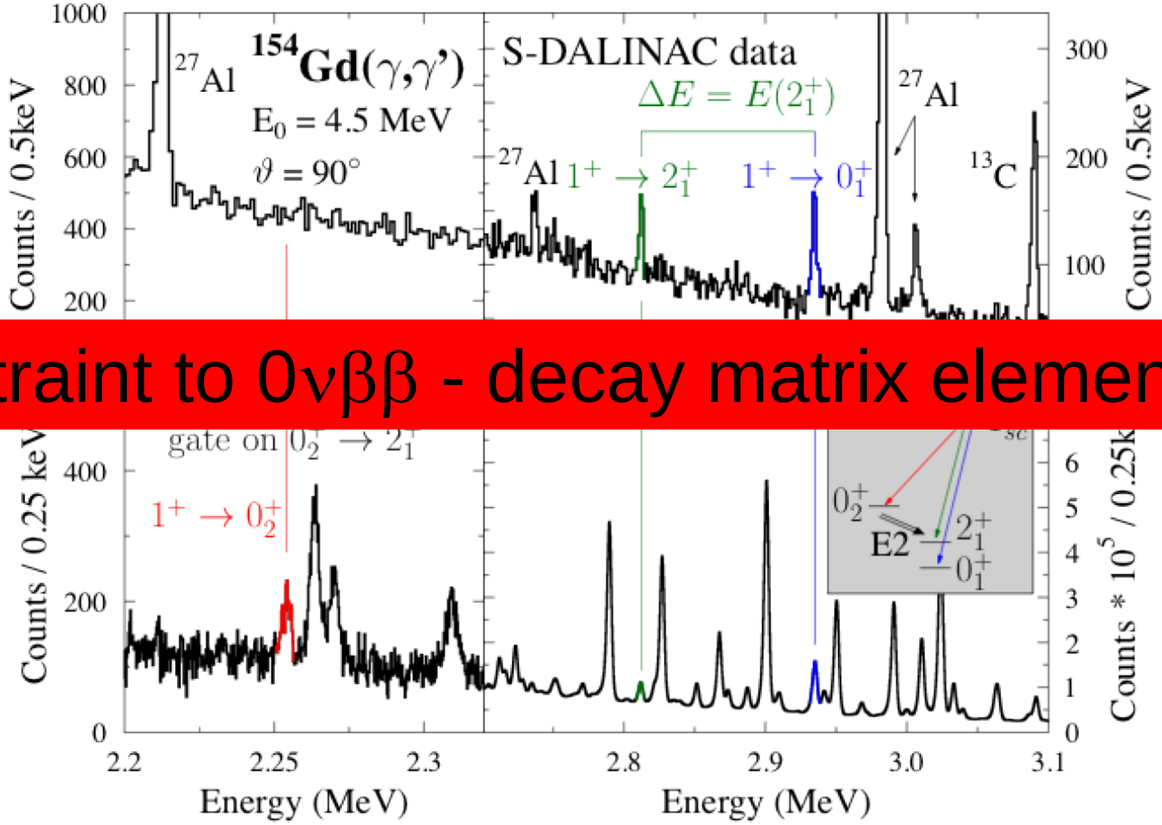
- Branching

  from γ-spectroscopy

  following EC decay

  (HORUS data)

  with Zilges-group



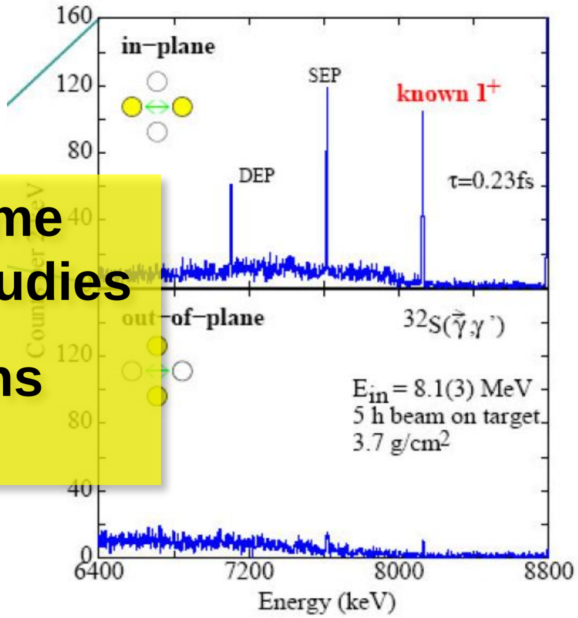
J.Beller, N.P. et al., Phys. Rev. Lett. 111, 172501 (2013).

1. Availability Frontier

- Current NRF measurements require gramm-size targets (~ 10^{22-21} nuclei)
- Required by
  - cross sections (~ eV b)
  - detection efficiency (~ 10%),
  - available luminosity (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.

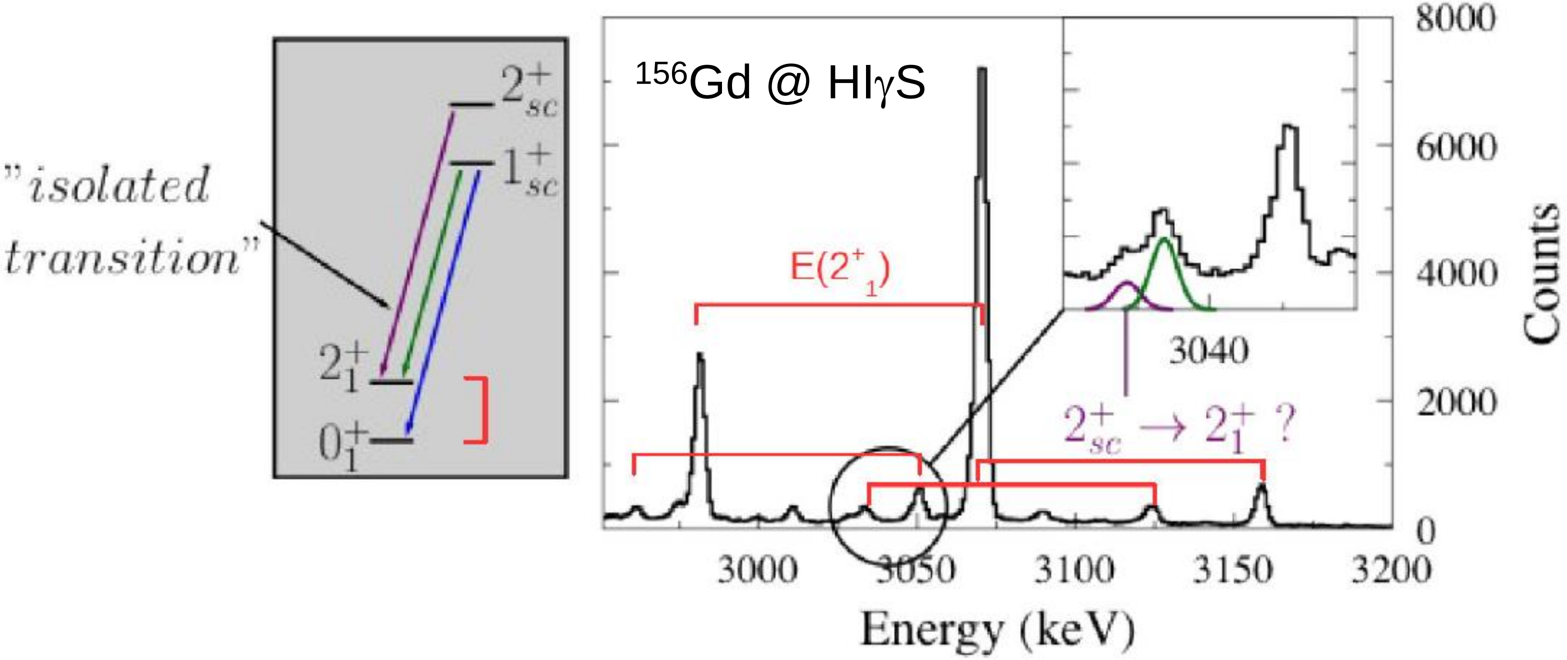


Some Examples for Science Cases on Rare or Long-lived Radioactive Isotopes

- **^{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**
- **$^{248}\mathrm{Cm}_{152}$: 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
- Ot



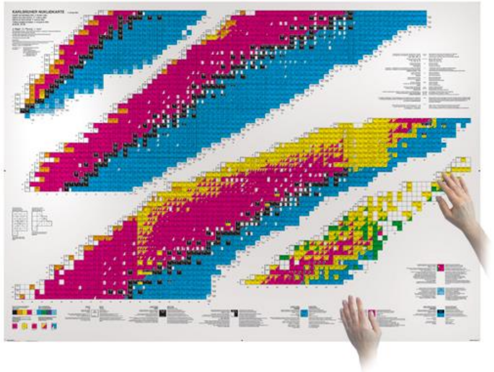
Data: J.Beller, TU Darmstadt

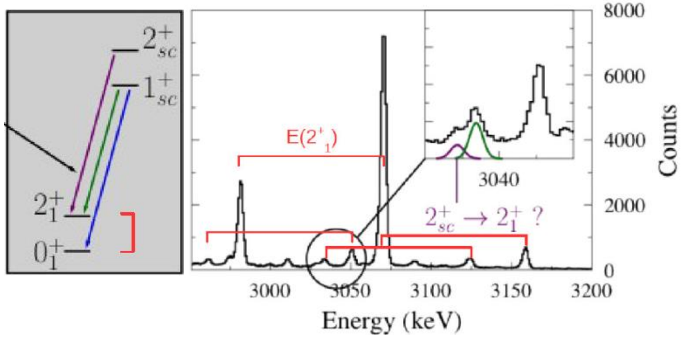
„Discovery Frontier“ for NRF at HIγS-2 / ELI-NP

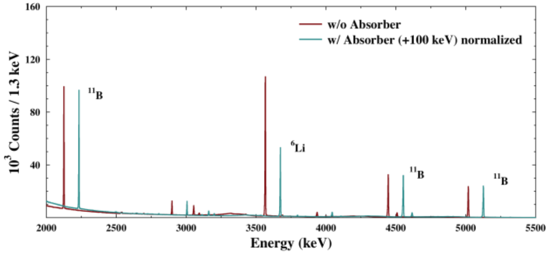
High-Intensity Frontier = „Discovery Frontier“

(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)

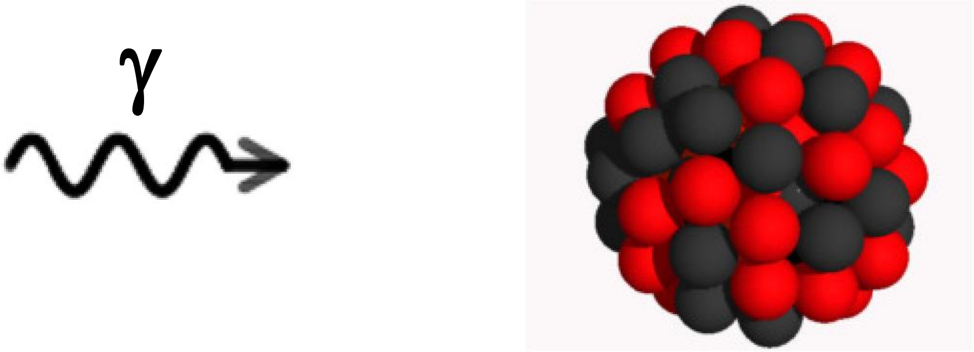




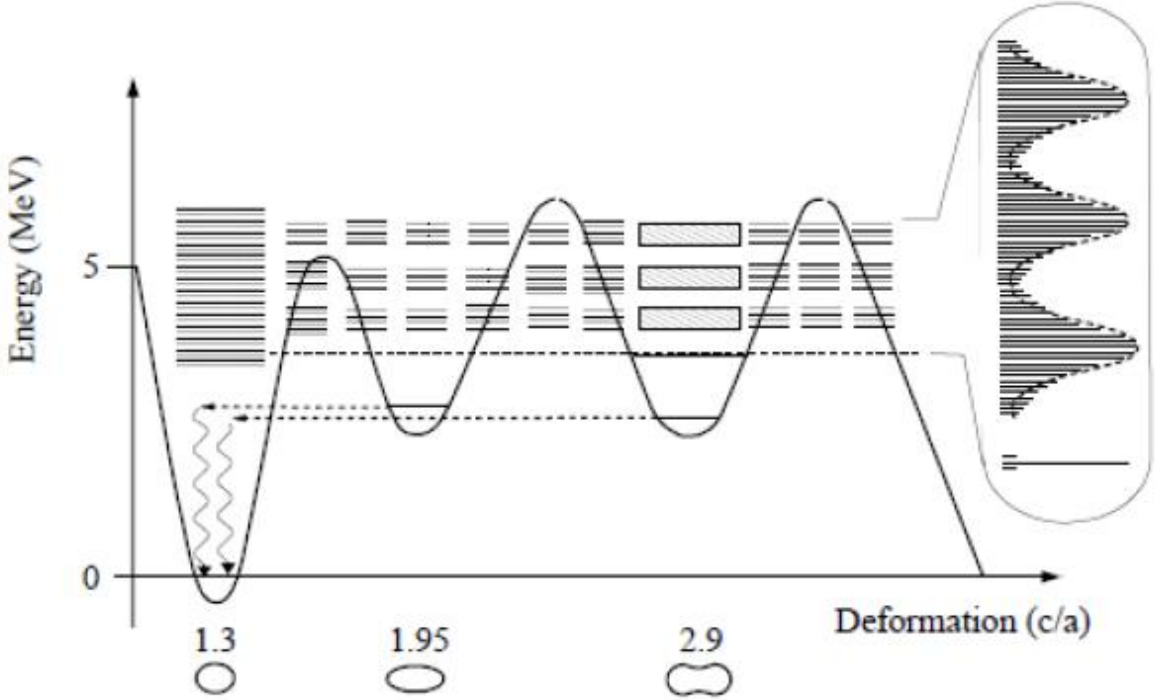


Thank you very much !

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



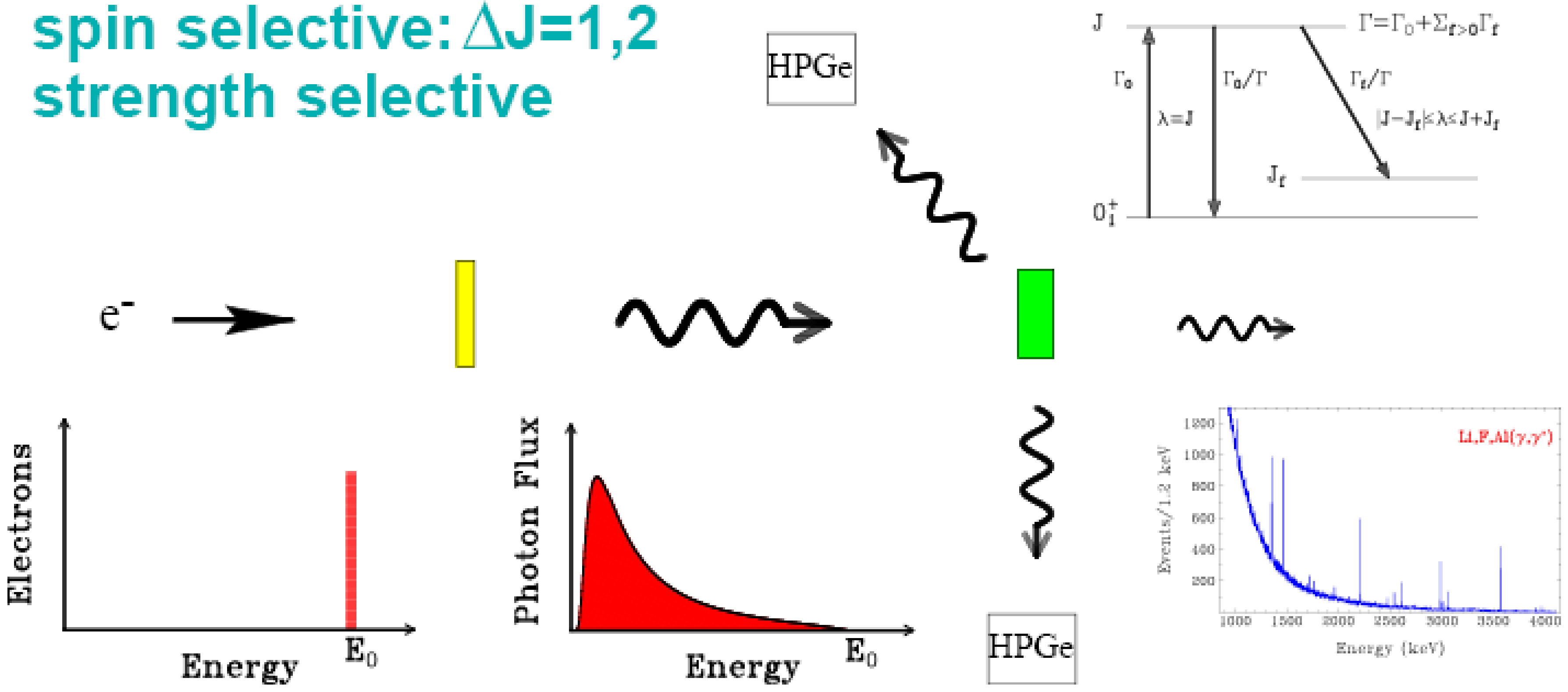
Photofission



Photon Scattering
(Nuclear Resonance Fluorescence)

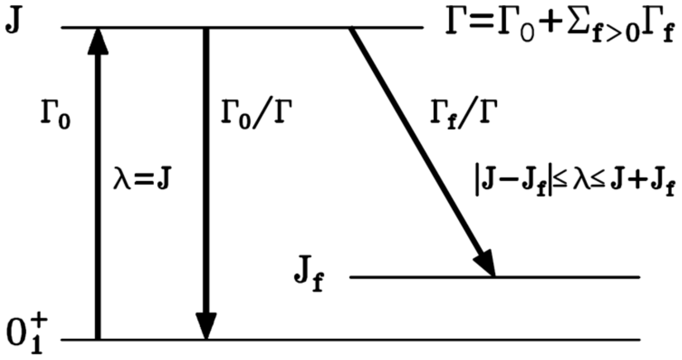
Traditionally Bremsstrahlung: Kneissl,Pietralla,Zilges, J.Phys.G 32, R217 (2006).

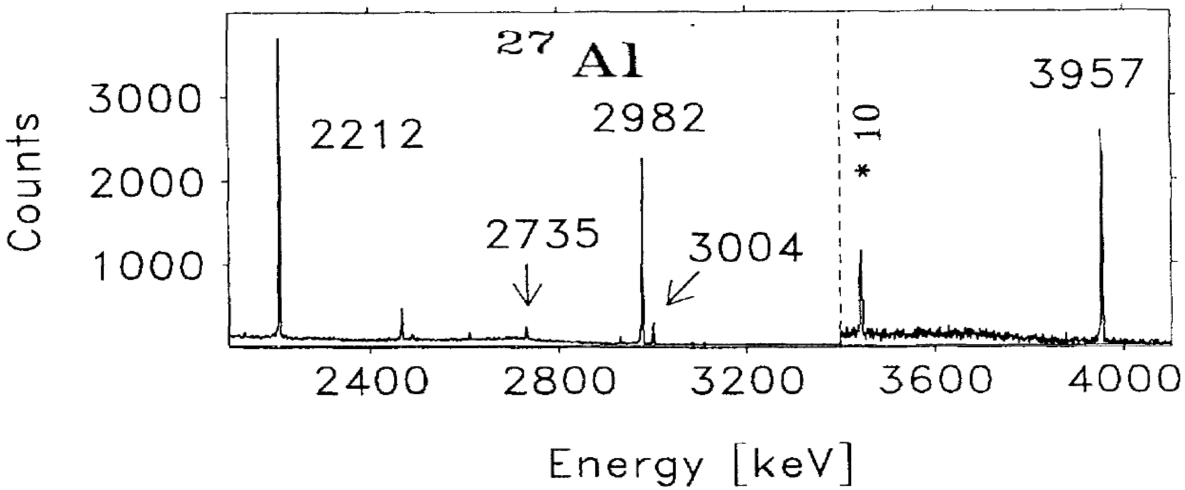
high energy resolution
spin selective: $\Delta J=1,2$
strength selective



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

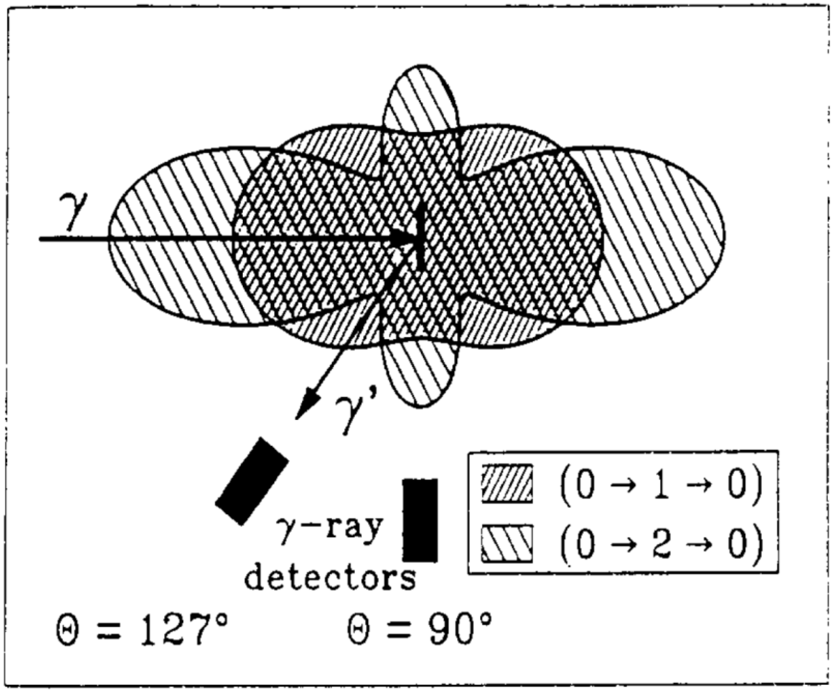
$$\left\langle \frac{d\sigma}{d\Omega} \right\rangle_f (\theta) = g \left(\frac{\pi \hbar c}{E_r} \right)^2 \Gamma_0 \frac{\Gamma_f}{\Gamma} \frac{W(\theta)}{4\pi} \equiv I_{s,f} \frac{W(\theta)}{4\pi} \ .$$

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)

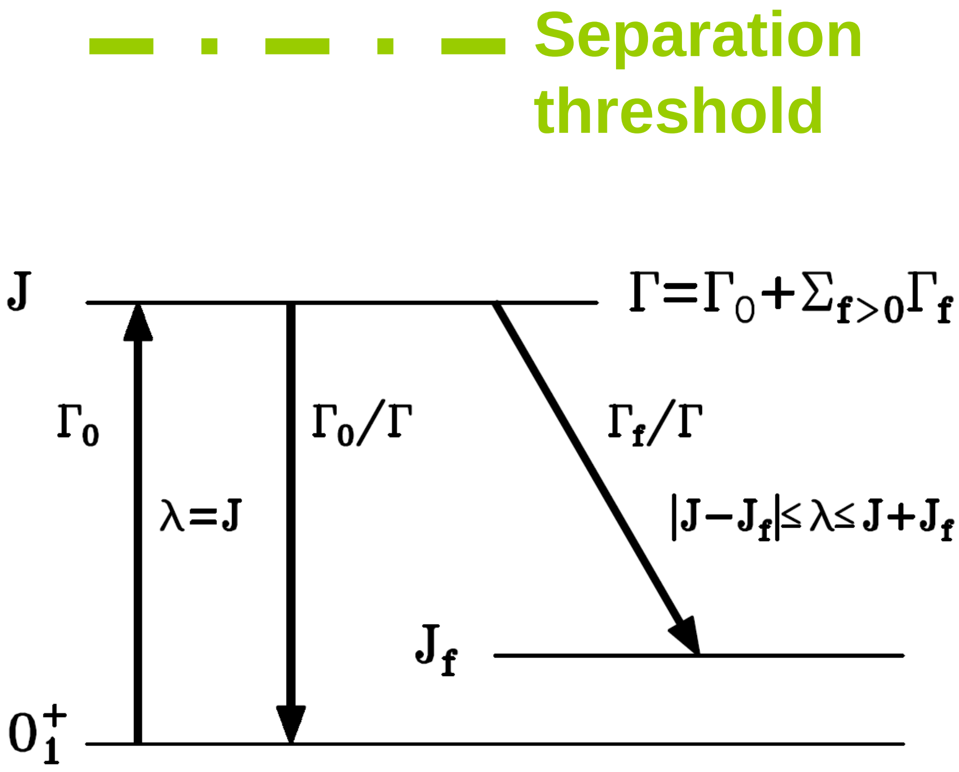
Angular distribution functions W(ϑ) from angular correlation theory

→ 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



Observables

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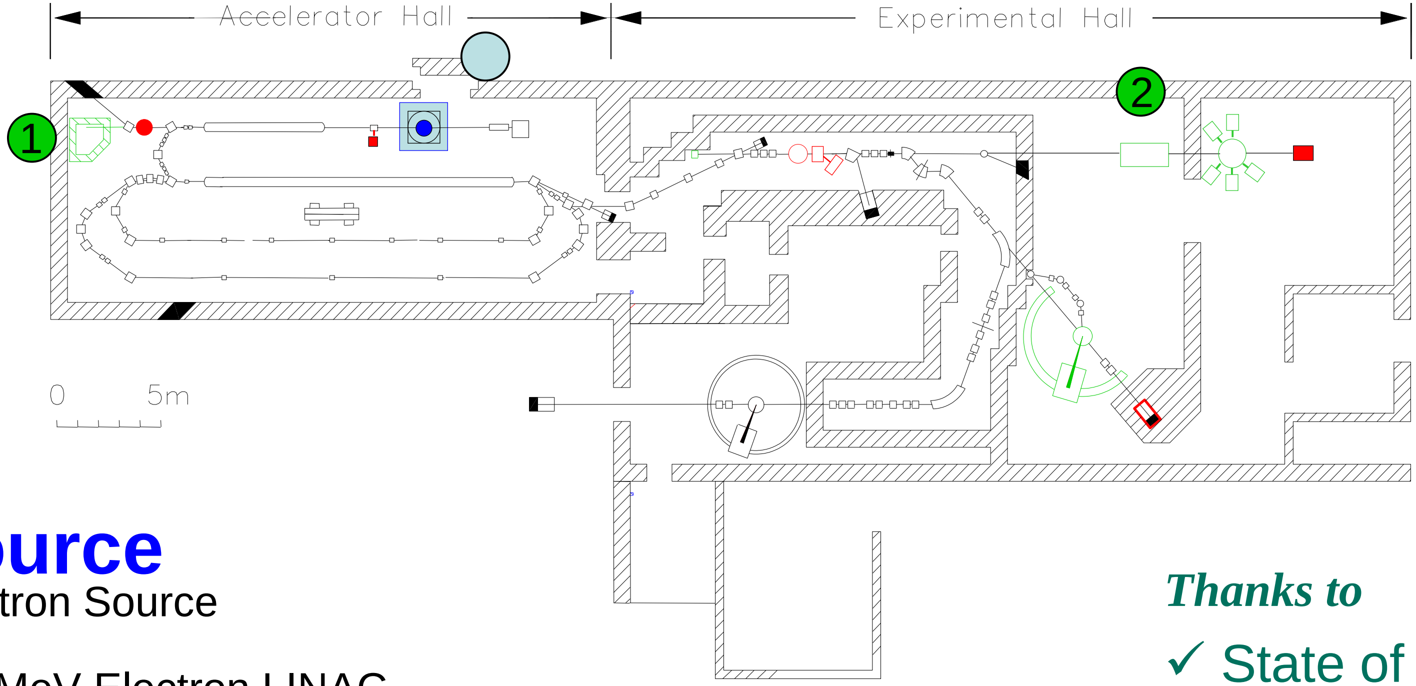
- Multipole Mixing δ
- Decay Strengths $B(\pi\lambda)$

S-DALINAC at TU Darmstadt



Source

○ Electron Source

● 130 MeV Electron LINAC

Photon Experiments

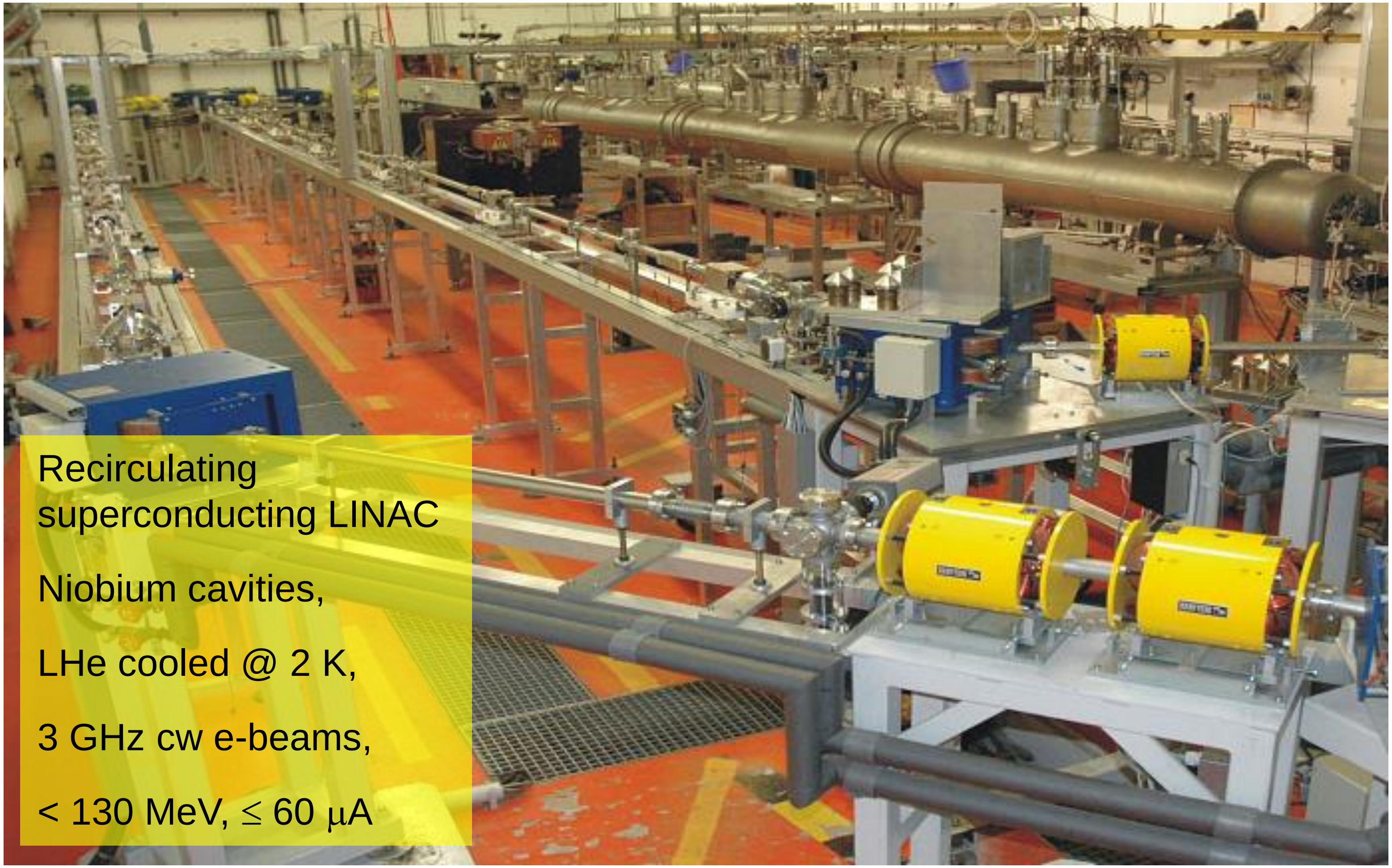
① 10 MeV Injector: Photon Scattering / Photofission

② < 30 MeV Tagger: Photodesintegration / Photon Scattering

Thanks to

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

S-DALINAC at TU Darmstadt



Recirculating superconducting LINAC

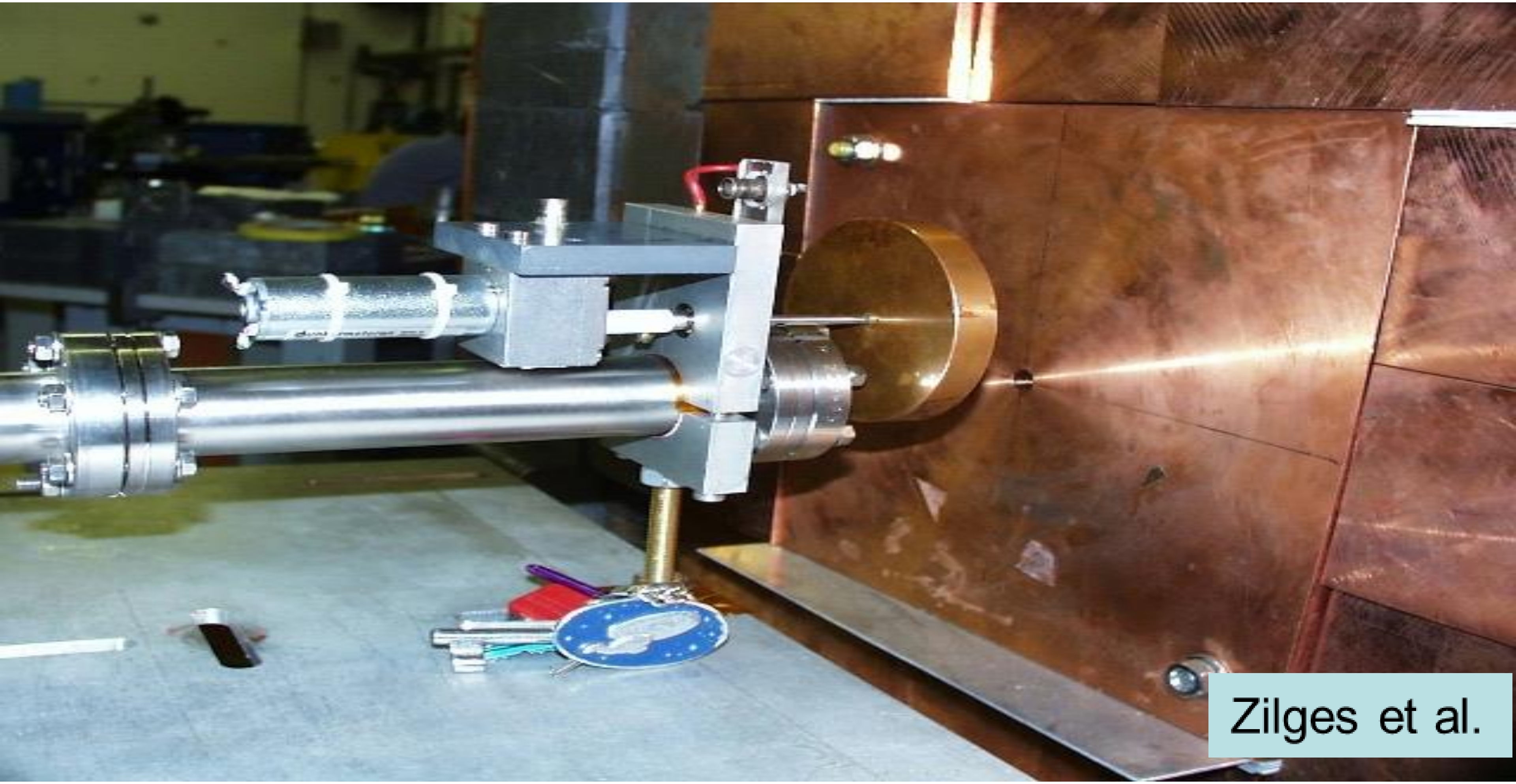
Niobium cavities,

LHe cooled @ 2 K,

3 GHz cw e-beams,

< 130 MeV, $\leq 60\ \mu$A

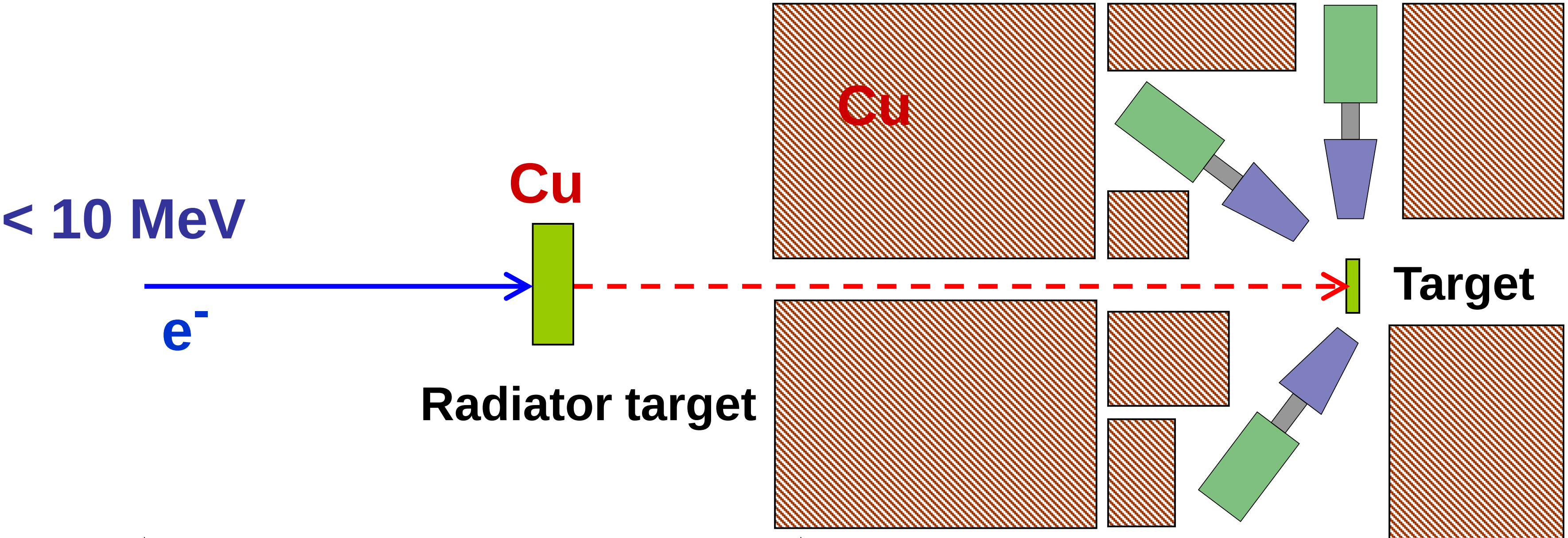
Bremsstrahlung-Site

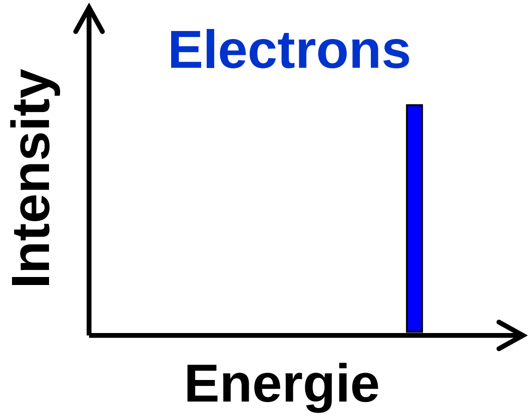


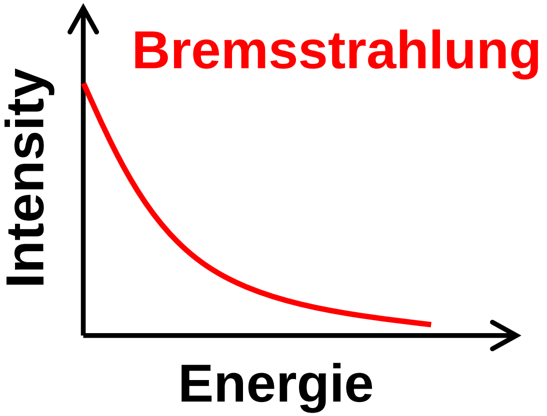
Zilges et al.

Darmstadt Low-Energy Photon Scattering Site at S-DALINAC

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

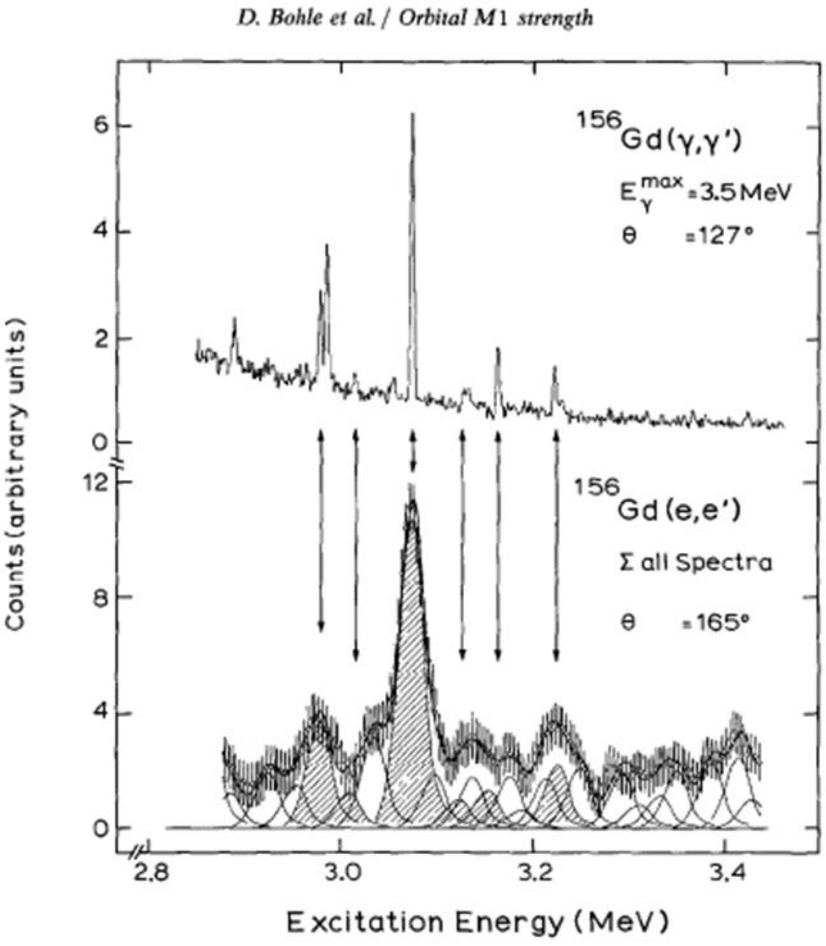




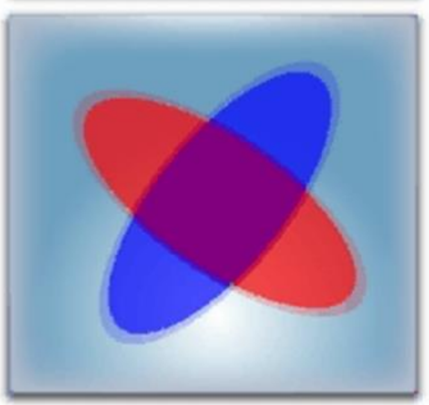


E_γ < 10 MeV

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

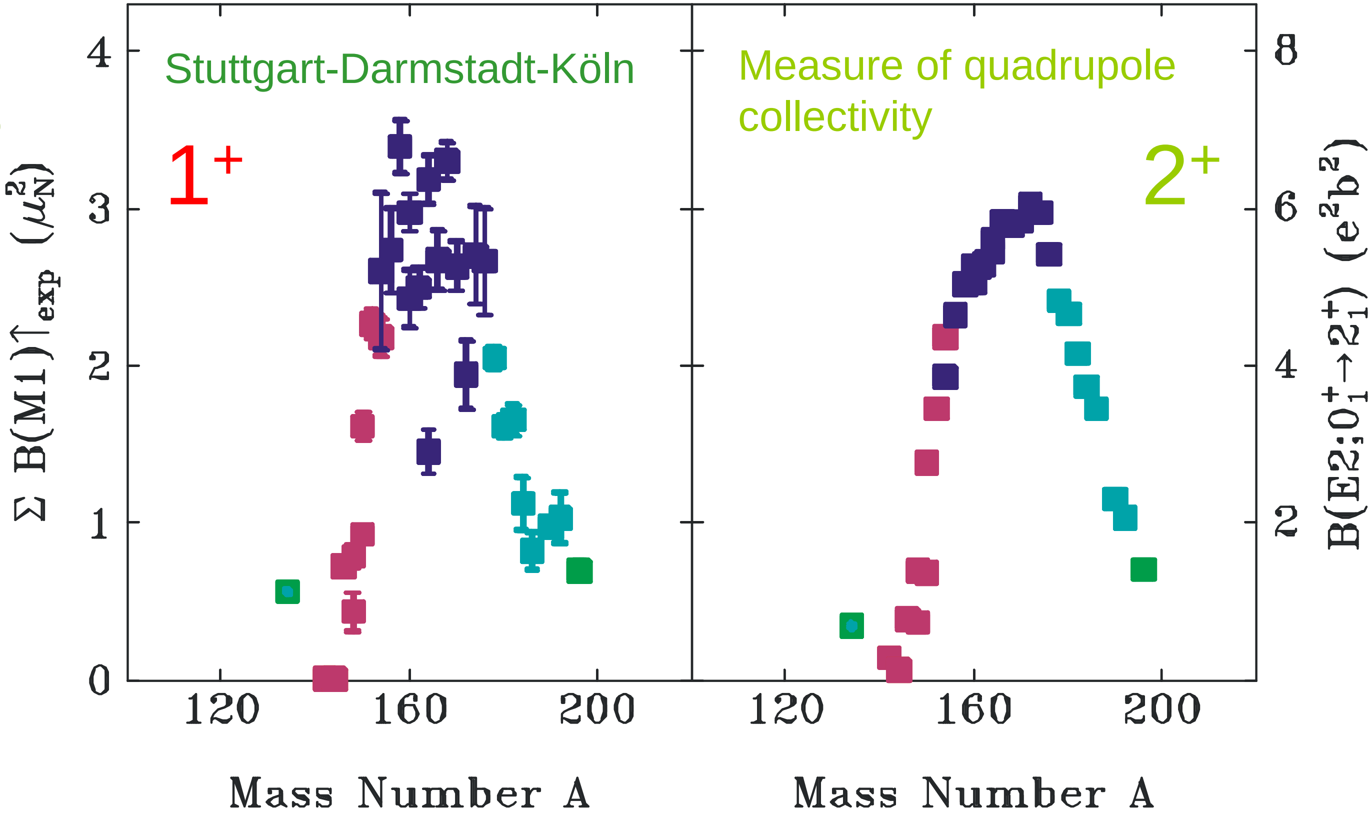
Systematics: photon scattering

Systematics of scissors mode in rare earth's

Collectivity of the Scissors Mode

Richter,
Kneissl,
von Brentano
et al.

M1

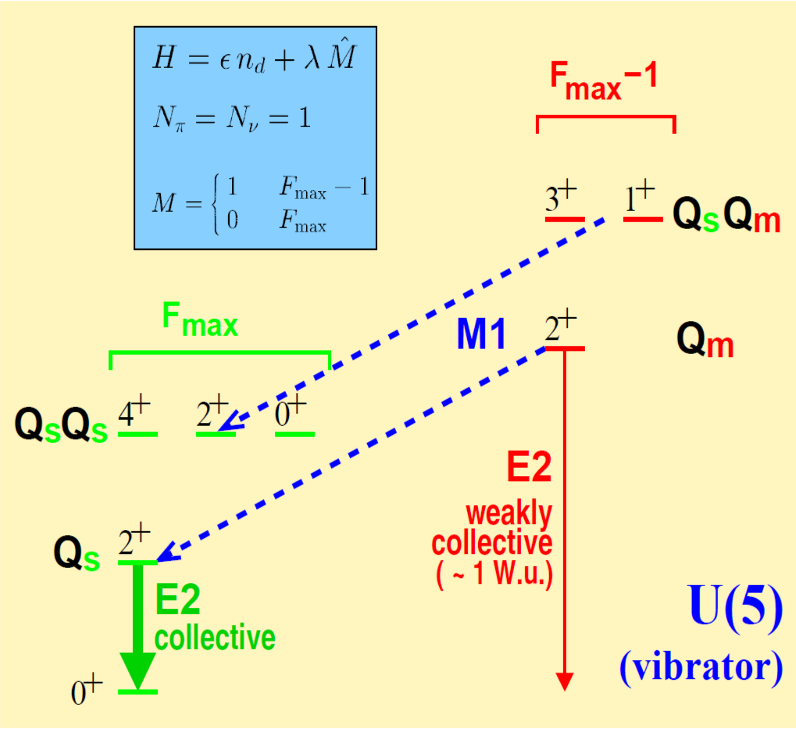


E2

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

Nuclear Structures with Mixed pn-Symmetry

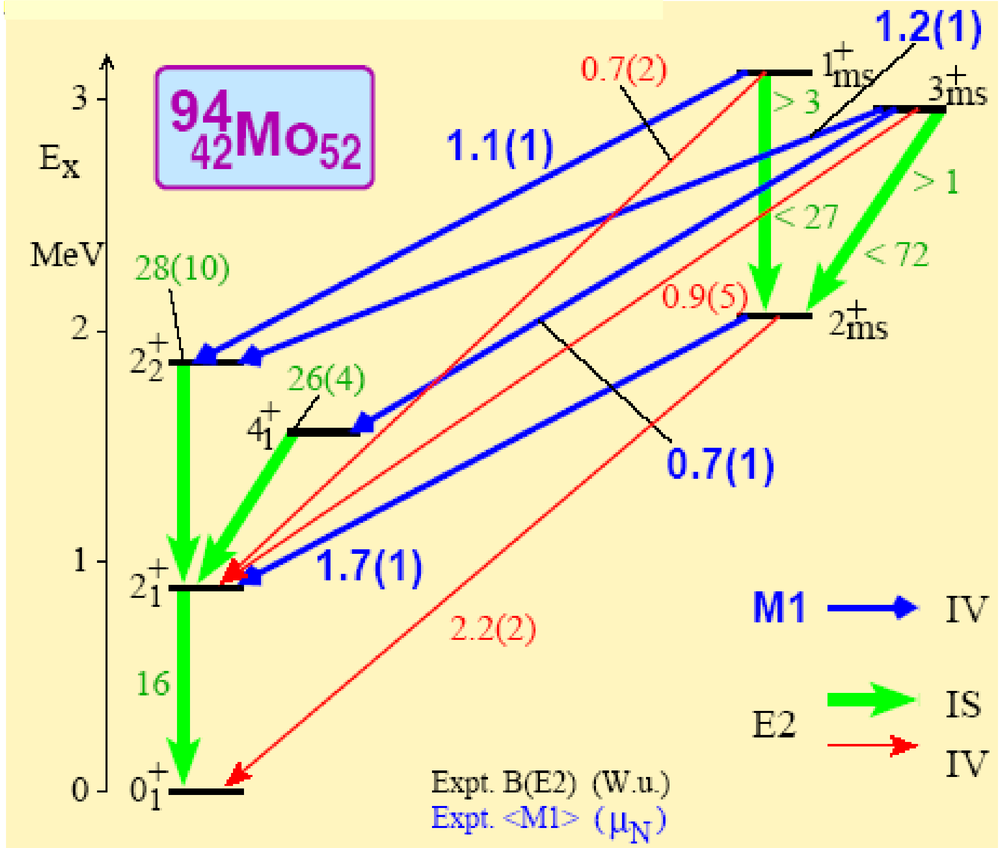
M1 as unique signature for mixed-symmetry states



$$H = \epsilon n_d + \lambda \hat{M}$$

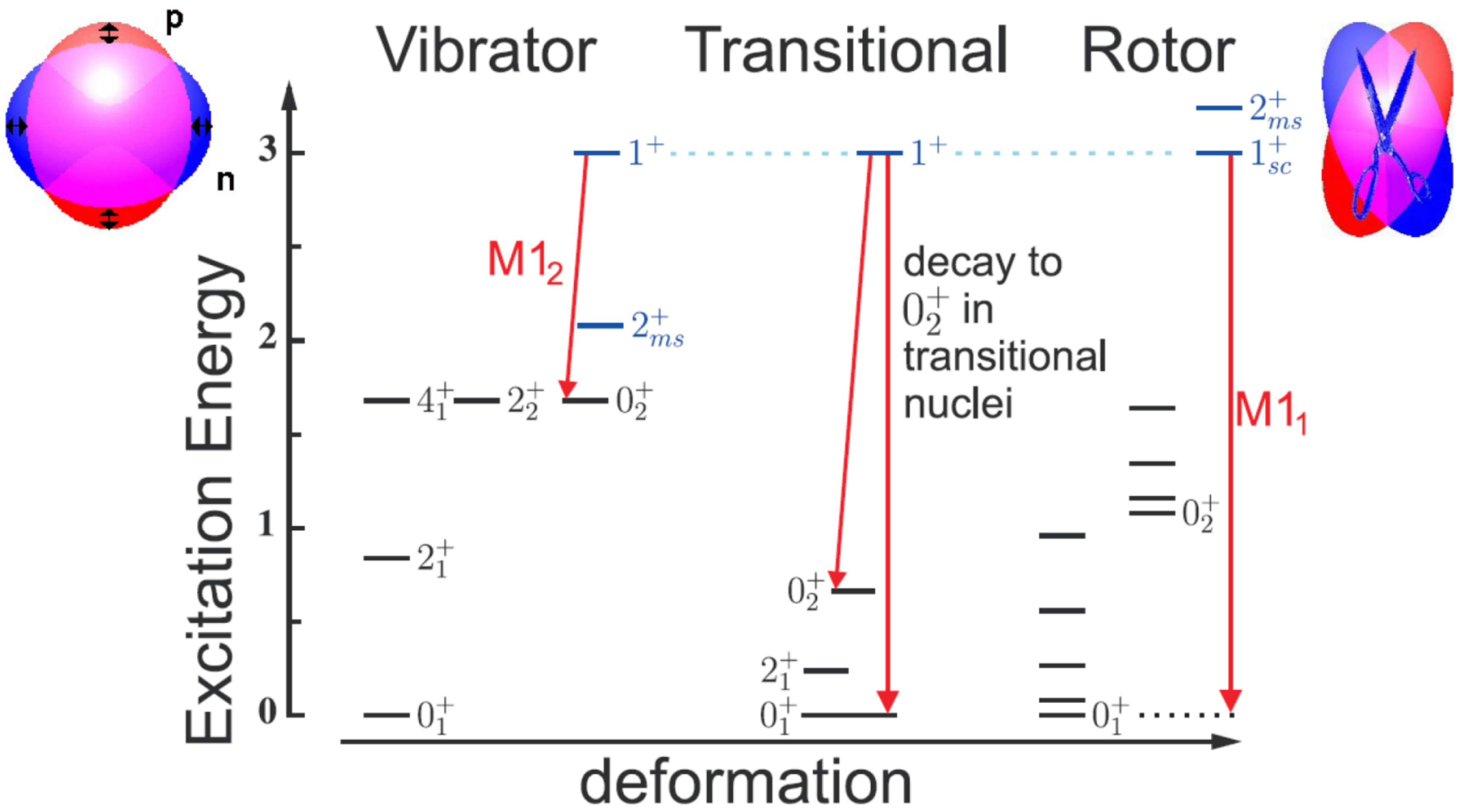
$$N_\pi = N_\nu = 1$$

$$M = \begin{cases} 1 & F_{\max} - 1 \\ 0 & F_{\max} \end{cases}$$



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

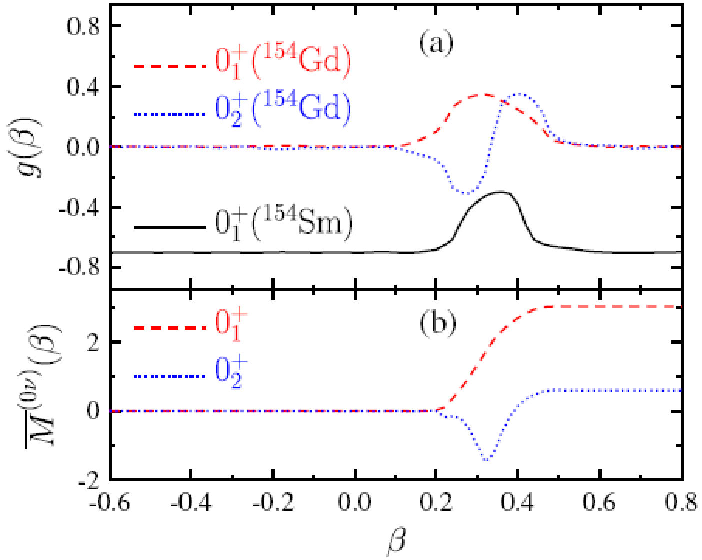


‚Application‘: Dipole strength and 0νββ-decays

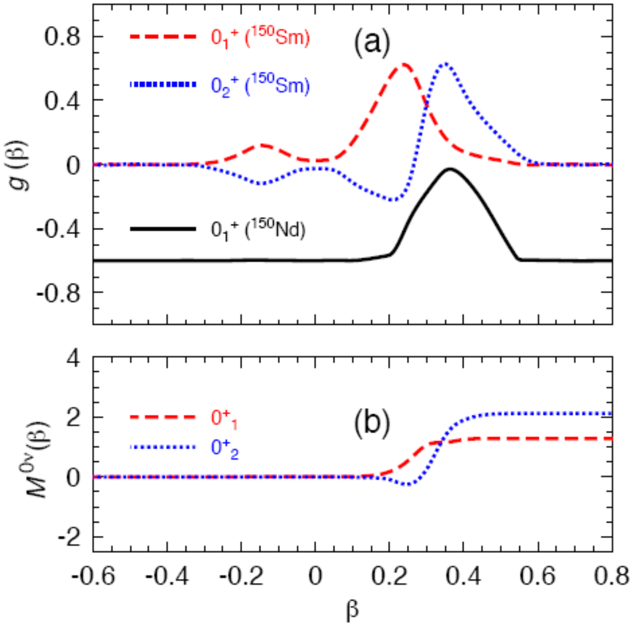
PRL **111,** 172501 (2013) PHYSICAL REVIEW LETTERS week ending 25 OCTOBER 2013

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

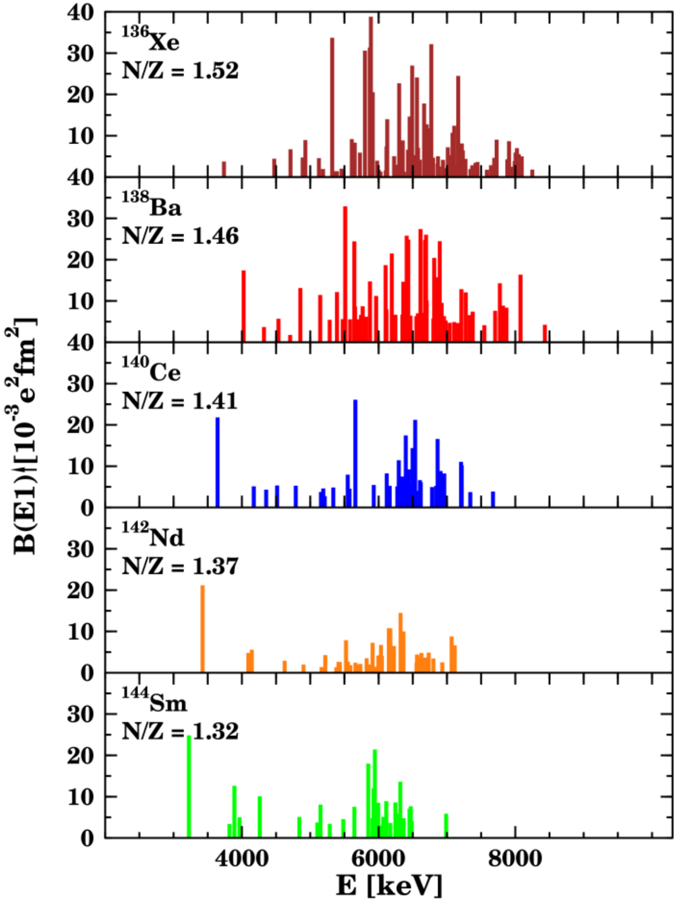
J. Beller,[1,*] N. Pietralla,[1] J. Barea,[2] M. Elvers,[3,†] J. Endres,[3,‡] C. Fransen,[3] J. Kotila,[4] O. Möller,[1] A. Richter,[1]
T. R. Rodríguez,[1] C. Romig,[1] D. Savran,[5,6] M. Scheck,[1,7] L. Schnorrenberger,[1] K. Sonnabend,[8]
V. Werner,[9] A. Zilges,[3] and M. Zweidinger[1]



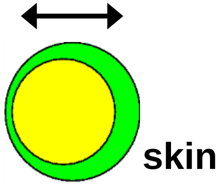
^{150}Nd:
larger **0νββ-**
decay branch
to 0^+_2 state
than to gs due
to QSPT at
N=90.



Pygmy Dipole Resonance



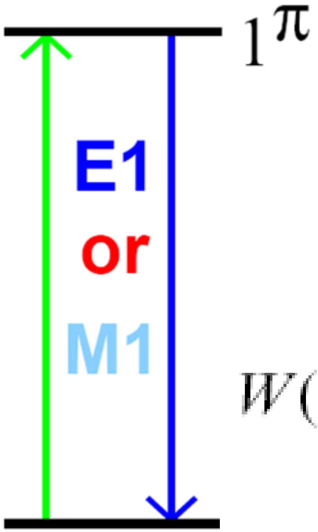
- **Concentration around 5-7 MeV**
- **Fragmented strength**
- **Summed strength: Scaling with N/Z ?**

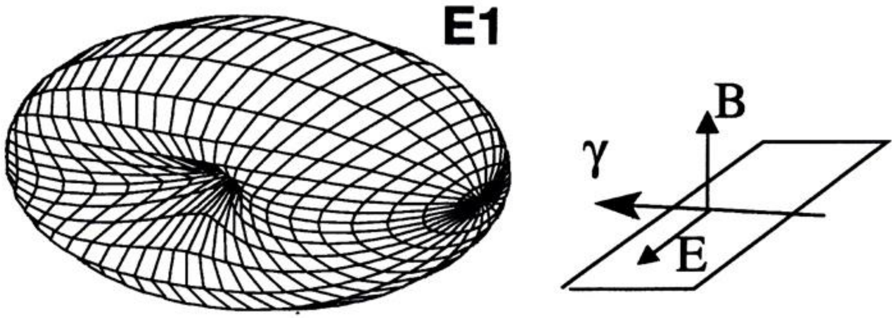


*R.-D. Herzberg et al., PLB **390**, 49 (1997).*
*A. Zilges et al., PLB **542**, 43 (2002).*
*D. Savran et al., PRC **84**, 024326 (2011).*

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

Parity quantum number π for J=1 states





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

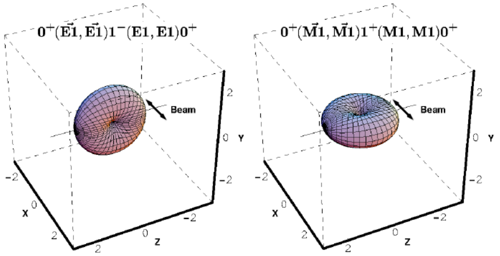
N.Pietralla, H.R. Weller et al.,
NIM A 483 (2002) 556.

Elastic scattering distribution not isotropic about incident polarization plane.

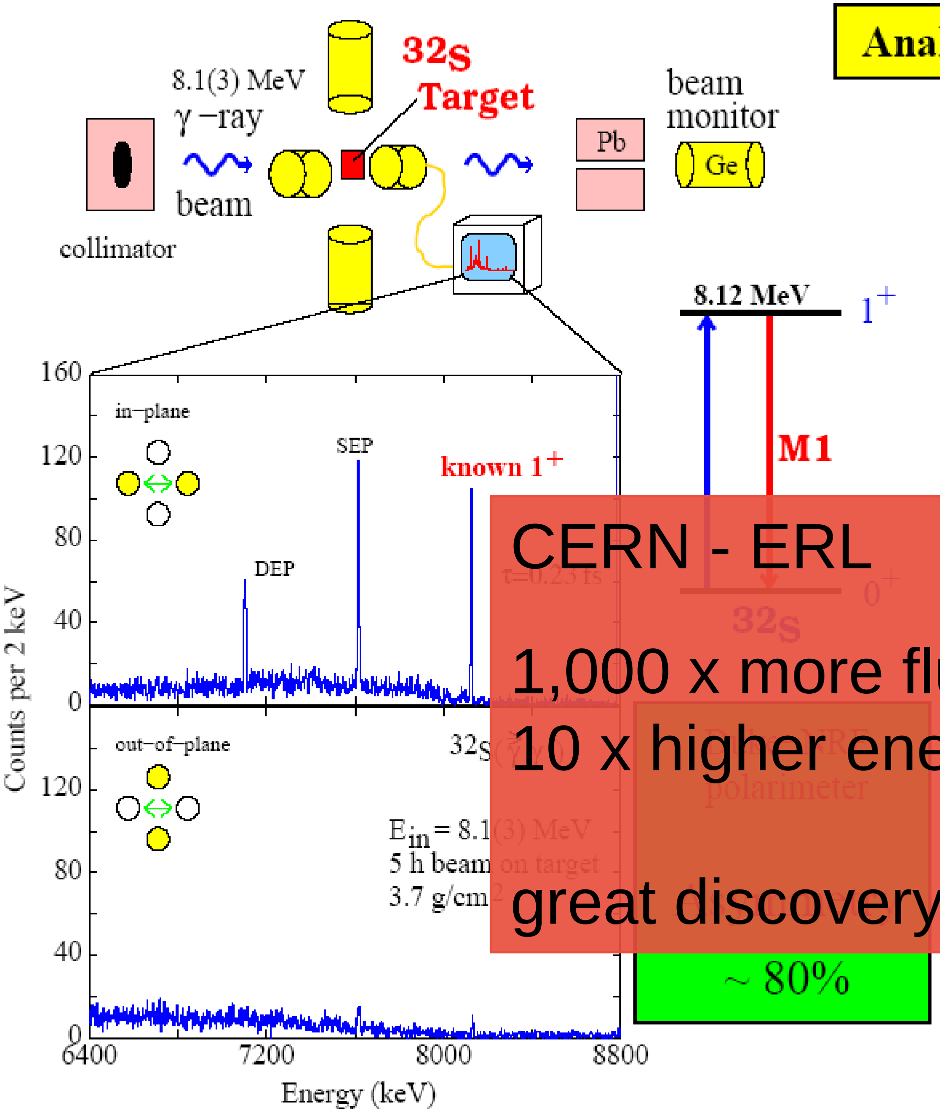
No intensity along oscillating dipole vector

Azimuthal rotation by 90° for M1 and E1 distributions

Observable only for linearly polarized beam

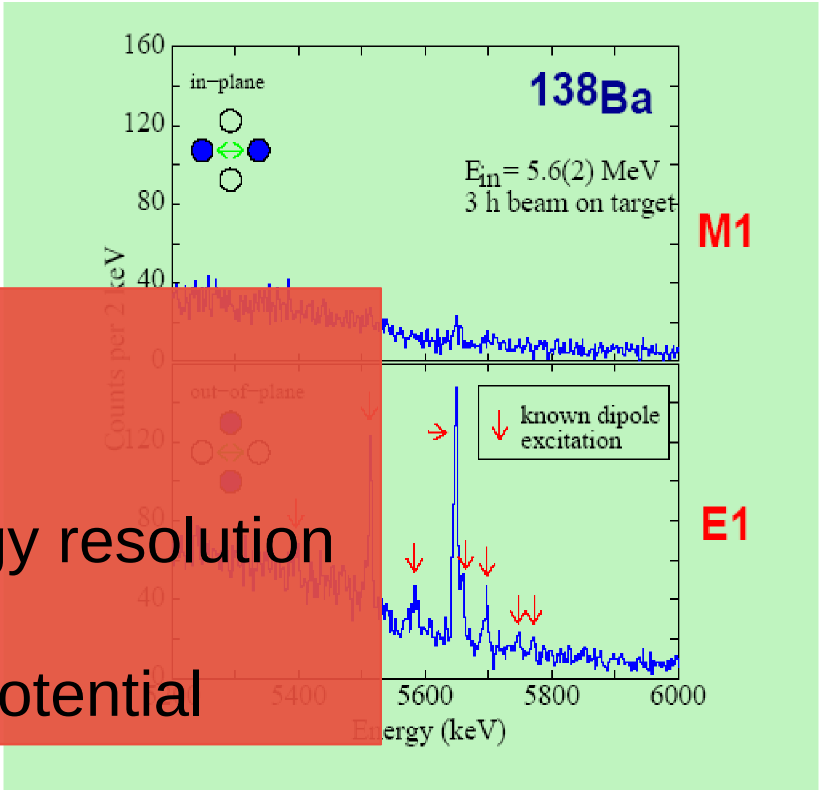


Analyzing Power for the Pygmy Resonance



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

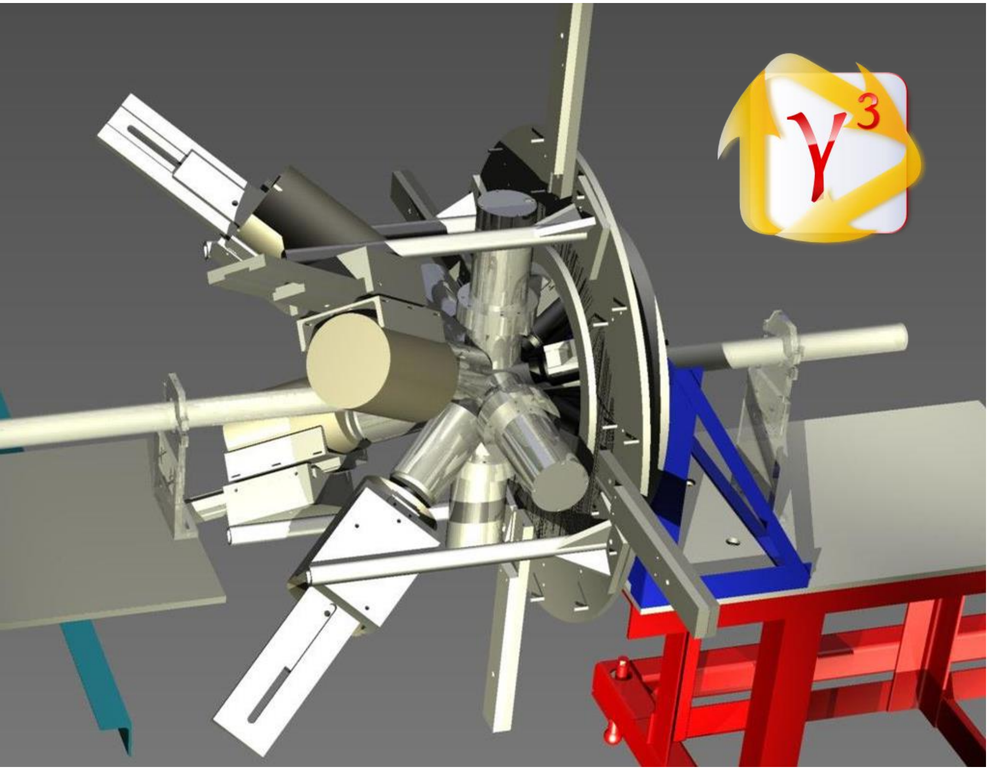
10 x higher energy resolution

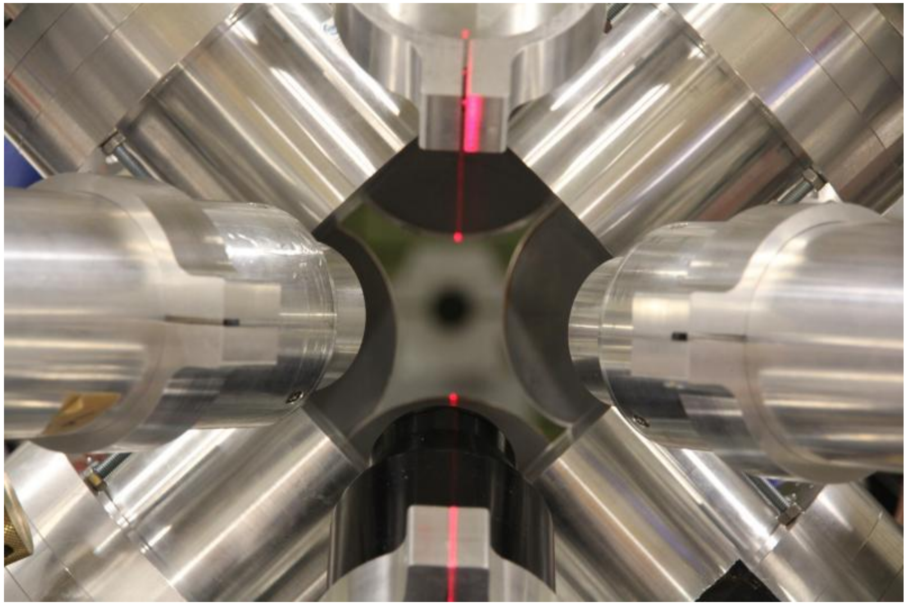
great discovery potential

established international community
(not only NRF!)

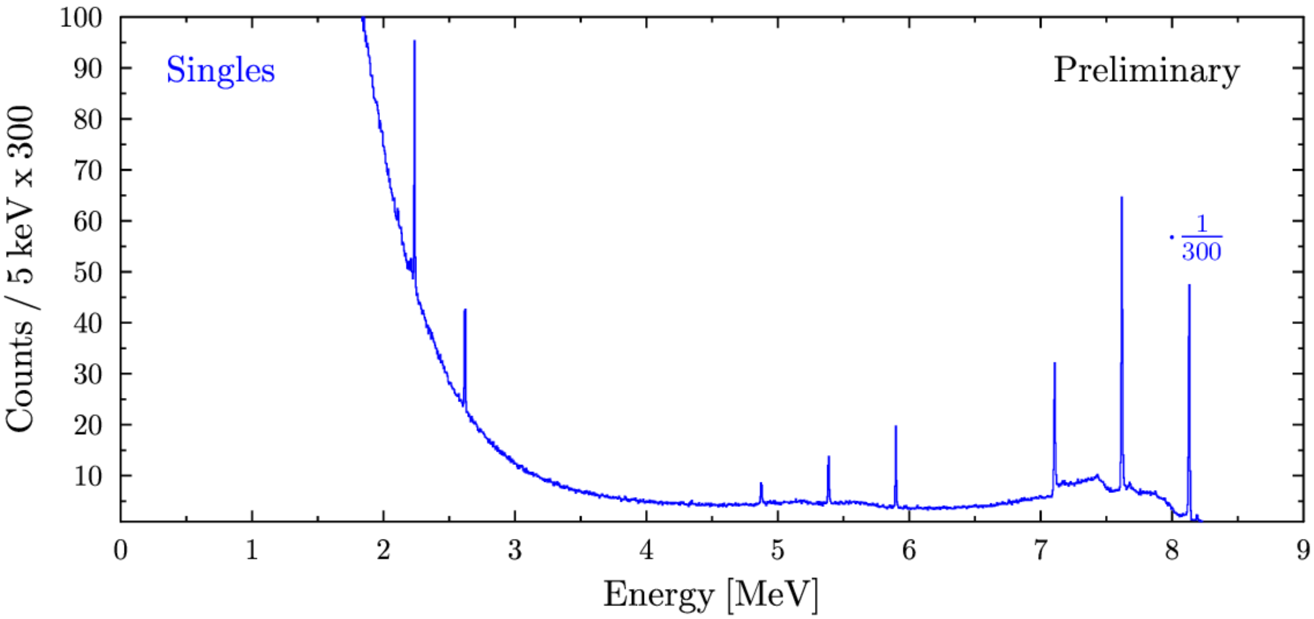
Advanced set-up: γ^3 at HIγS

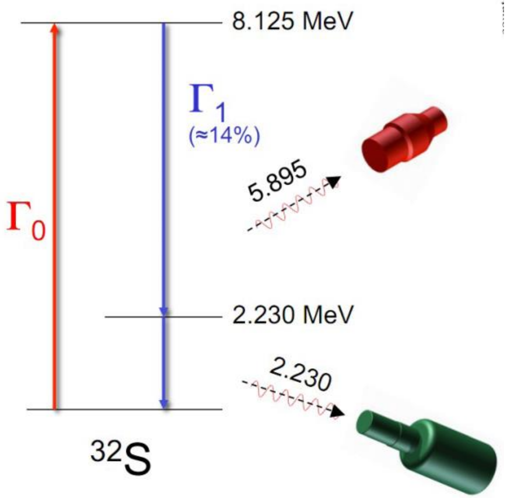
B. Löher et al., Nucl. Instruments Methods Phys. Res. Sect. A **723**, 136–142 (2013).





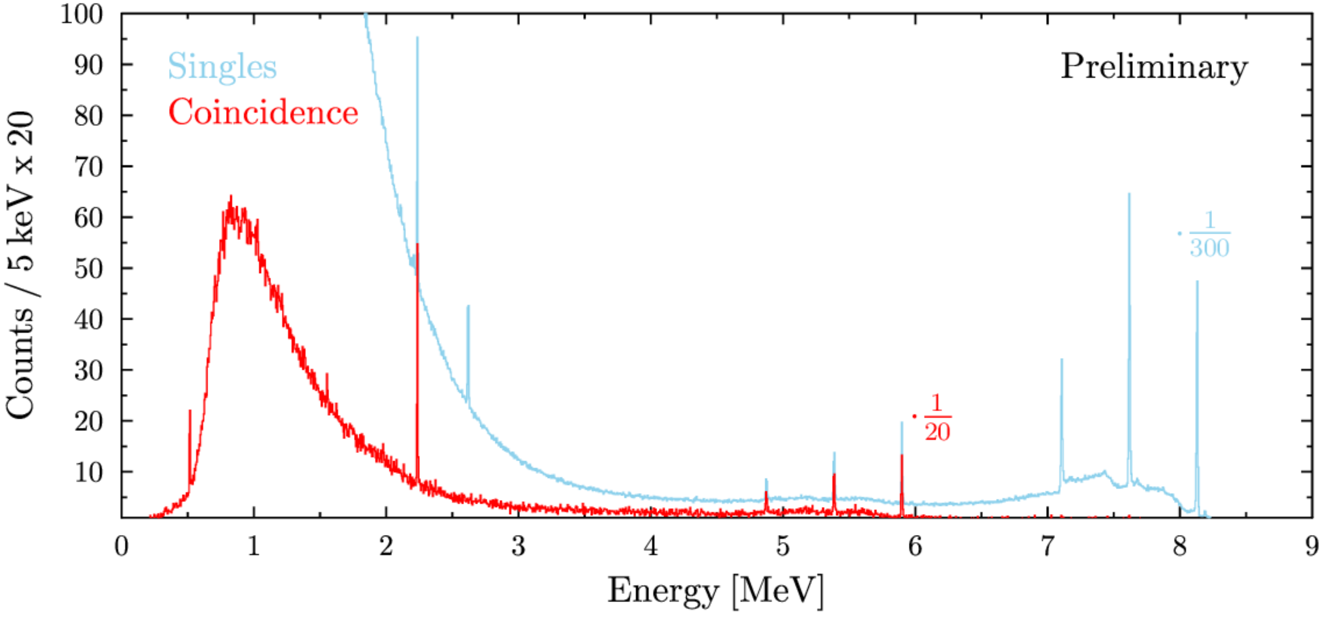
First γγ-coincidences in a γ-beam: γ³ @ HIγS

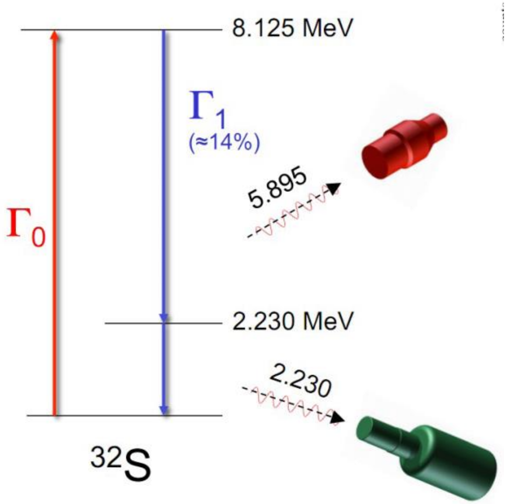




B. Löher et al., Nucl. Instruments Methods Phys. Res. Sect. A **723**, 136–142 (2013).

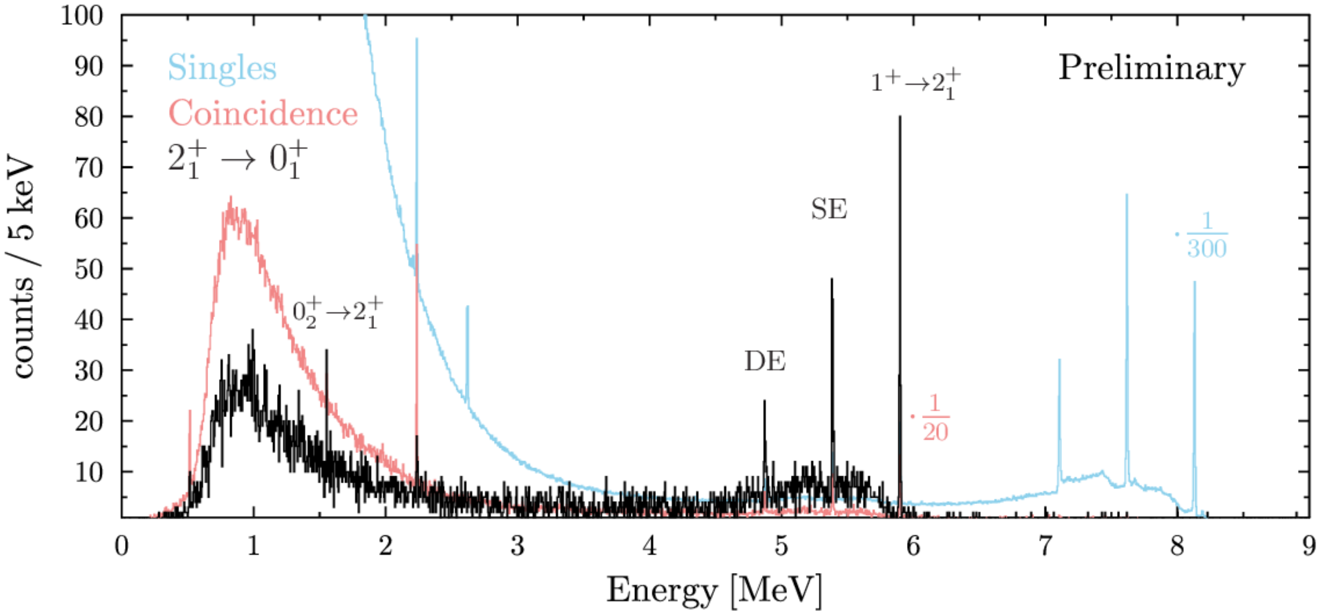
First $\gamma\gamma$-coincidences in a γ-beam: γ^3 @ HIγS

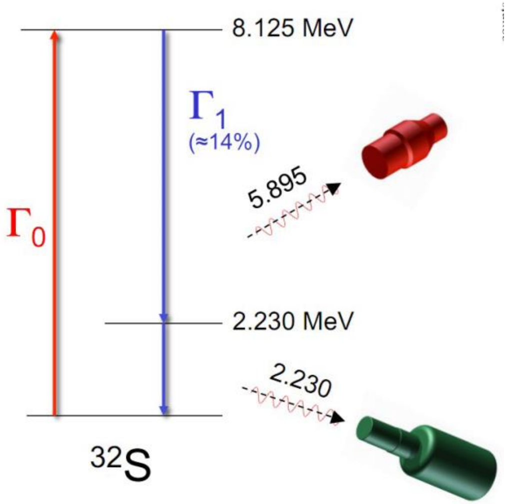




B. Löher et al., Nucl. Instruments Methods Phys. Res. Sect. A **723**, 136–142 (2013).

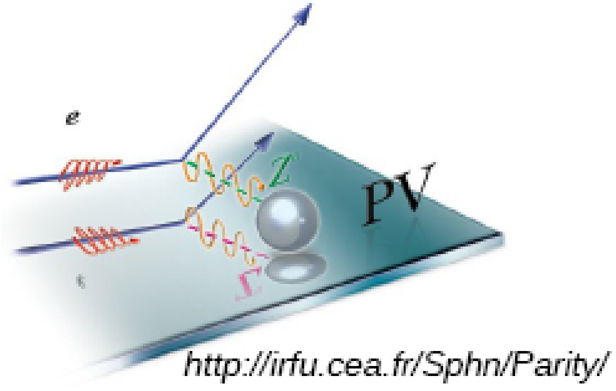
First γγ-coincidences in a γ-beam: γ³ @ HIγS





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

Parity Violation in Nuclear Structure?



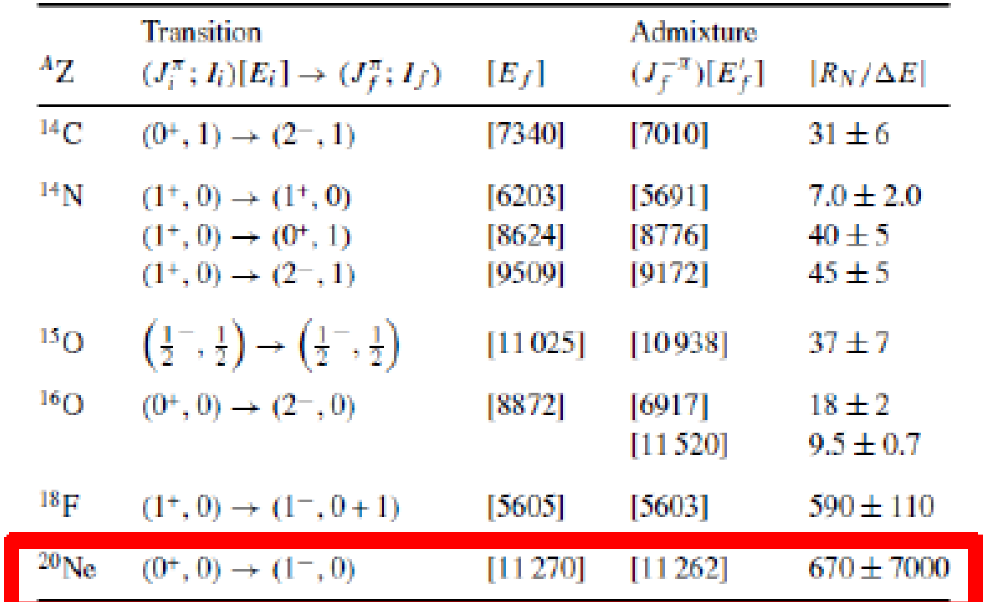
http://irfu.cea.fr/Sphn/Parity/

- 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]

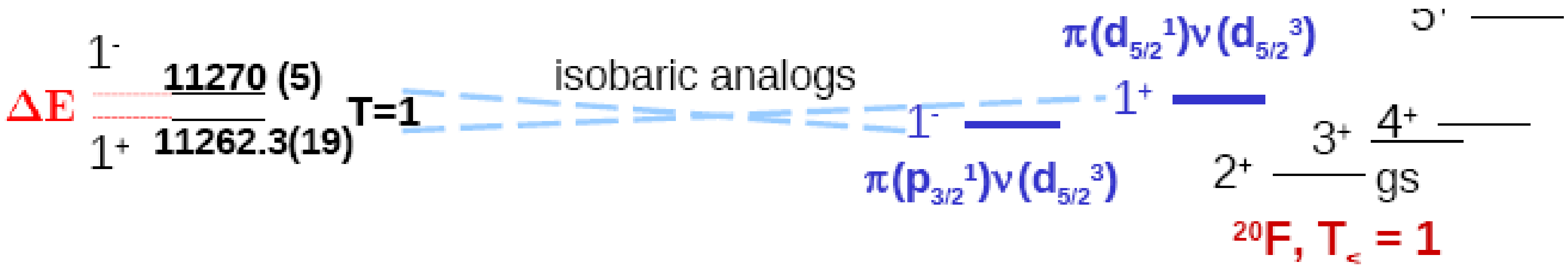
$$A^{a}_{RL} = \frac{\sigma^{a}_{R} - \sigma^{a}_{L}}{\sigma^{a}_{R} + \sigma^{a}_{L}} \sim \frac{2R}{E_{\pi} - E_{-\pi}} \langle \phi_{-\pi} | V_{PNC} | \phi_{\pi} \rangle$$



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

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

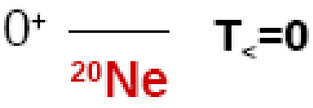
^{20}Ne Parity Doublet



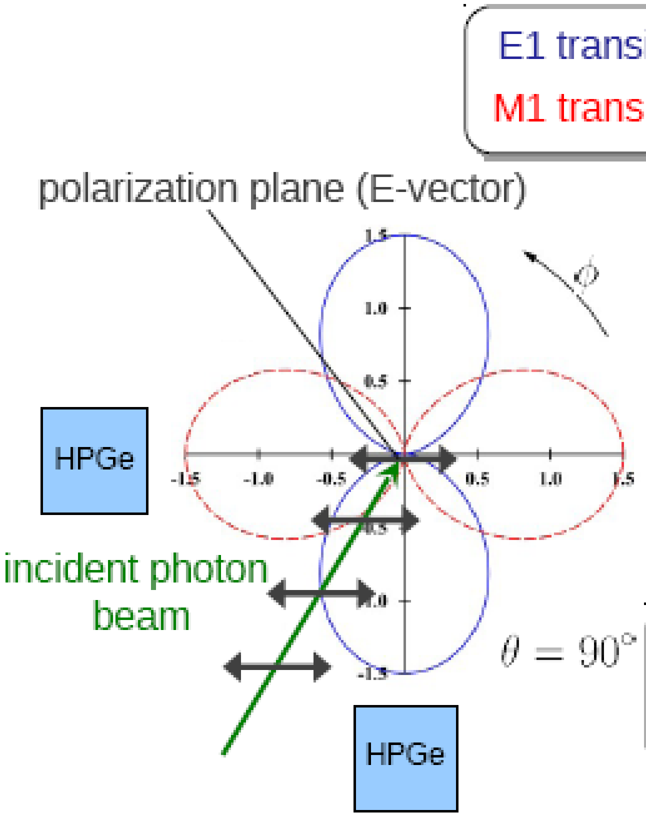
- doublet is isobaric analog of simple shell model states
- high nuclear enhancement factor [1]:
  - overlapping wavefunctions
  - small energy splitting (large uncertainty)

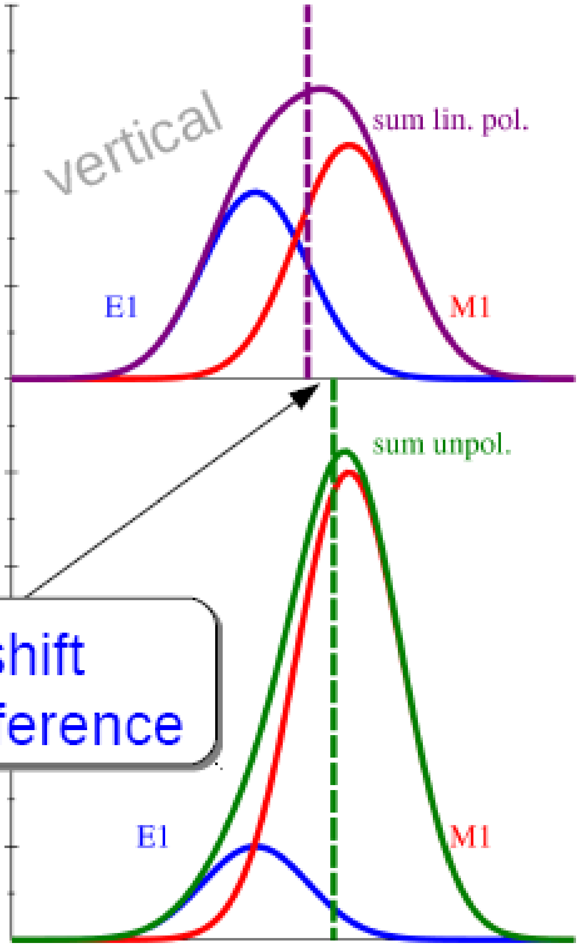
$$|R_N/\Delta E| = (670 \pm 7000) \quad \Delta E = (7.7 \pm 5.3)\ \mathrm{keV}$$

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



Energy Splitting of ^{20}Ne Parity Doublet

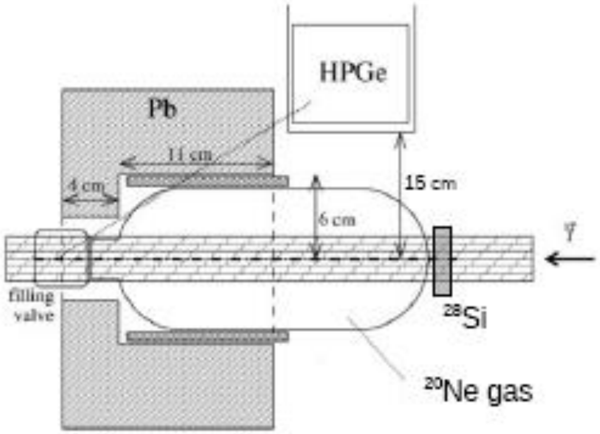




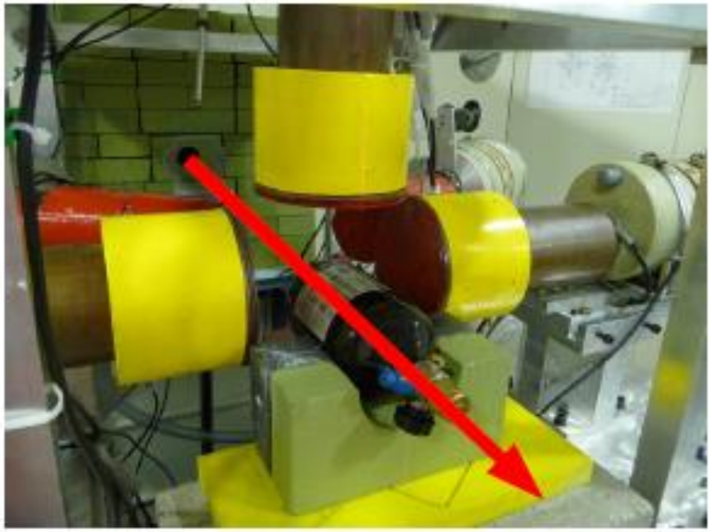
Centroid shift
→ energy difference

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

Experiment on ^{20}Ne at HIγS



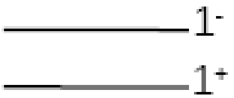
adapted from
T.C. Li *et al.*, Phys. Rev. C **73** 054306 (2006)



- 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

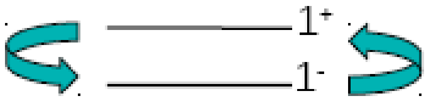
- before:



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

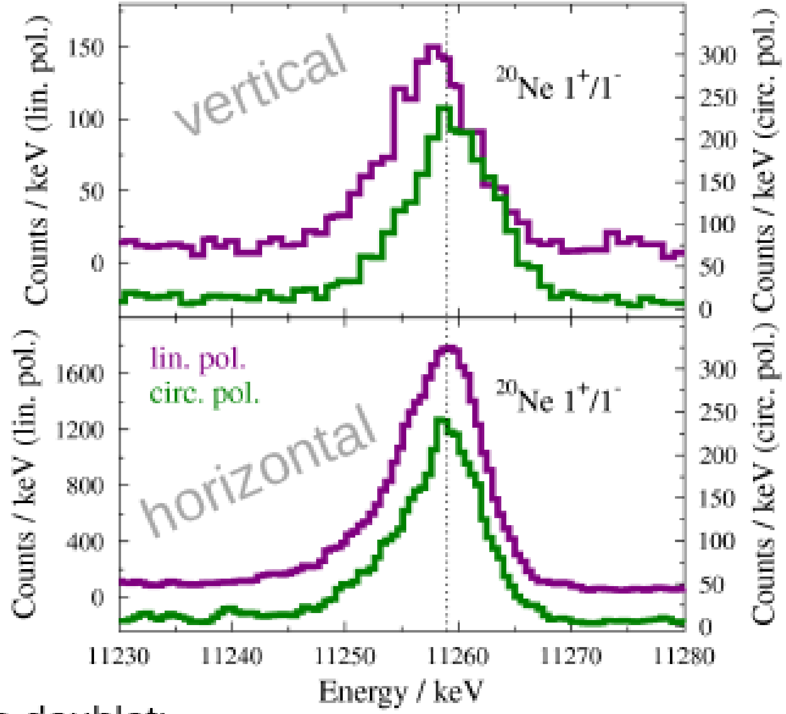
$$\frac{R_N}{\Delta E} = 670 \pm 700$$

- now:



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

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



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

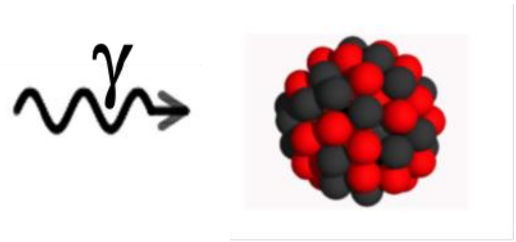
- ^{20}Ne doublet:
  - strong M1: $\Gamma_{0,\ 1^+} = 11.2(20)\ \mathrm{eV}$ [2]
  - weak E1: $\Gamma_{0,\ 1^-} = 0.39(5)\ \mathrm{eV}$ [2]

[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**



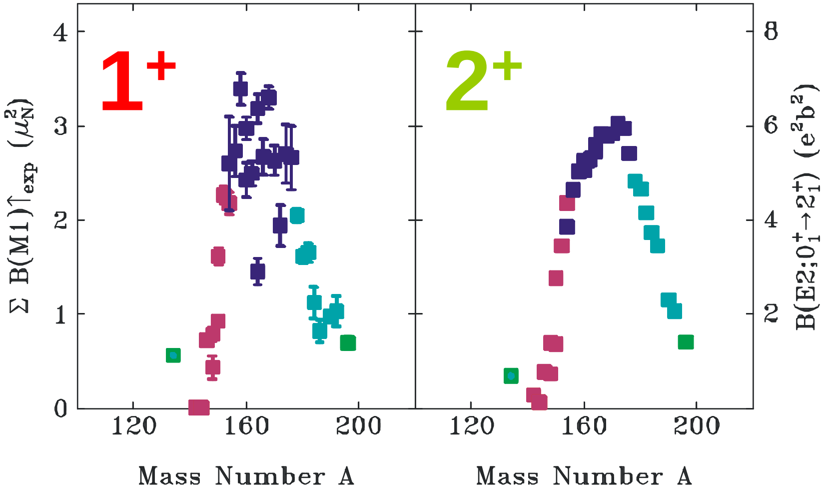
- **Intensity Frontier (instrumental challenge)** → **„Discovery Frontier“**

  (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“…**

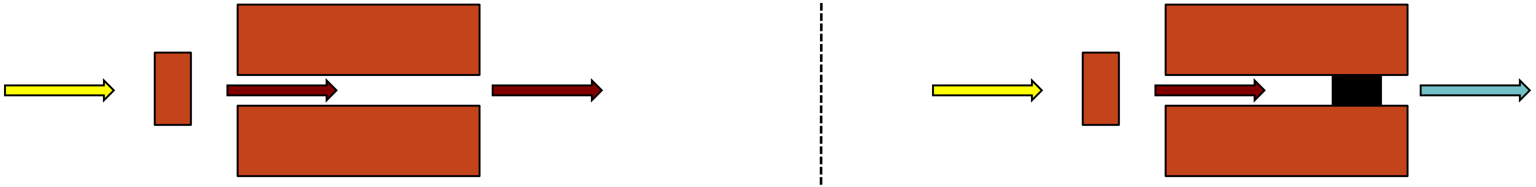


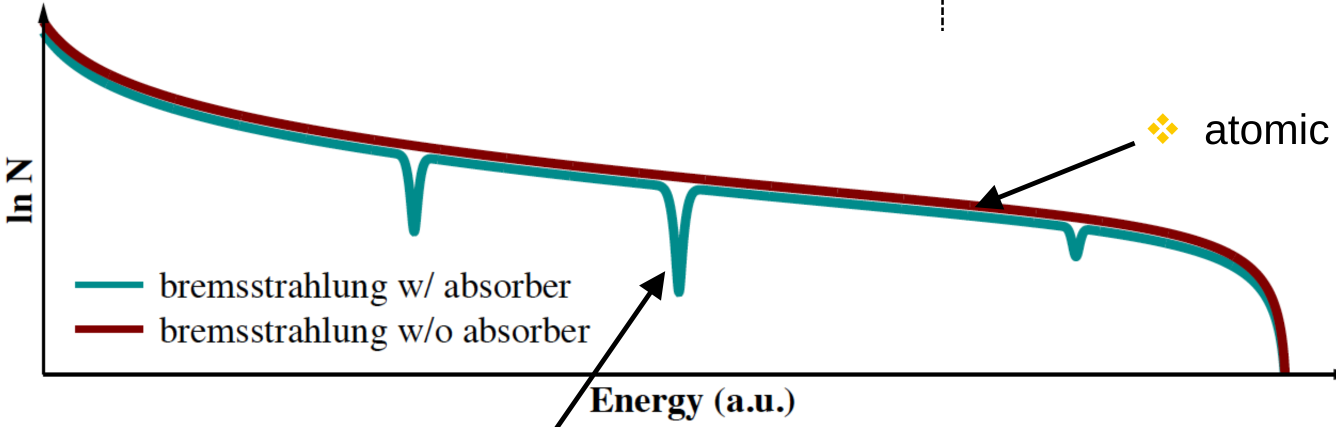
N. Pietralla et al., PRC **58**, 184 (1998)

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

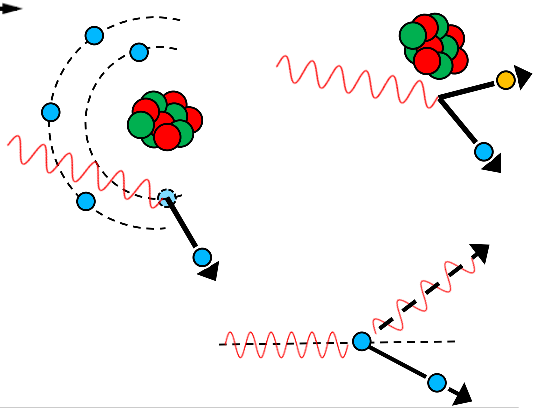
Absorption Processes

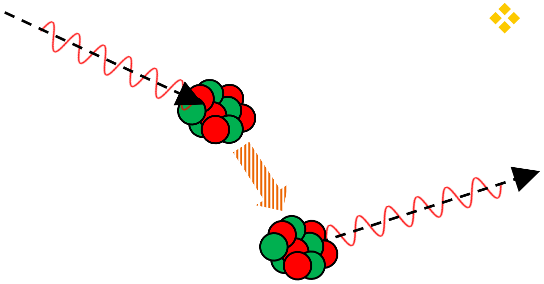
Absorption lines only a few eV wide!





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





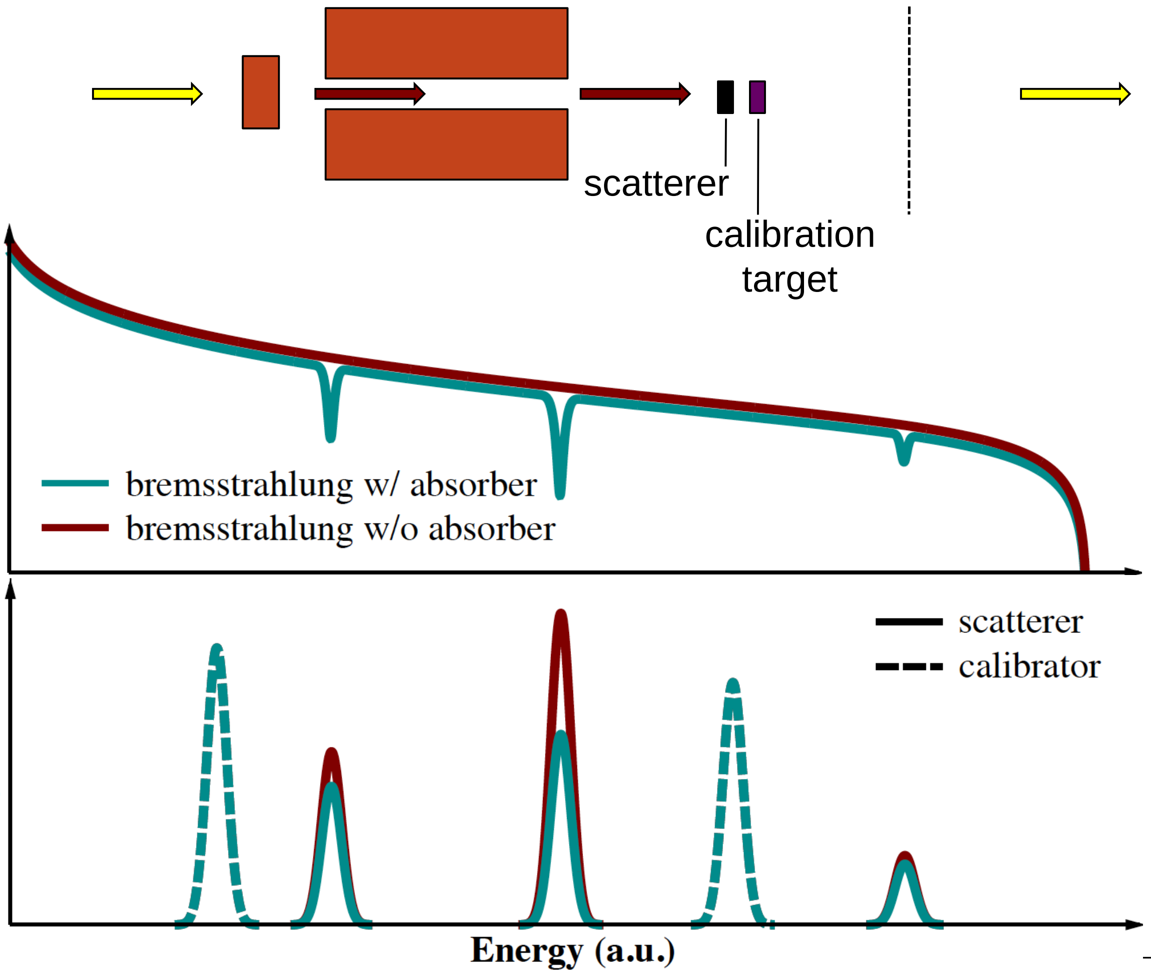
- resonant absorption
  - only at resonance energies
  - depends on Γ_0

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

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“.



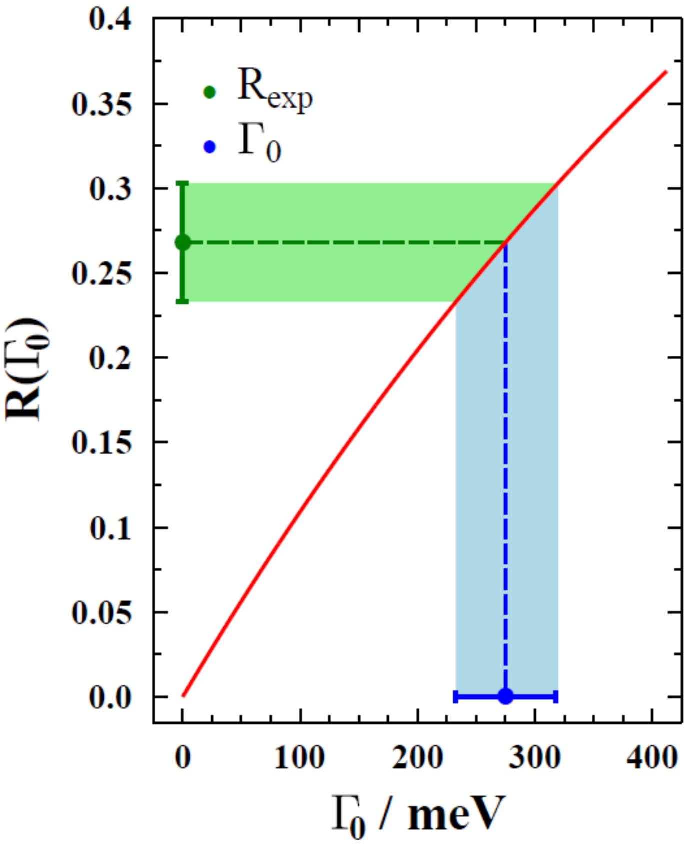
Self Absorption:
Decrease of Scattered Photons because of Resonant Absorption

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

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

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

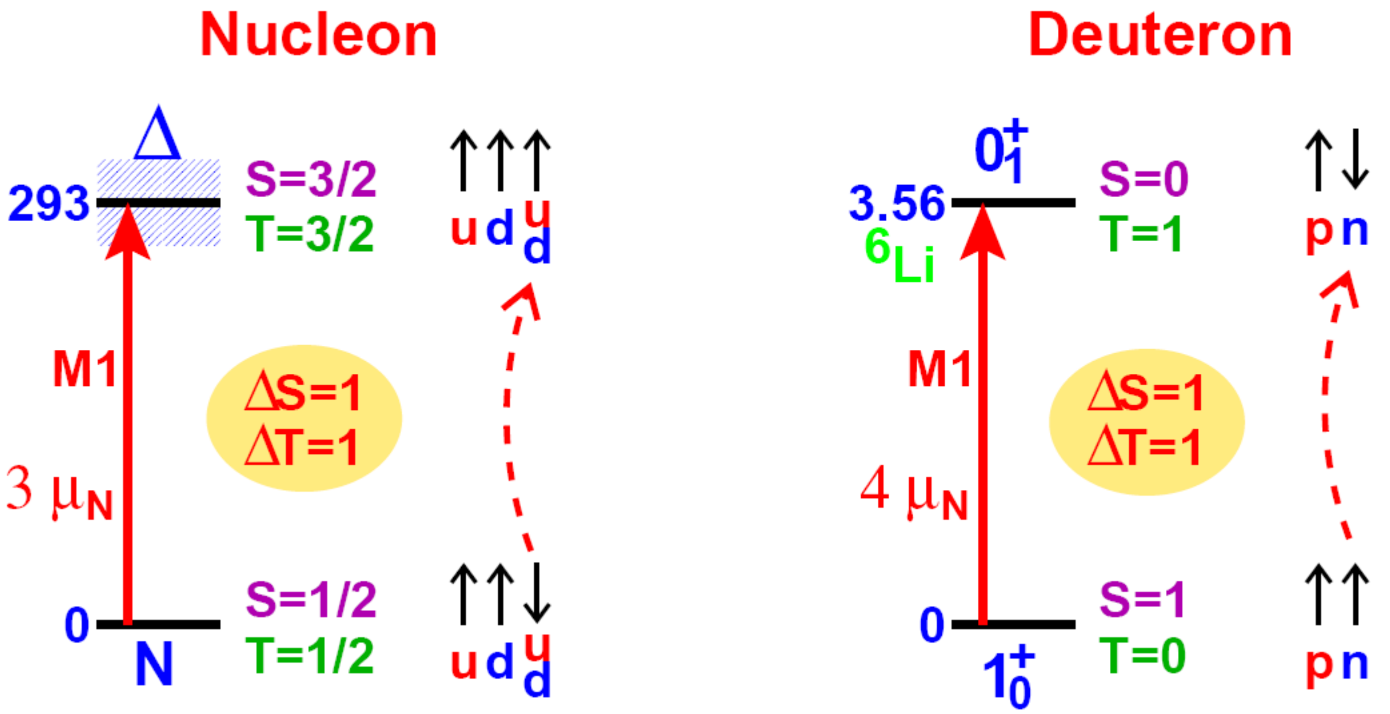
- calculate *R* as function of Γ_0
- self absorption R_{exp} determined experimentally
- comparison of experiment and calculation gives ground-state transition width Γ_0
- NRF measurement gives $\Gamma_0 \cdot \frac{\Gamma_0}{\Gamma}$
- thus total transition width Γ and branching ratio Γ_0/Γ to ground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



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

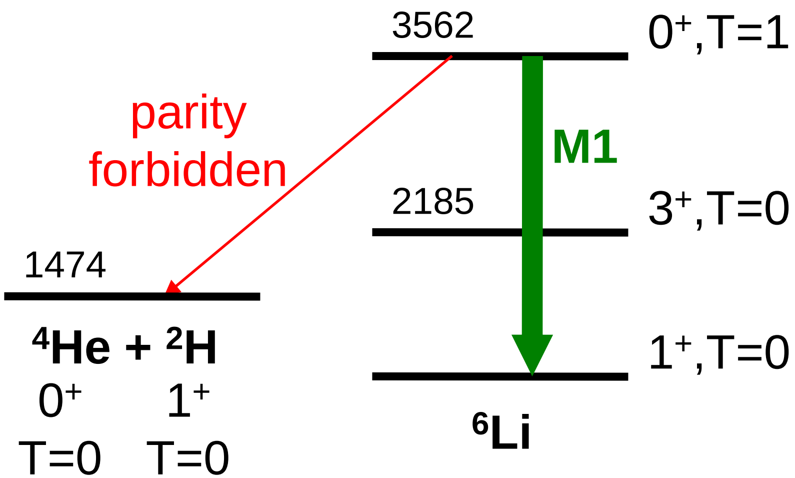
TECHNISCHE UNIVERSITÄT DARMSTADT

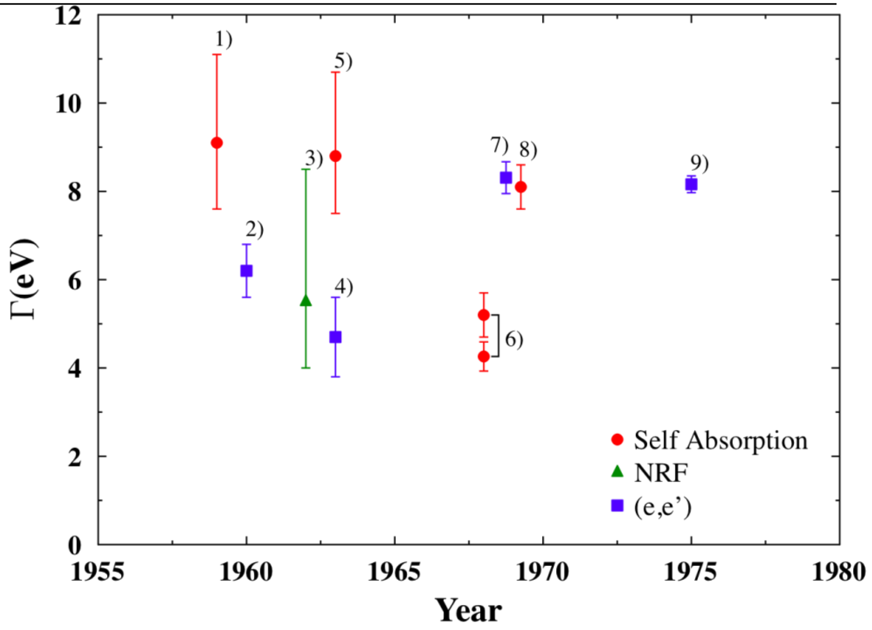
Isospin Excitations of Nucleons and Nuclei



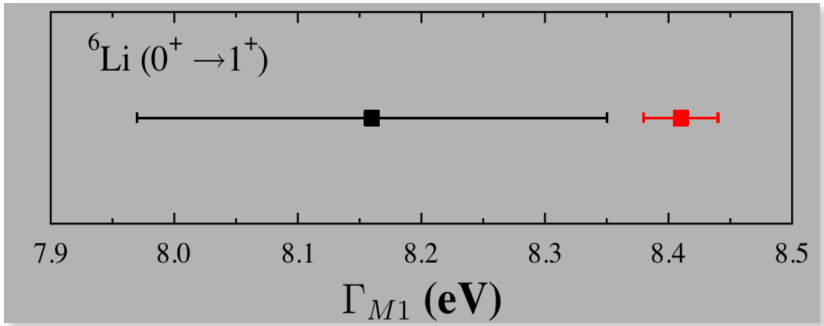
Nuclear Quasideuteron-Configurations: A.F.Lisetskiy et al., Phys. Rev. C **60**, 064310 (1999).

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





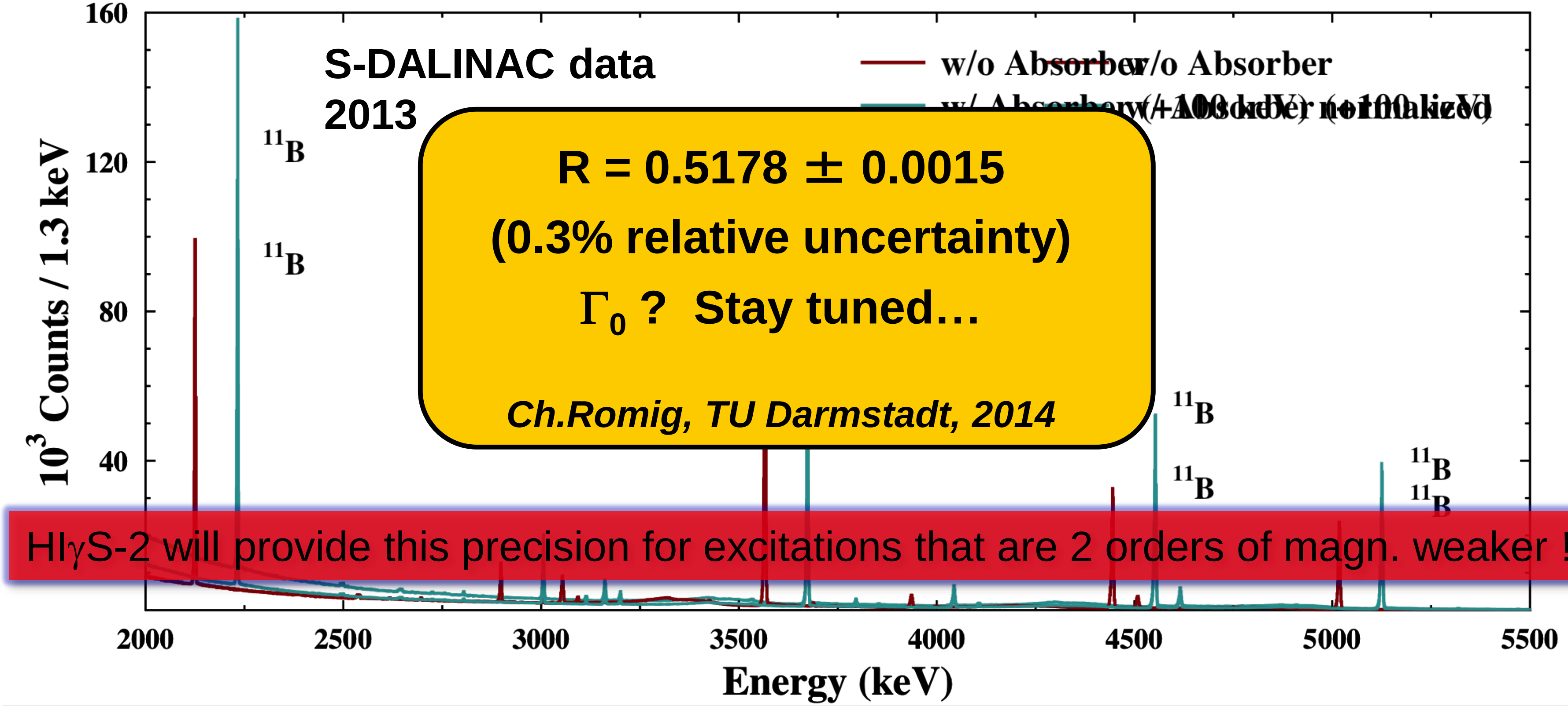
- Exp.: Γ_{M1}=**8.16(19) eV** (from (e,e'))
- S. Pastore *et al.*, PRC **87** (2013): chiral currents contribute significantly to Γ_{M1}
- GFMC with one-body EM current operator at leading order (impulse approximation): **6.90(2) eV**
- GFMC with additional two-body meson-exchange currents up to N^{3}LO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



Self Absorption Measurement on ^{6}Li

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

- ✧ 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 !