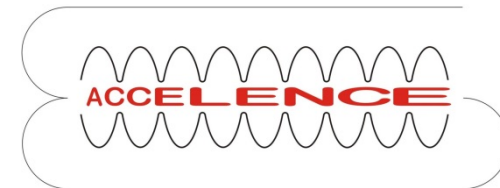


# Photonuclear Reactions: Basic facts, opportunities, and limitations



TECHNISCHE  
UNIVERSITÄT  
DARMSTADT

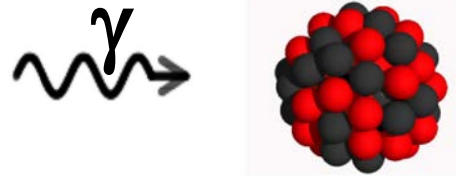
Norbert Pietralla, TU Darmstadt



# Nuclear Photonics:

An attempt of a definition

„***Nuclear Photonics*** is the cross-disciplinary field of Physics and Engineering which addresses **controlled** photonuclear reactions with laser-driven beams, e.g. artificial  $\gamma$ -ray beams, and their applications.“



„controlled“

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

„artificial  $\gamma$ -ray beams“

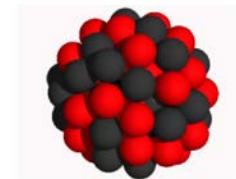
- usage of artificially shaped  $\gamma$ -ray beams w.r.t. spectral intensity profile

„cross-disciplinary“

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

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

- **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**



# Nuclear Physics with MeV-range photon beams

Pure EM-interaction

**(nuclear-) model independent**

**“small“ cross sections, thick targets**

Minimum projectile mass

**min. angular momentum transfer,**

**spin-selective: dipole-modes**

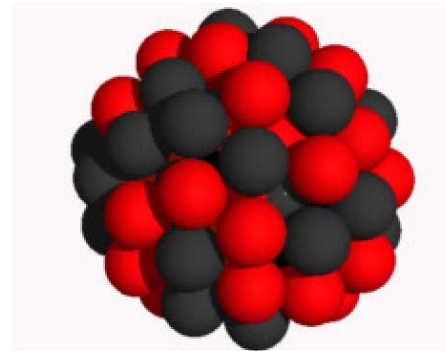
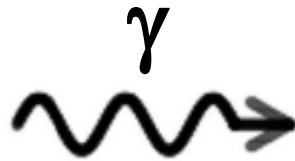
Polarisation

**„Parity Physics“**

Narrow Bandwidth (at HI $\gamma$ S, VEGA@ELI-NP)

**„Selective Manipulation of Nuclear States“**

# Photonuclear Reactions

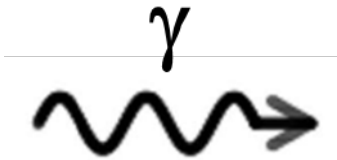


What happens?

# Facts about photons

Energy

$$E_\gamma = h\nu = \frac{2\pi\hbar c}{\lambda}$$



Wave length

$$\lambda = \frac{2\pi\hbar c}{E_\gamma}$$

*100 fm for a 12 MeV photon*

*>> nuclear radius*

# Elastic Direct Scattering: Nuclear Thomson

Klein-Nishina:

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



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

typical Compton cross section:

**40 mb** (per electron)

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

**4 pb** (per nucleus)

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

→ focus here on inelastic/resonant scattering

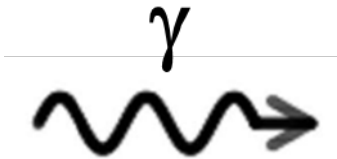
# Facts about photons

**Intensity density**

$$|\vec{S}| = \sqrt{\frac{\epsilon_0}{\mu_0}} |\vec{E}|^2$$

= energy / (area x time)

i.e. depends on coherence length



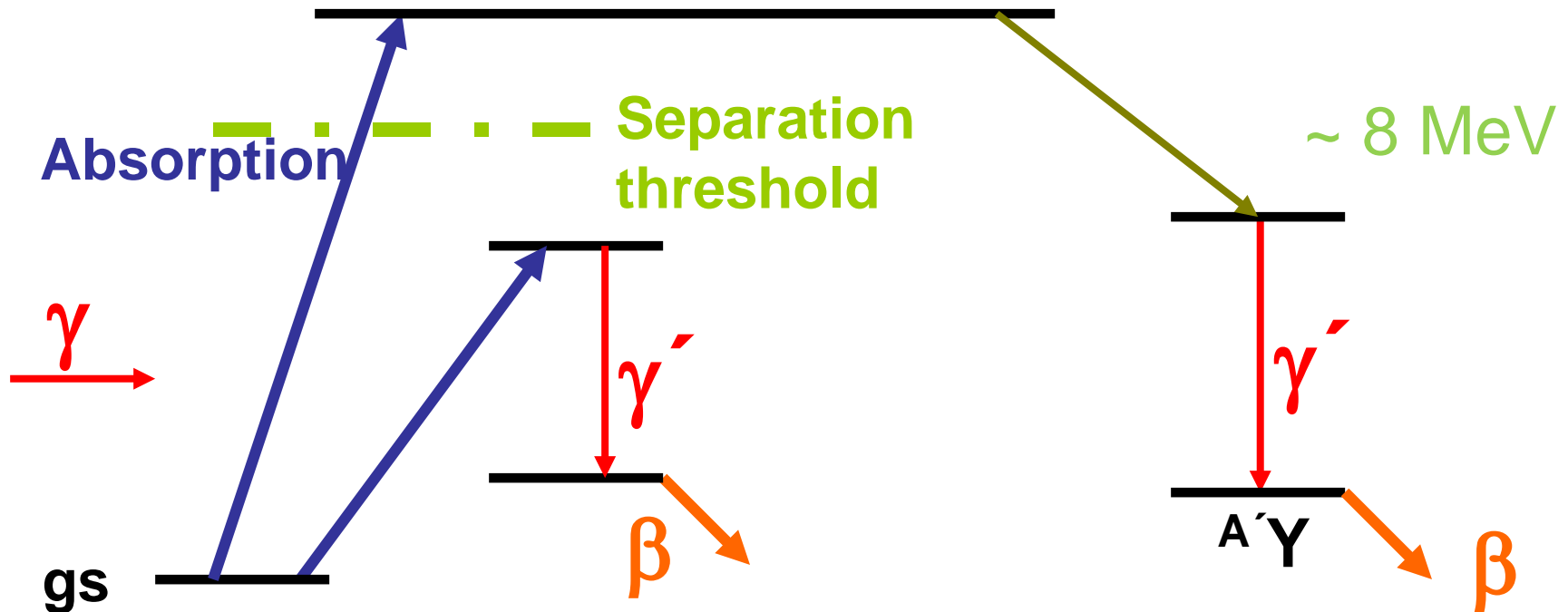
**Electric field** (depends on coherence length)

good estimate:  $E_0 = 10^{15}$  V/m

→ instantaneous force on p:  $F \approx 1$  eV/fm

→ resonance reactions

# Photonuclear Reactions



**Nuclear Resonance Fluorescence (NRF)**  
**Photoactivation**  
**Photodesintegration (-activation)**  
**Photofission**

## 1937: **Atomumwandlungen durch $\gamma$ -Strahlen.**

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

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

### *6. Diskussion.*

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

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

## 1938: Nuclear Photo-effects

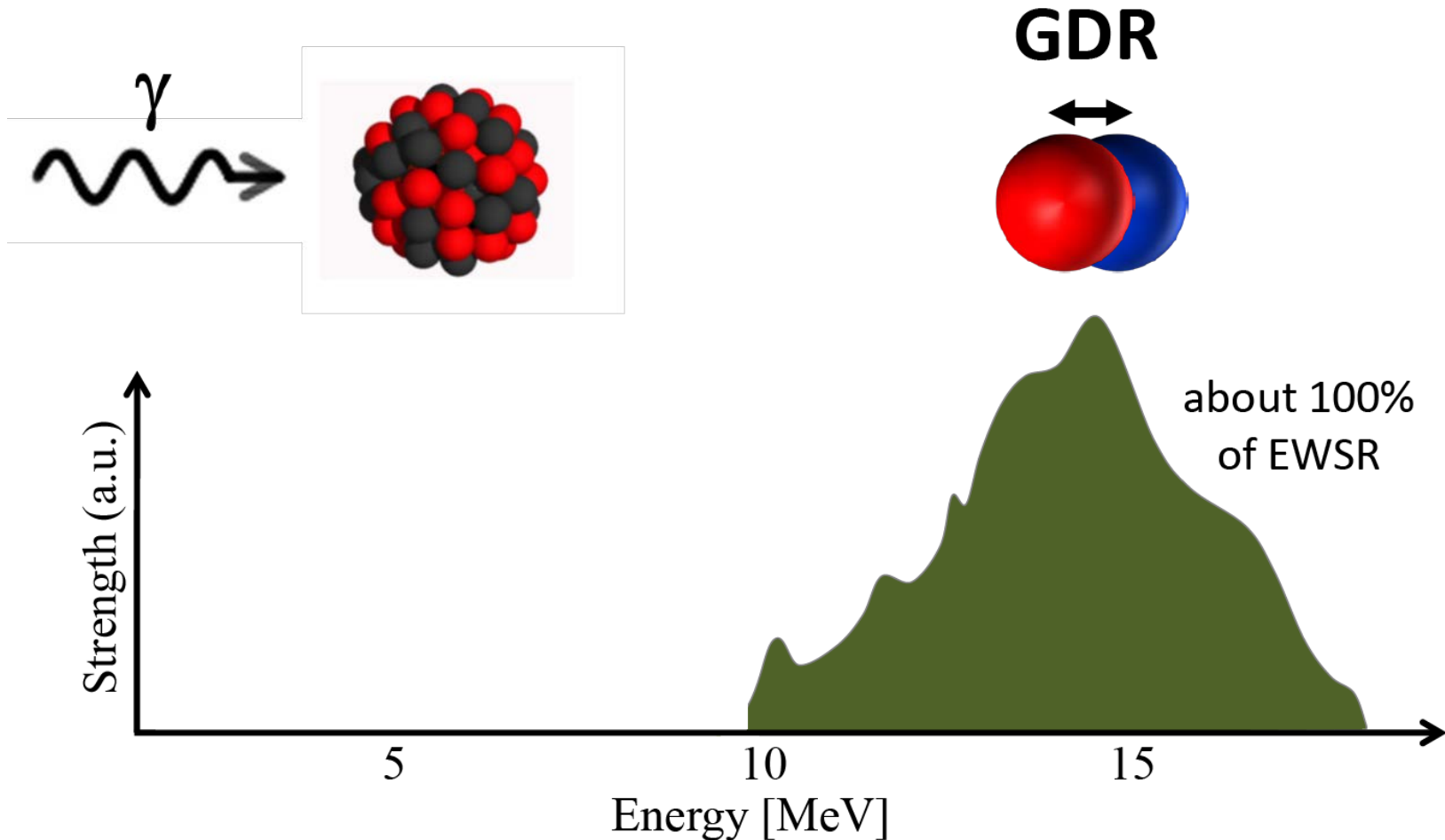
**THE** beautiful experiments of Bothe and Gentner<sup>1</sup> on the ejection of neutrons from heavier nuclei by means of  $\gamma$ -rays with energy of about 17 M.v. resulting from impact of protons on lithium, have revealed a remarkable selectivity of these nuclear photo-effects. ...

**N. BOHR.**

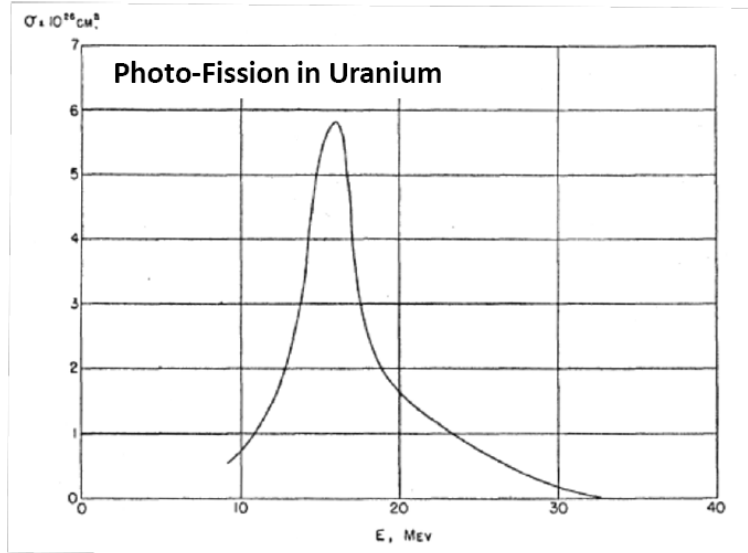
Universitetets Institut  
for Teoretisk Fysik,  
Copenhagen, ø  
Jan. 31.

*nature* **141** (1938) 326

# Dominant Mode of Photo-Response



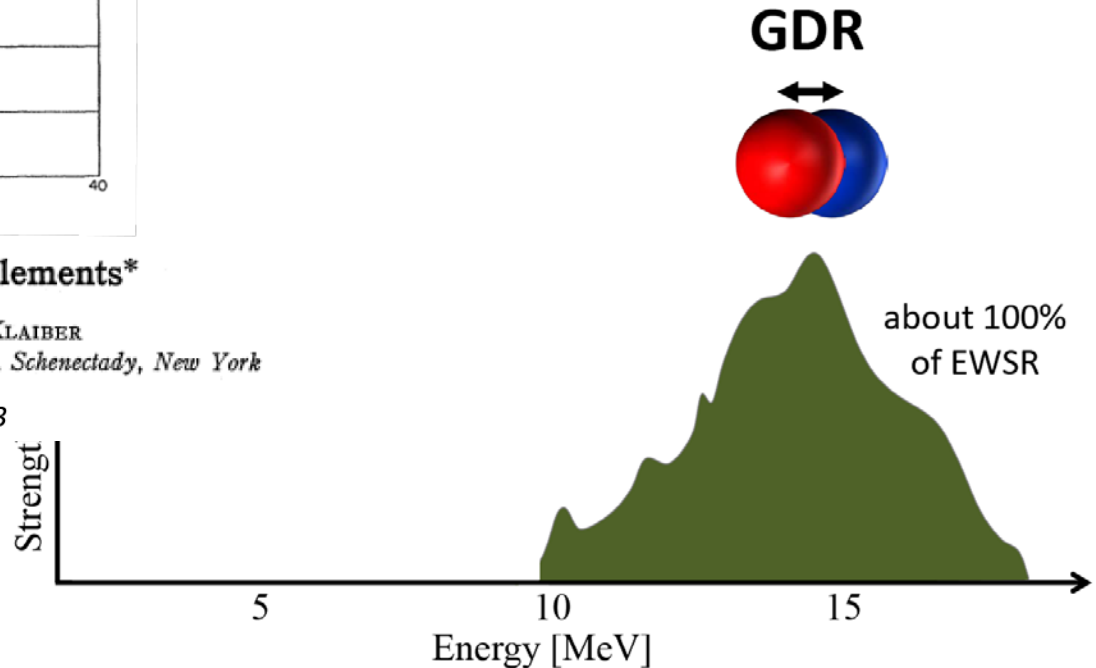
# Dominant Mode of Photo-Response



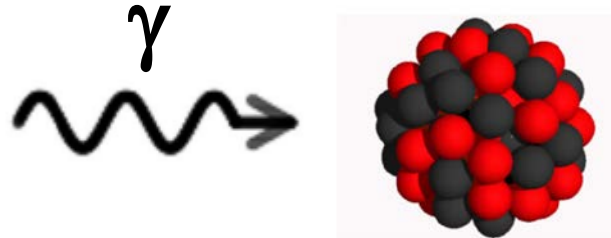
## Photo-Fission in Heavy Elements\*

G. C. BALDWIN AND G. S. KLAIBER  
*Research Laboratory, General Electric Company, Schenectady, New York*

*Phys. Rev. 71 (1947) 3*

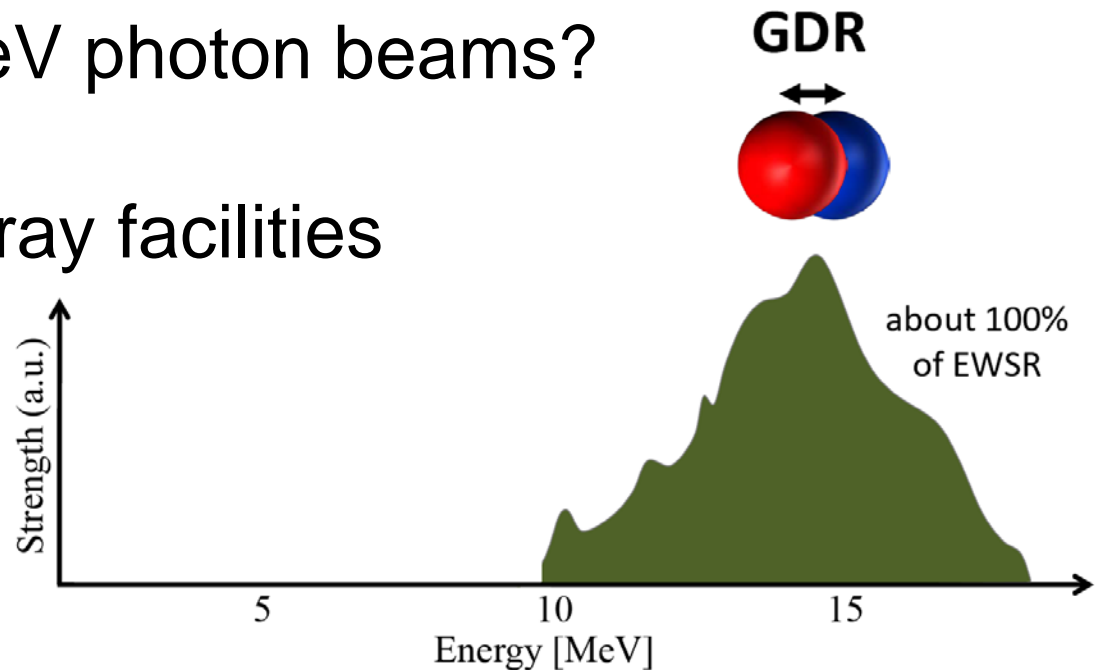


# Dominant Mode of Photo-Response



How to produce MeV photon beams?

Overview: gamma-ray facilities



# Gamma-ray beam production

## Nuclear reactions

- E.g.,  $(p,\gamma)$ ,  $(n,\gamma)$ ,... [ Bothe/Gentner 1937: 17 MeV from  ${}^7\text{Li}(p,\gamma){}^8\text{Be}$  ]
- Uncontrollable energy / spectral shape

## Positron-annihilation in flight

- Tunable energy, low intensity

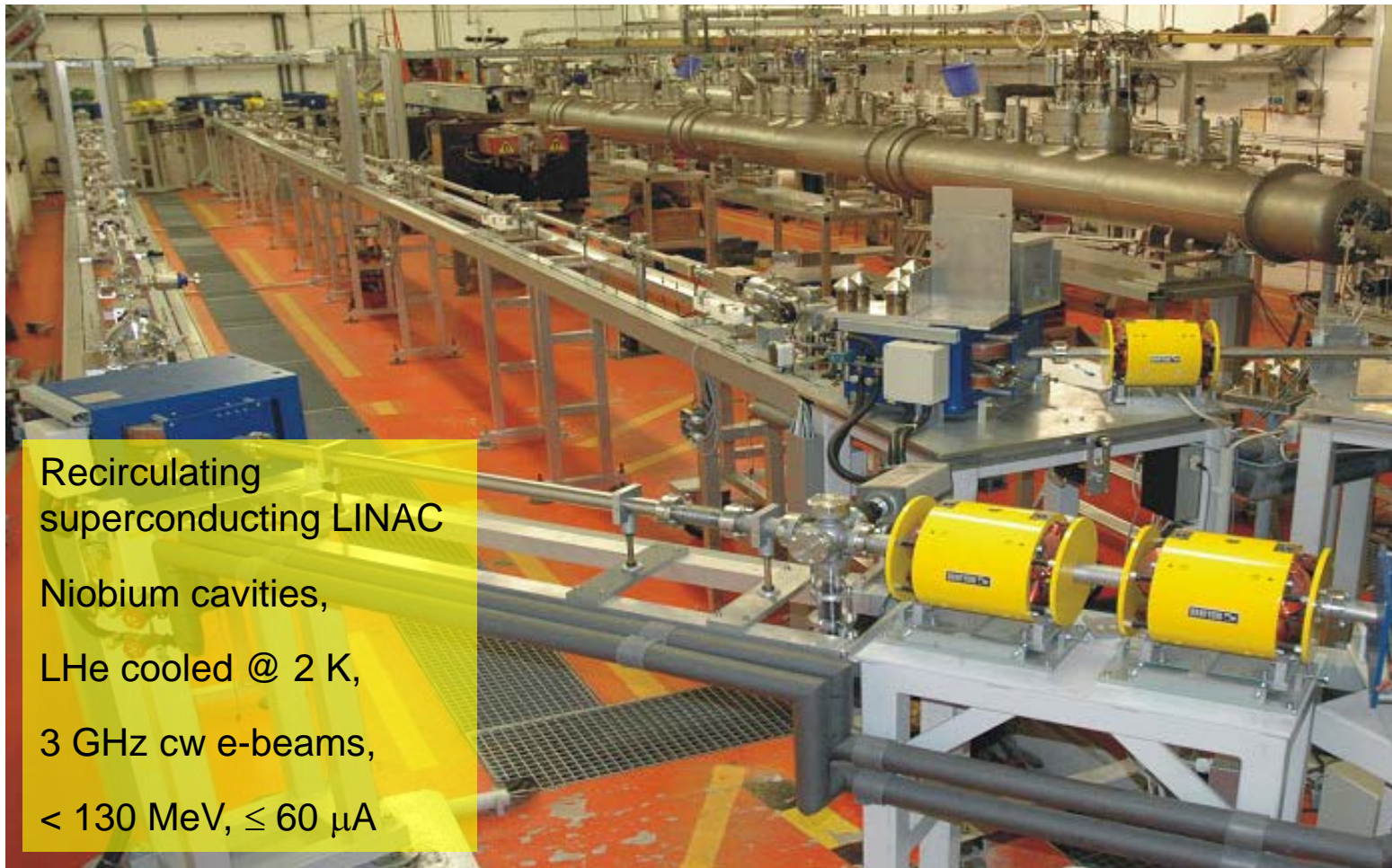
## Electron bremsstrahlung [ today: S-DALINAC, ELBE, ... ]

- High intensity, tunable energy, „white“ spectrum, no/modest polarization

## LASER-Compton backscattering [ HI $\gamma$ S @ TUNL, SPRING8, VEGA@ELI-NP ]

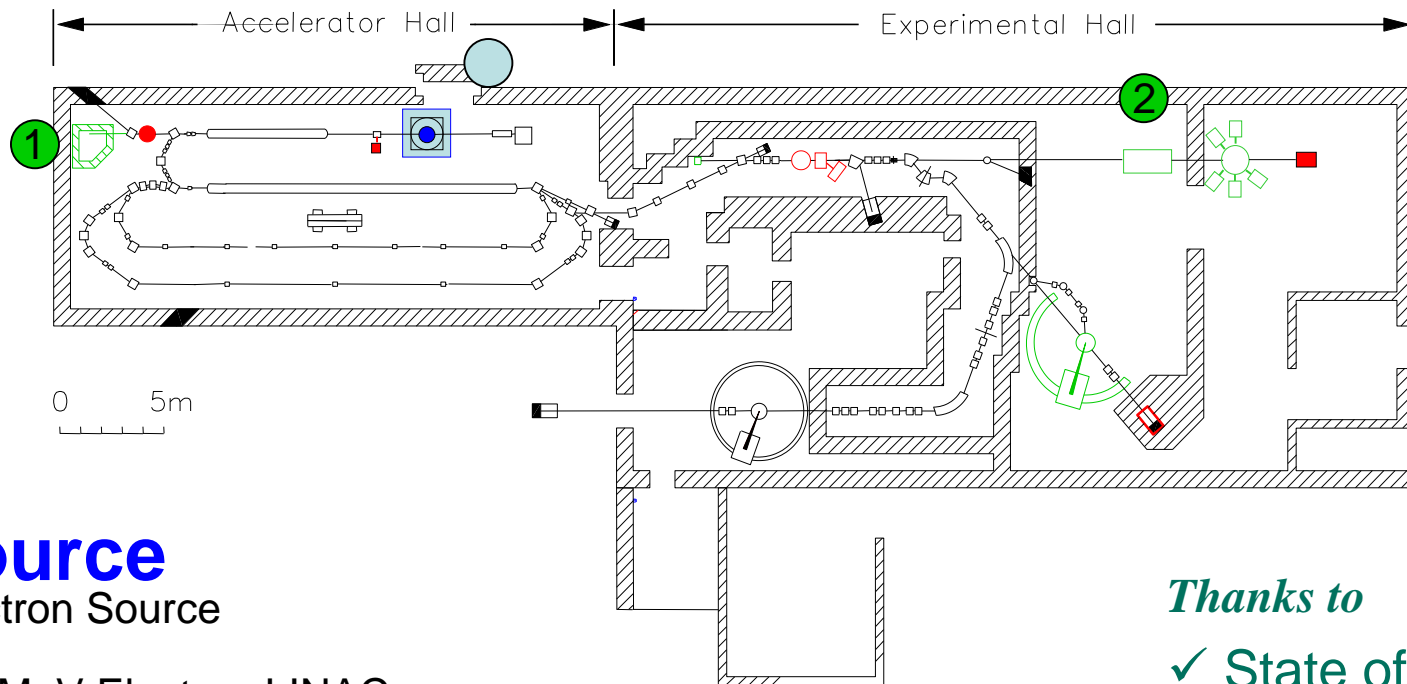
- High peak intensity, tunable energy, narrow band width, polarized

# S-DALINAC at TU Darmstadt



Recirculating  
superconducting LINAC  
Niobium cavities,  
LHe cooled @ 2 K,  
3 GHz cw e-beams,  
< 130 MeV,  $\leq 60 \mu\text{A}$

# S-DALINAC at TU Darmstadt



## Source

● Electron Source

● 130 MeV Electron LINAC

## Photon Experiments

① 10 MeV Injector: Photon Scattering / Photofission

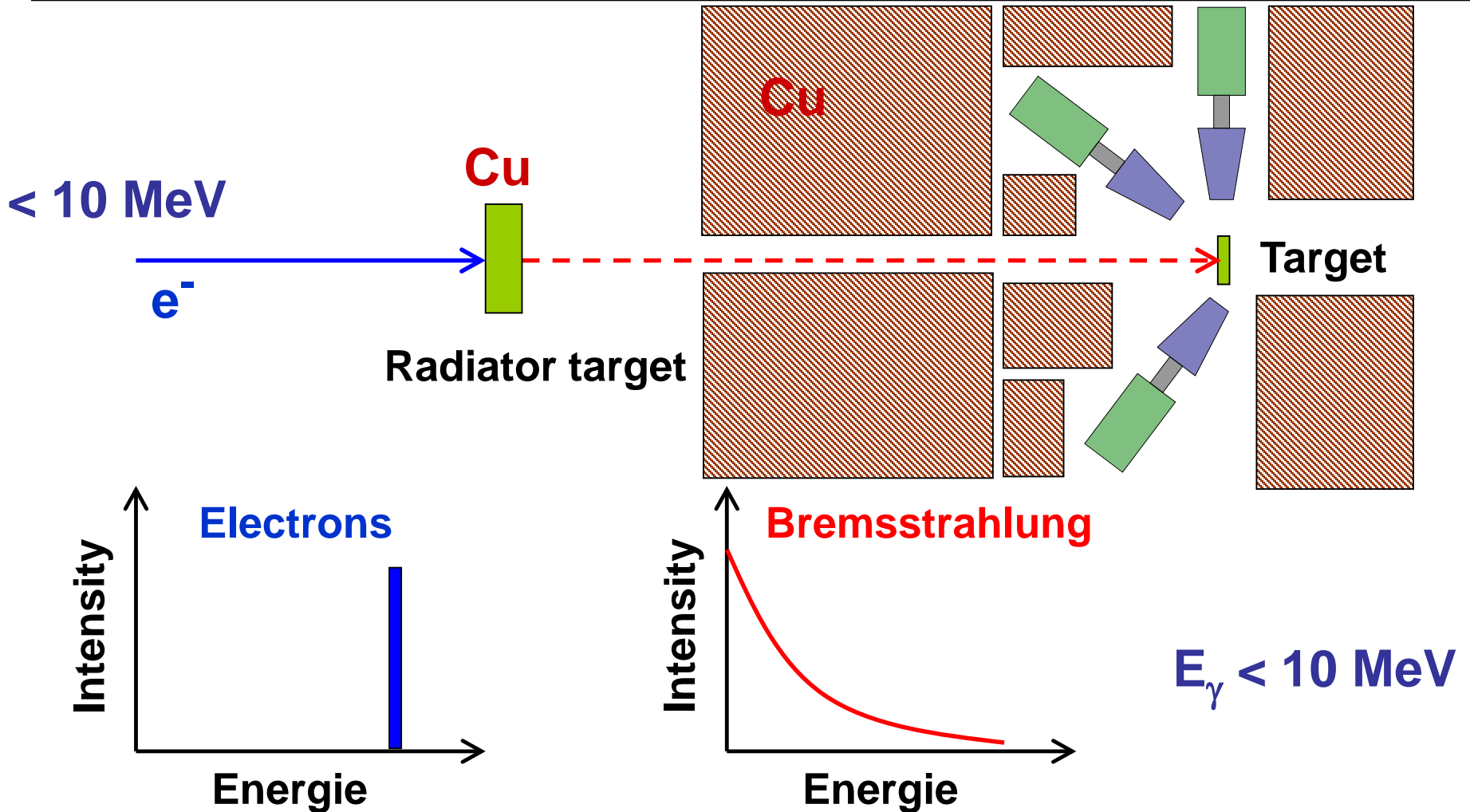
② < 30 MeV Tagger: Photodesintegration / Photon Scattering

*Thanks to*

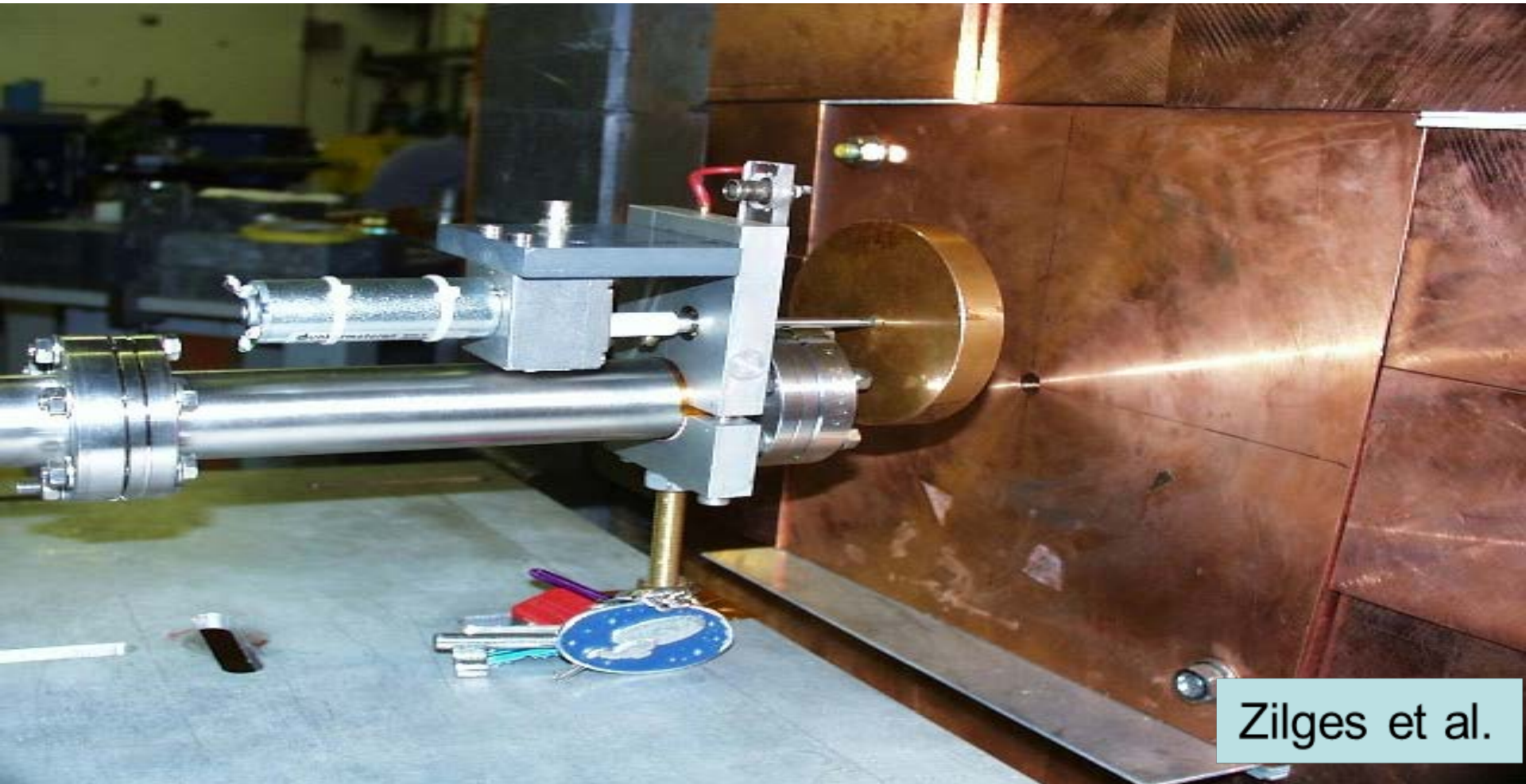
- ✓ State of Hesse
- ✓ TU Darmstadt
- ✓ DFG

# Darmstadt Low-Energy Photon Scattering Site at S-DALINAC

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



# Bremsstrahlung-Site

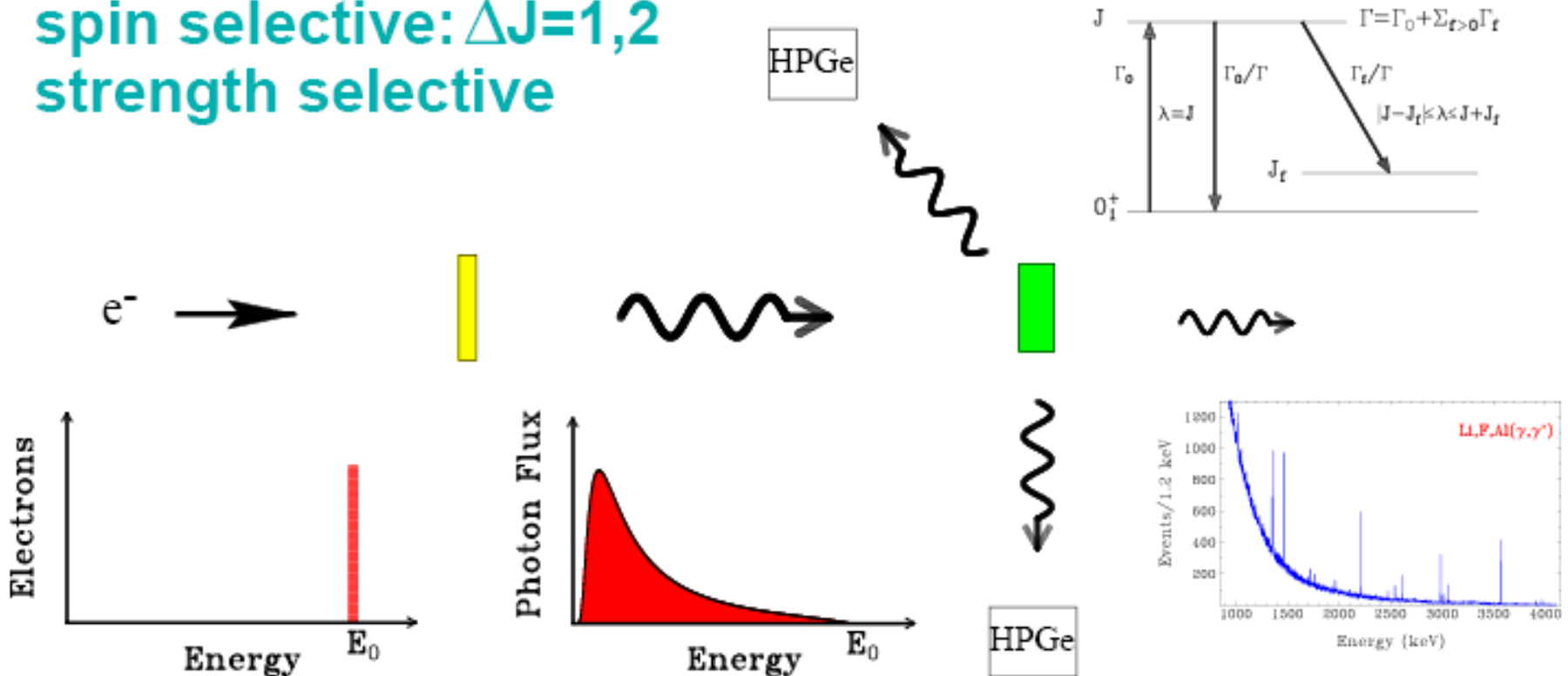


Zilges et al.

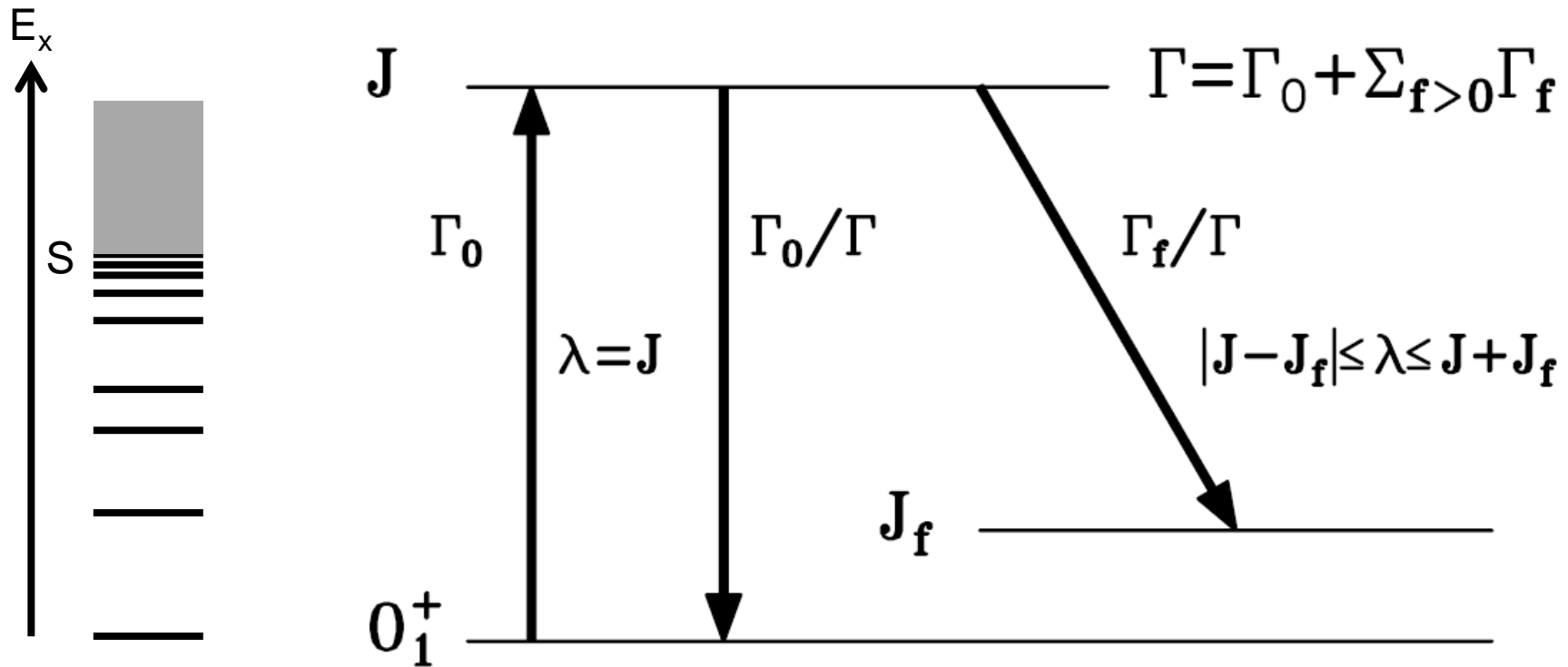
# Photon Scattering (Nuclear Resonance Fluorescence)

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

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



# Nuclear Resonance Fluorescence (NRF)



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

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

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

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

$$\rightarrow \quad \sigma_0 \cong \mathbf{200 \text{ b}} \quad (\text{for } \Gamma_0 = \Gamma, \quad E = 5 \text{ MeV})$$

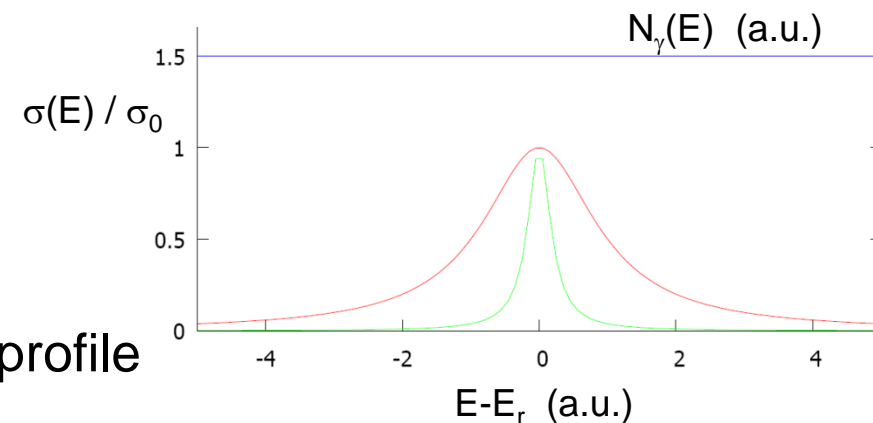
- Irrespective of multipolarity !
- However, resonances are very narrow ( $\Gamma_0$ )

# NRF cross section

- Photonuclear excitation widths  $\Gamma_0$  depend on nuclear wave functions

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

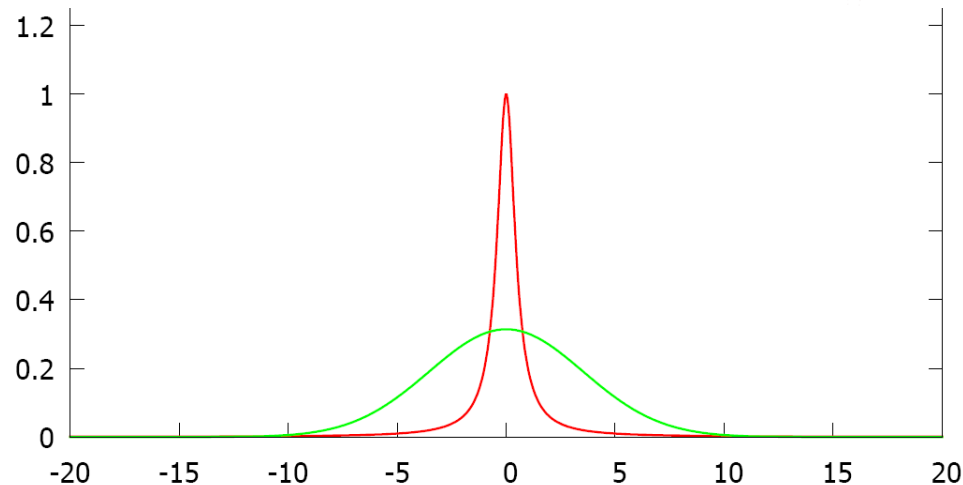
- with typical widths  $\Gamma_0$  for photonuclear excitations (use Weisskopf estimate for  $A=50$  and use  $E=5$  MeV)
  - E1 (use 1 mW.u.): 0.1 eV
  - M1: 2.6 eV
  - E2: 30 meV
  - M2: 0.6 meV
  - E3: 4  $\mu$ eV
- much more narrow than photon beam profile
- $\rightarrow$  Integrated cross section



# NRF cross section

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

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

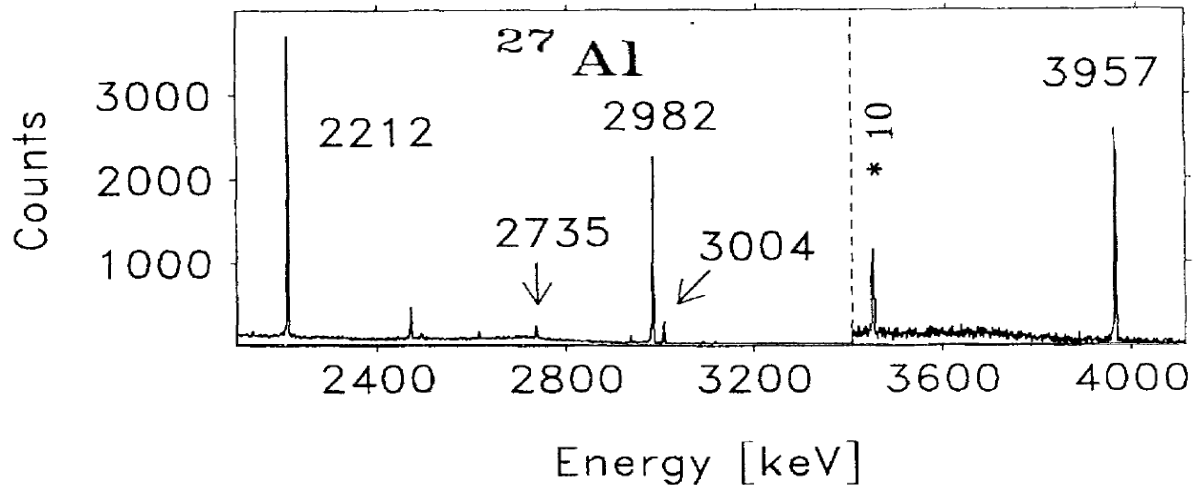
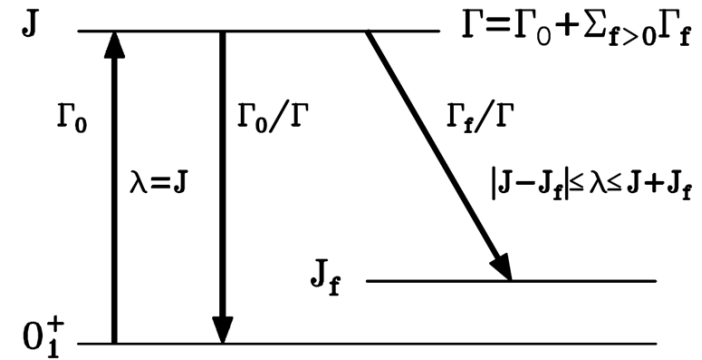


Energy-integrated absorption cross section:  $I_a = \int \tilde{\sigma}_a^D(E) dE = \frac{\pi}{2} \sigma_0 \Gamma \sim \Gamma_0$

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

# 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

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

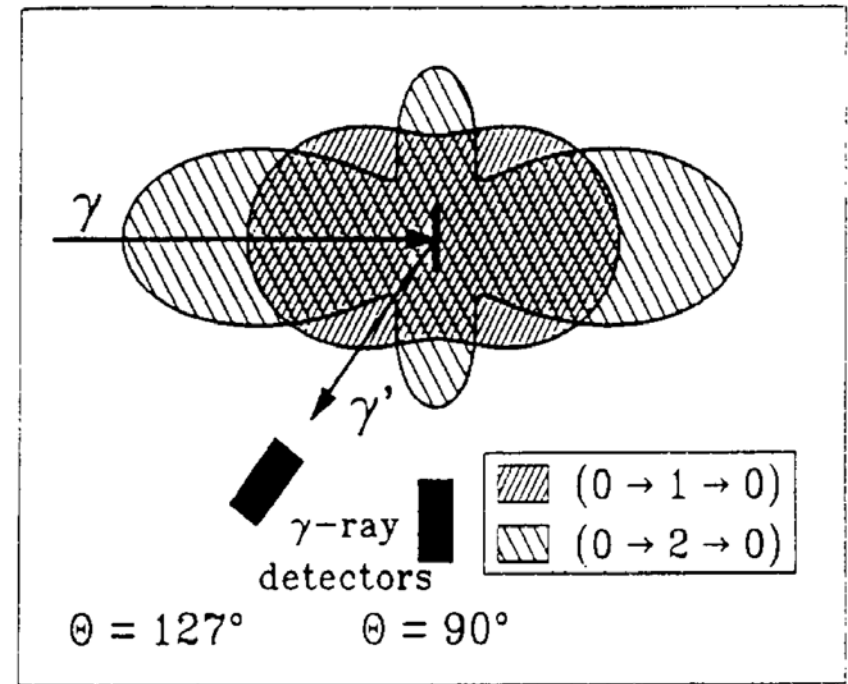
Photon helicity 1,  $m = \pm 1$

→ non-isotropically alignment of photo-excited state (even oriented for circularly polarized beam)

Pronounced angular correlations when involving spin-0 states

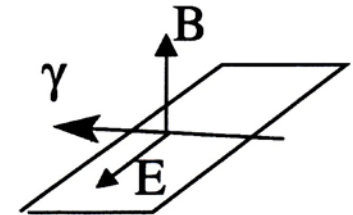
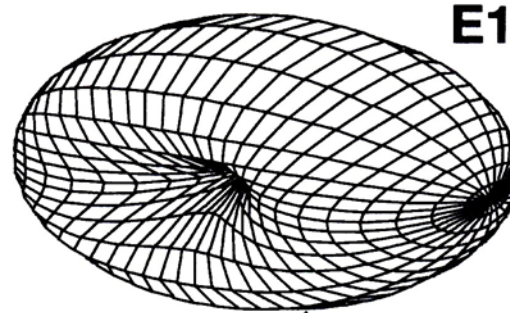
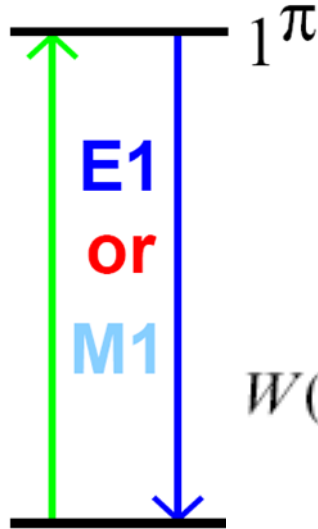
Angular distribution functions  $W(\vartheta)$  from angular correlation theory

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



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

# Parity quantum number $\pi$ for $J=1$ states



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

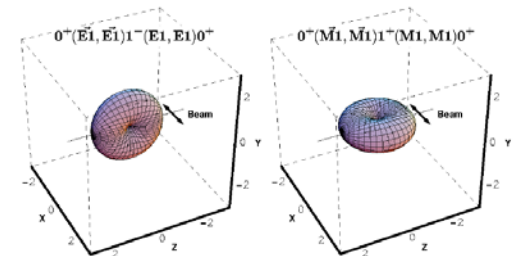
N.Pietralla, H.R. Weller et al.,  
NIM A 483 (2002) 556.

Elastic scattering distribution not isotropic about incident polarization plane.

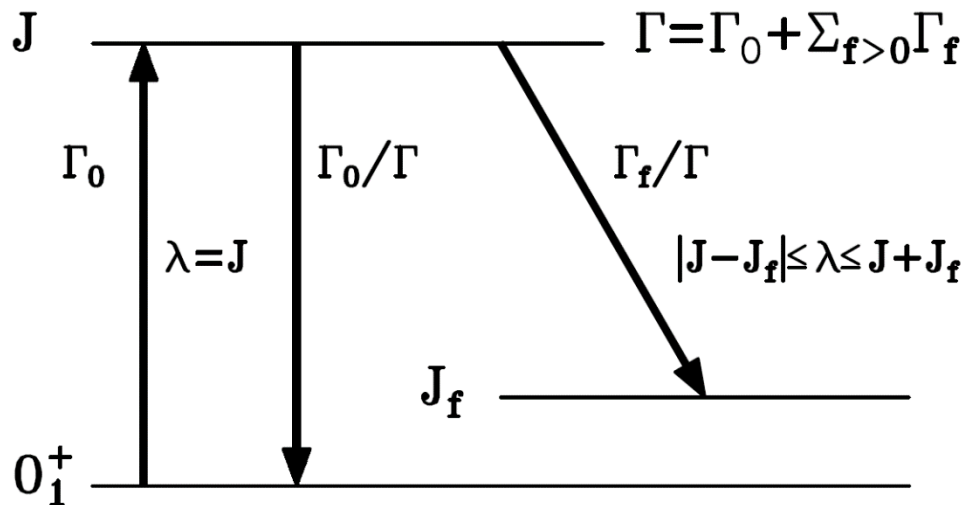
No intensity along oscillating dipole vector

Azimuthal rotation by  $90^\circ$  for M1 and E1 distributions

Observable only for linearly polarized beam



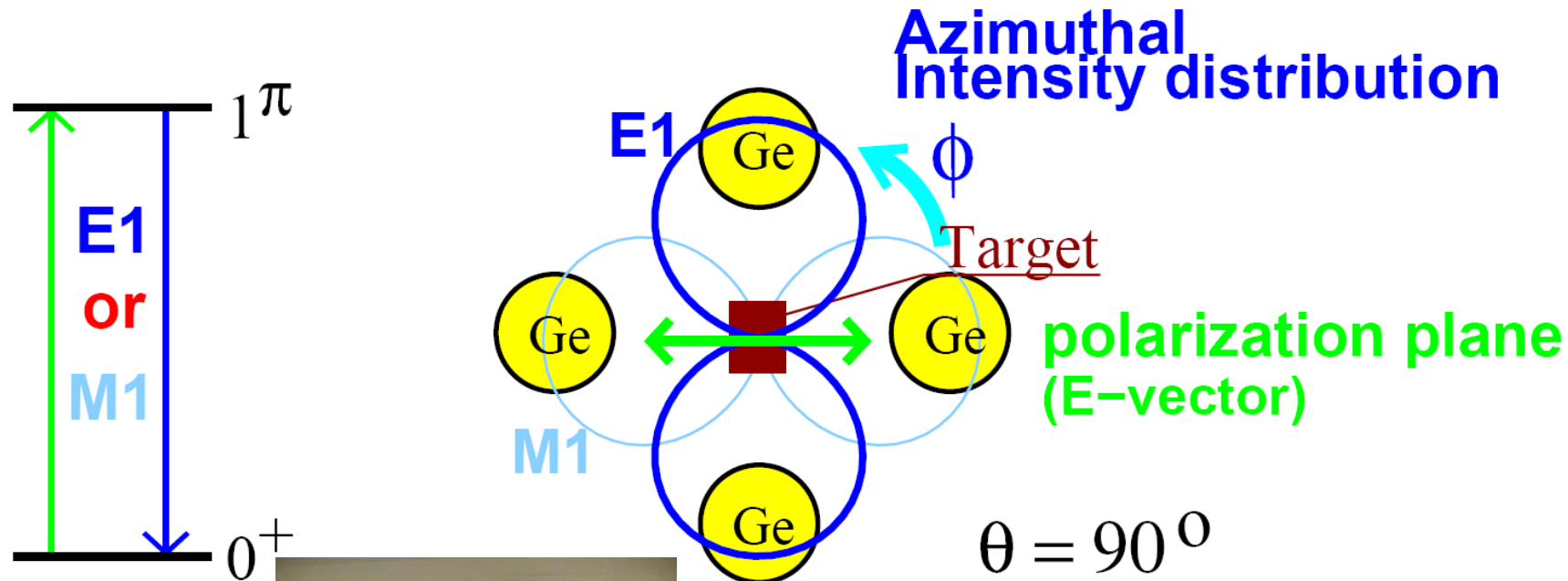
## — . — . — Separation threshold



## Observables

- Excitation Energy  $E_r$
- Spin  $J$
- Parity  $\pi$
- Decay Energies  $E_\gamma$
- Partial Widths  $\Gamma_i/\Gamma_0$
- Multipole Mixing  $\delta$
- Decay Strengths  $B(\pi\lambda)$
- Level Width  $\Gamma$  (eV)
- Lifetime  $\tau$  (ps – as)

# Linearly-polarized photon beam: Parity measurement by azimuthal distribution



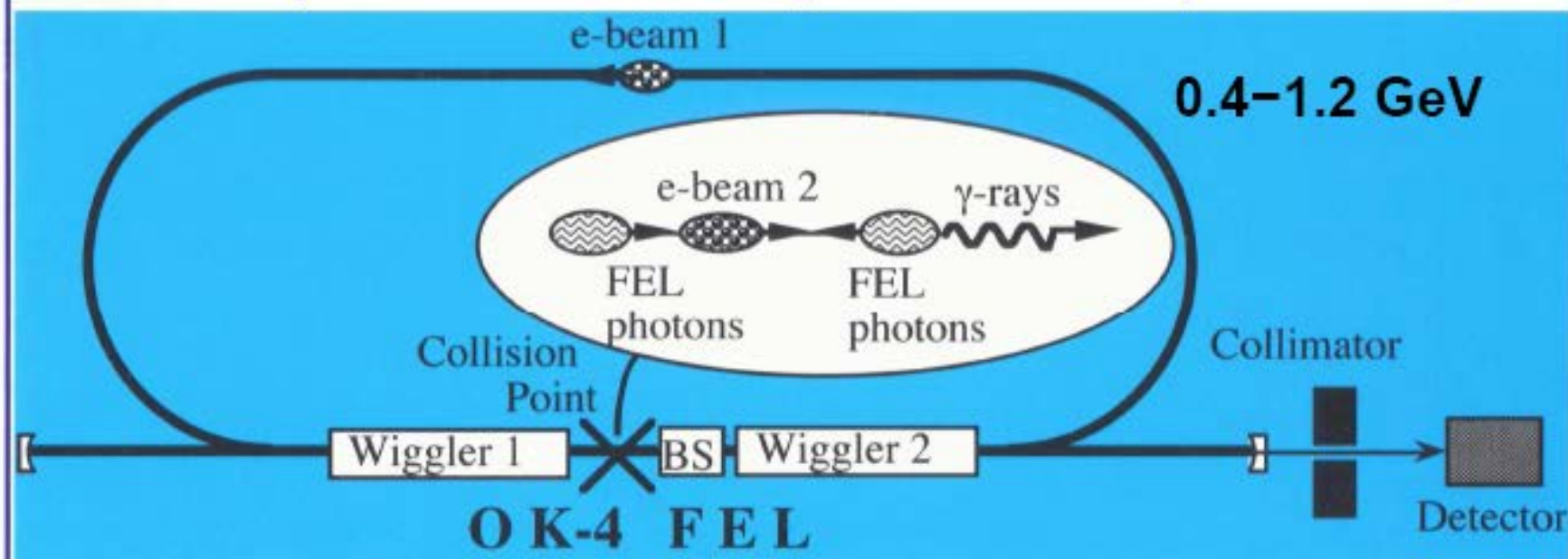
How to produce a linearly-polarized  $\gamma$ -ray beam?

# High Intensity $\gamma$ -Ray Source (HlgS)



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

## Compton Backscattering of Intra-cavity Laser Light



**2 - 60 MeV**

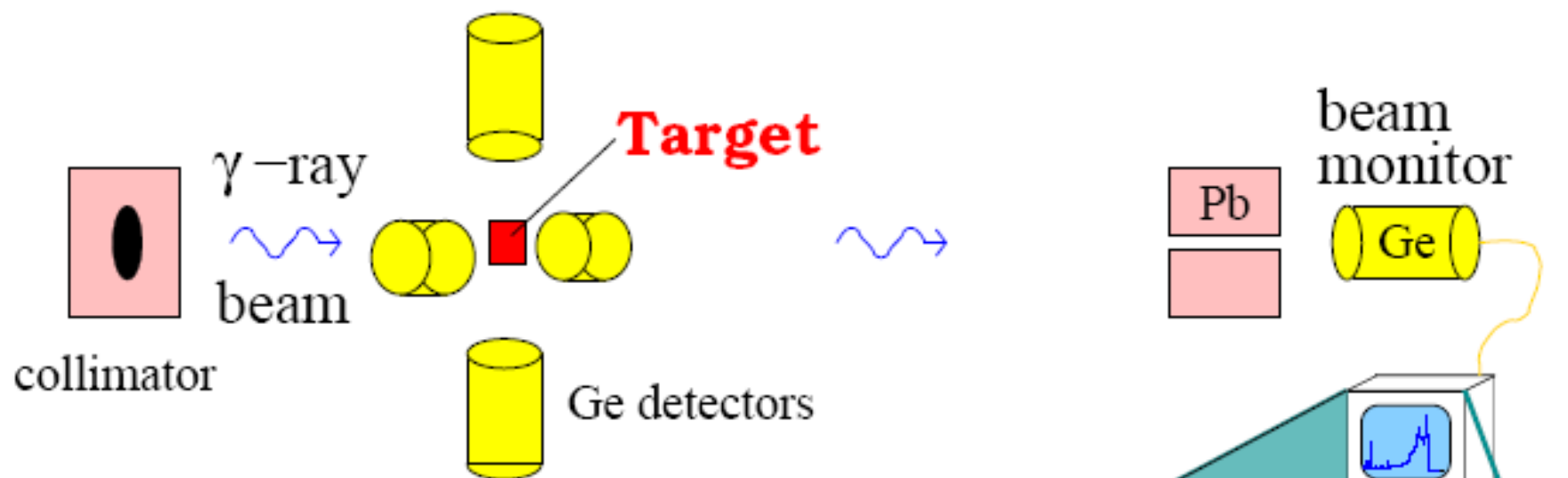
**1.7 - 6.4 eV**

**~ 1000**

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

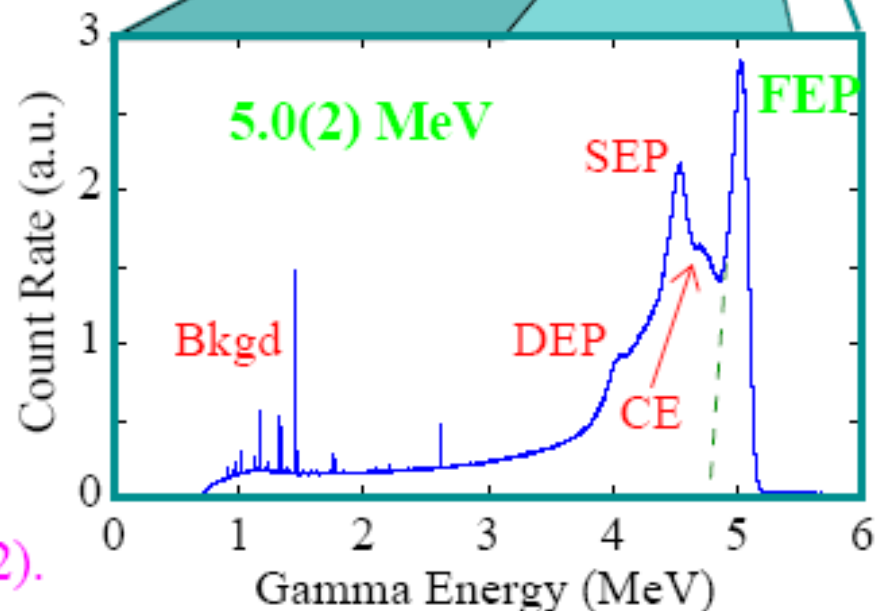
**nearly monochromatic, tunable, completely polarized**

# Looking at the HIGS Gamma-Ray Beam

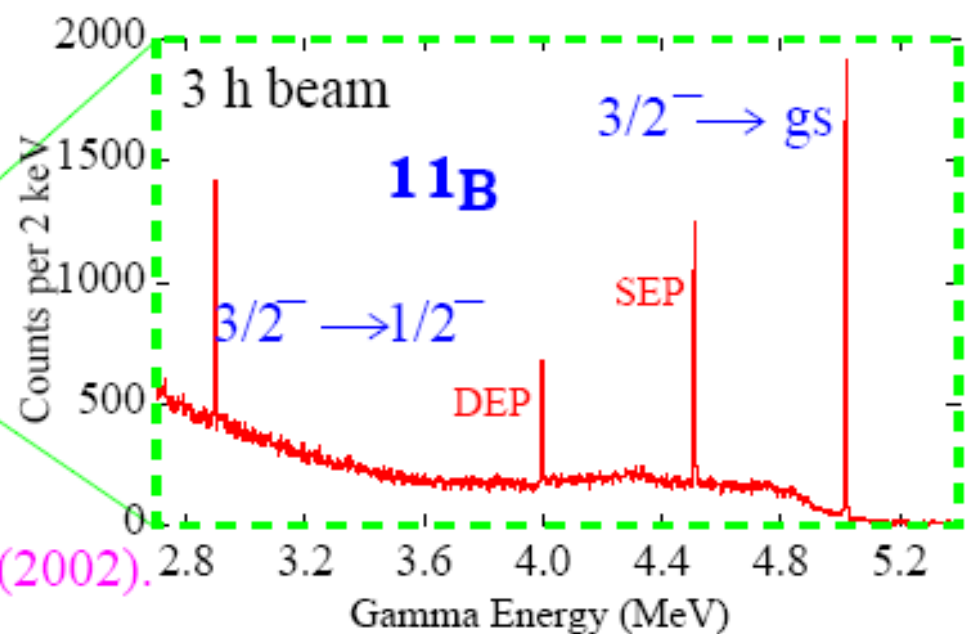
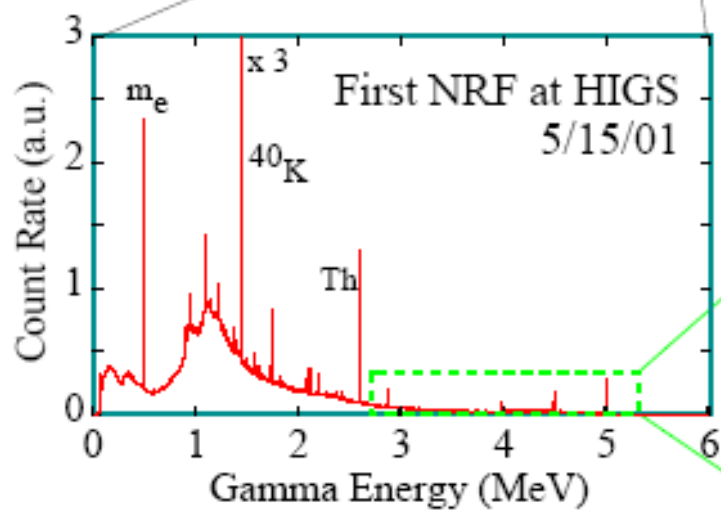
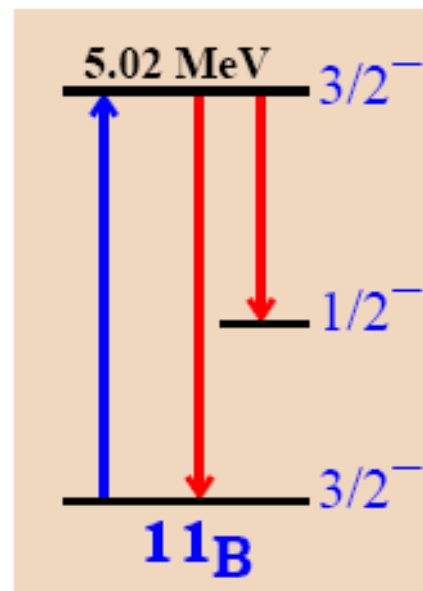
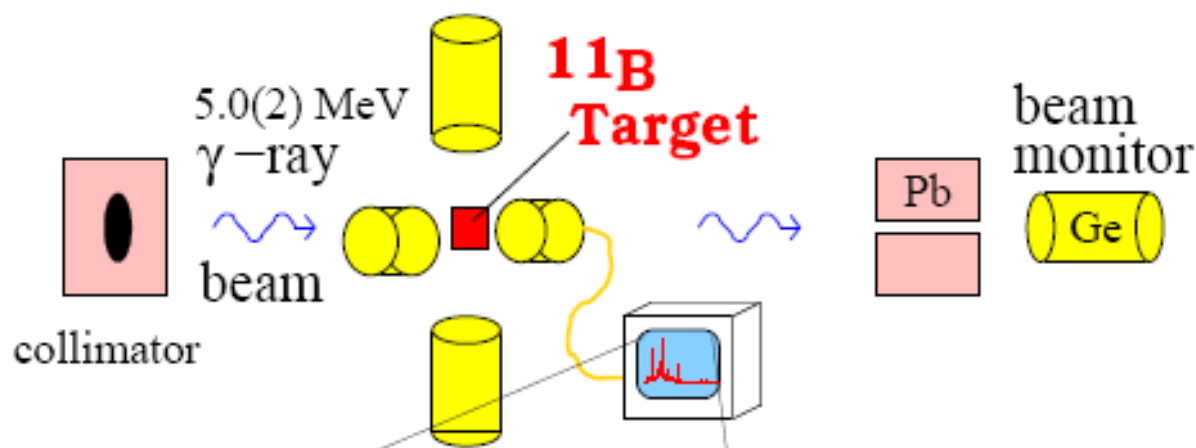


Flux at target:  $10^7/s$   
at maximum:  $10^5/(s \text{ keV})$   
Resolution: 3%  
(with 1" collimator)

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

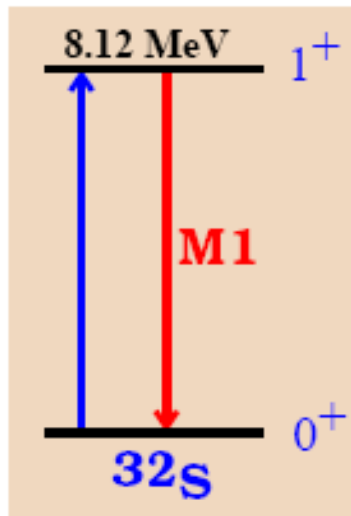
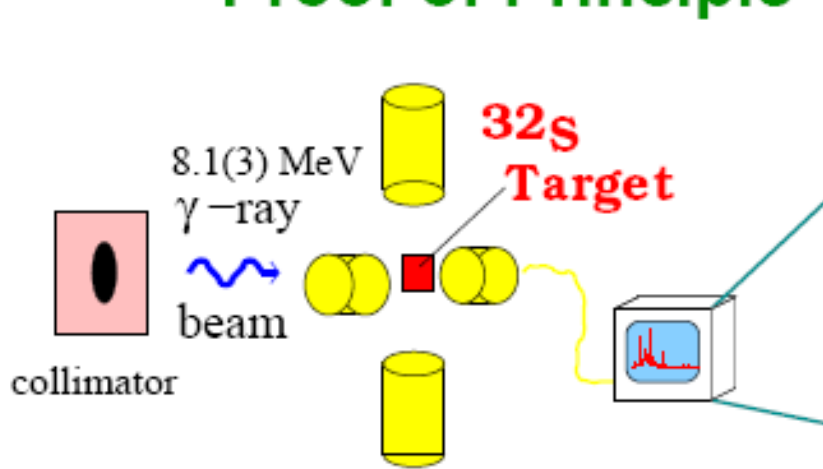


# Looking at the Target

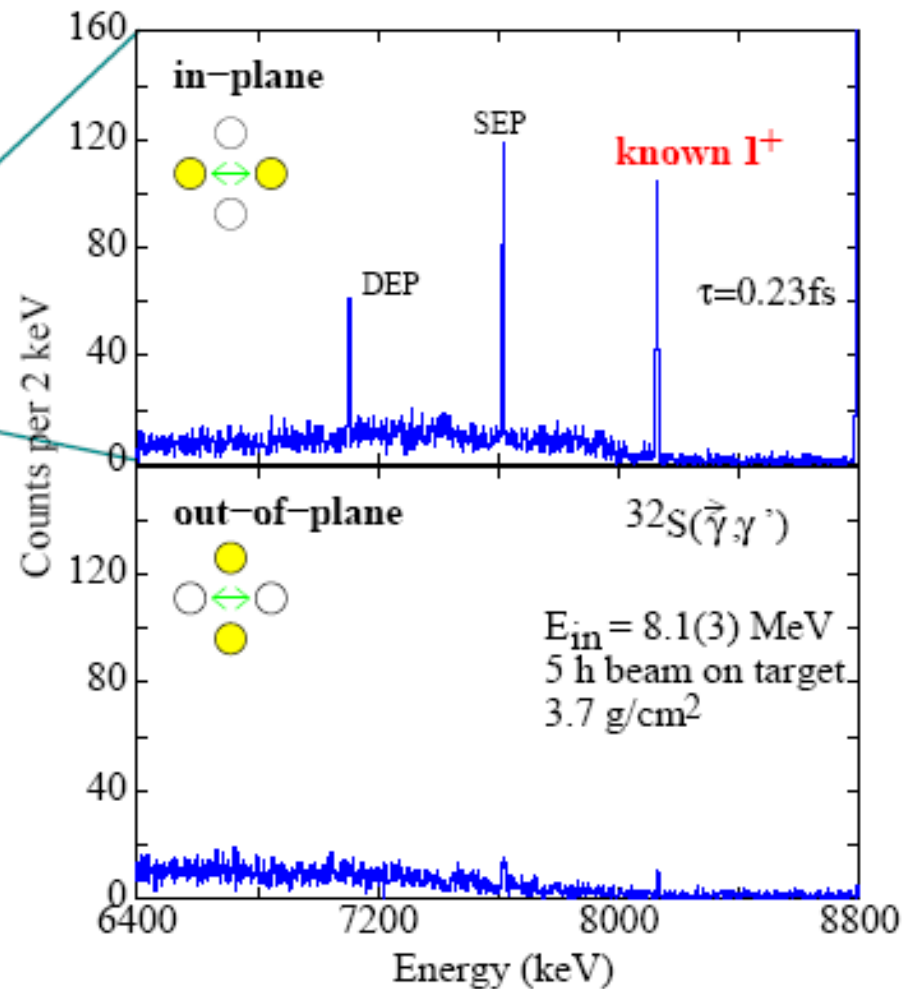


N. Pietralla et al.  
Nucl. Instrum. Methods A483, 556 (2002).

# Proof of Principle

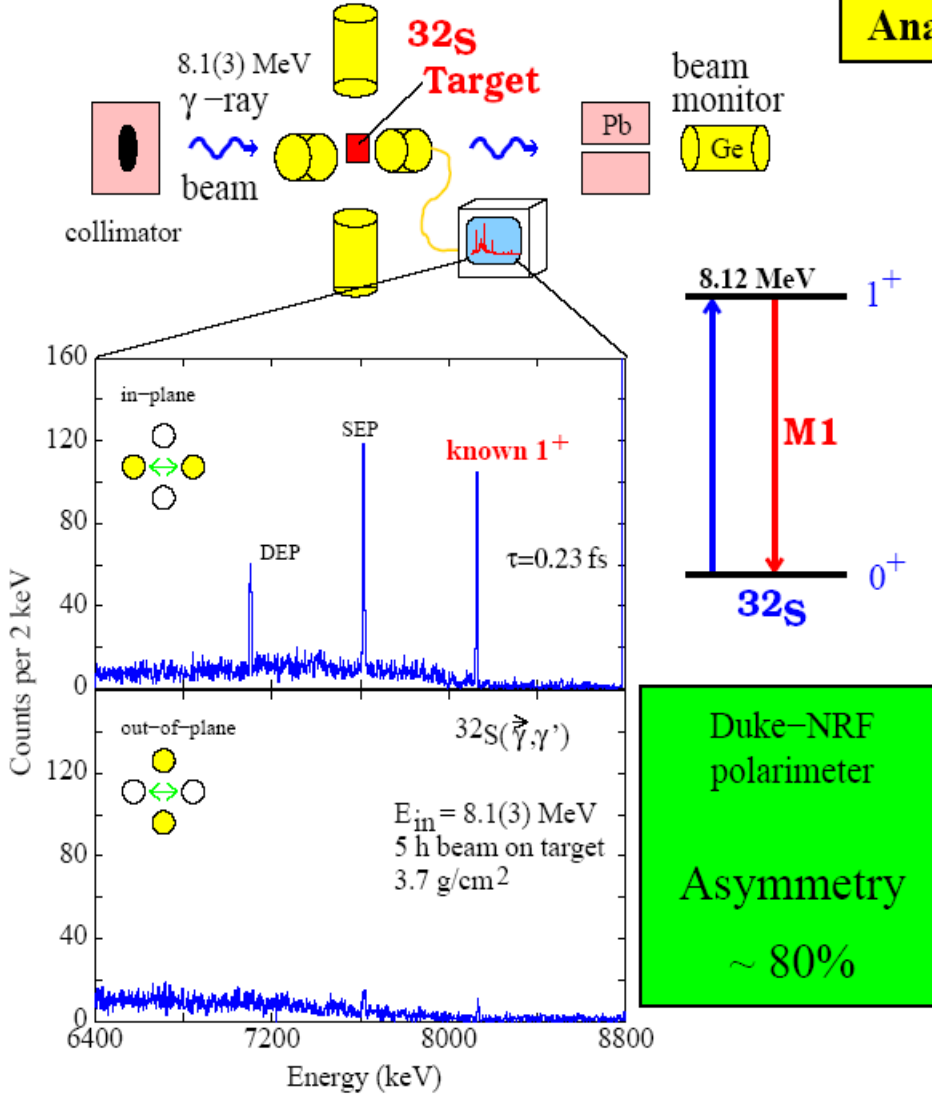


DFELL/TUNL  
polarimeter  
**Asymmetry**  
 $\sim 80\%$



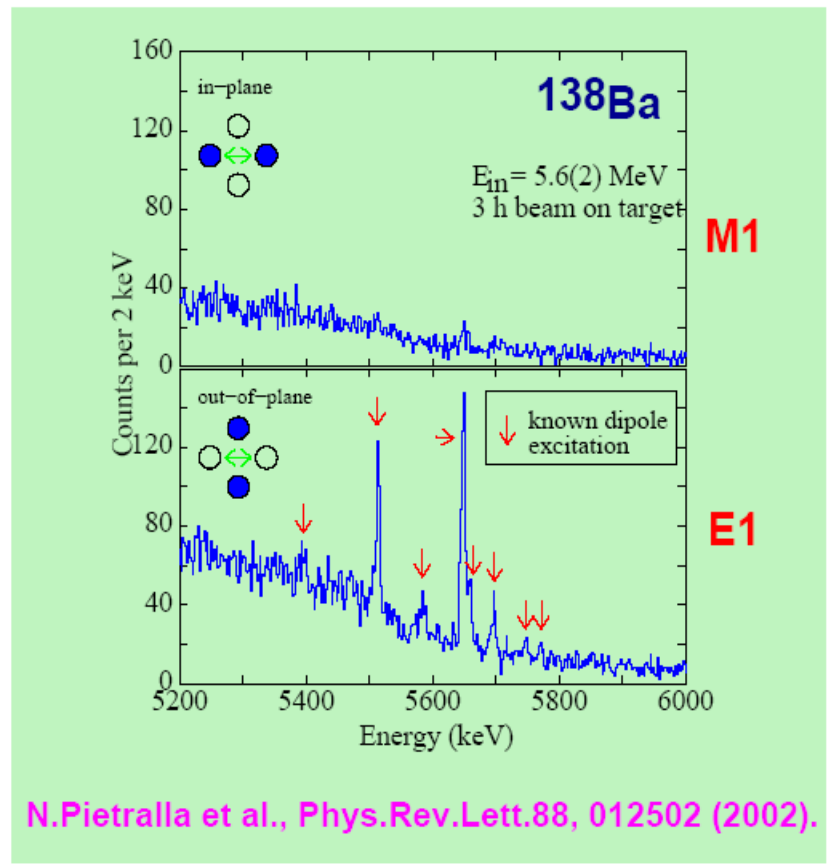
N.Pietralla et al., Nucl.Instrum.Methods A483, 556 (2002).

## Analyzing Power for the Pygmy Resonance



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

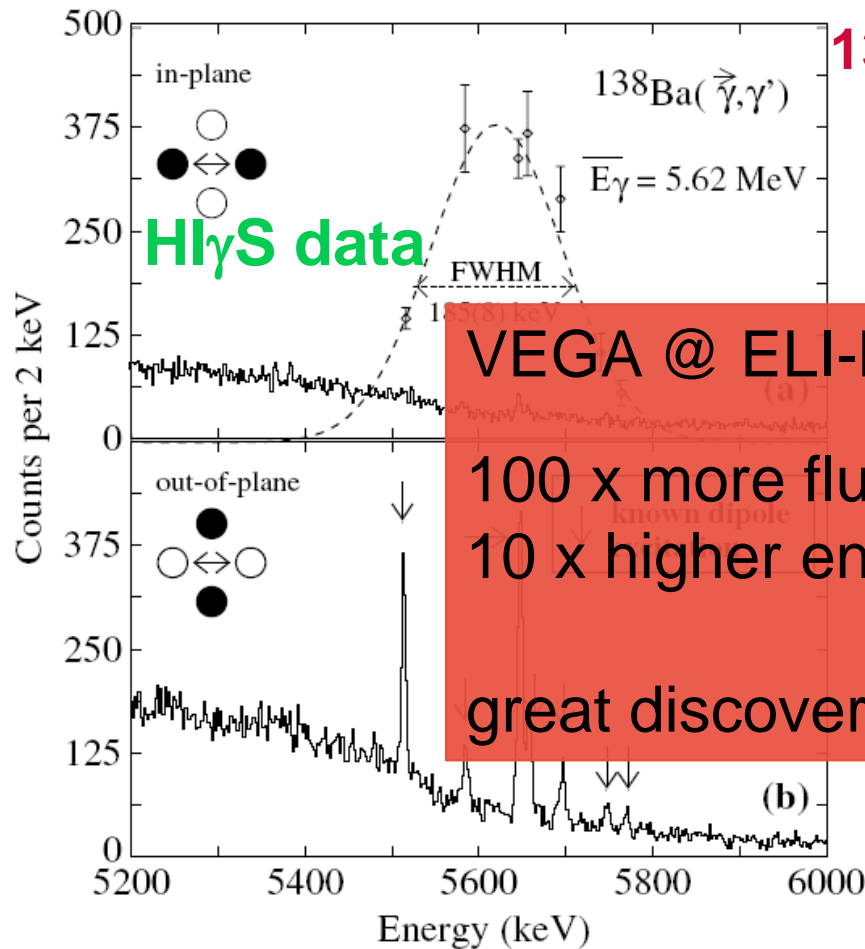
"pygmy resonance": all E1 !



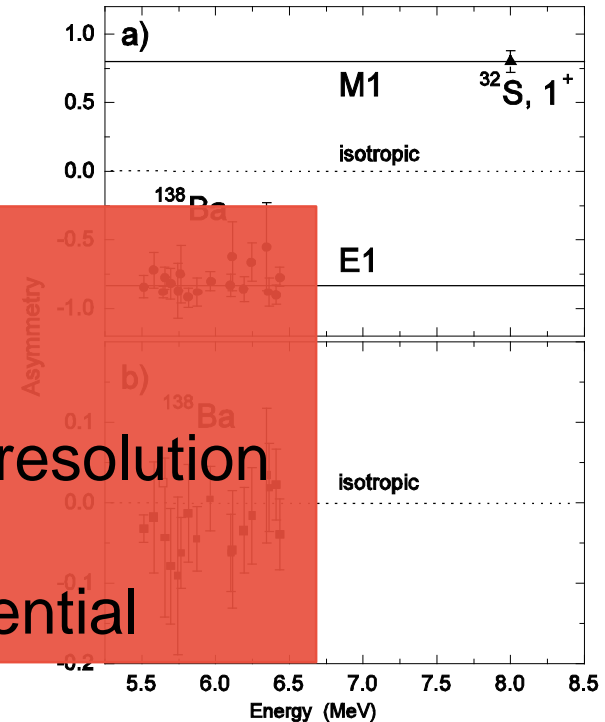
N.Pietralla et al., Phys.Rev.Lett.88, 012502 (2002).

established international community (not only NRF!)

# H $\gamma$ S Beam Profile; Parity of Pygmy Resonance



**$^{138}\text{Ba}$**  Polarized photon beam: H $\gamma$ S 2001



Compton-polarimeter

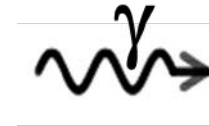
EUROBALL Cluster 1999

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

# 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



# Limitations

## w.r.t. atomic quantum optics

- available  $\gamma$ -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  $\gamma$ -bunch length:  $\sim 0.3$   $\mu\text{m}$
  - corresponds to  $10^{-30}$  for a 3 GHz – accelerator
  - half-value thickness:  $\sim 5$  cm  $\Rightarrow \sim 1$  nucleus / b
  - necessary flux for double- $\gamma$  excitation:  $\sim 1 \gamma / (\text{eV b fs}) = 10^{39} \gamma / (\text{eV cm}^2 \text{ s})$
- spectral shaping of  $\gamma$ -ray flux by absorption  $\rightarrow$  loss of intensity

“**Nuclear Photonics is an emerging field of science.**”

„***Nuclear Photonics*** is the cross-disciplinary field of Physics and Engineering which addresses **controlled** photonuclear reactions with laser-driven particle beams, e.g. artificial  $\gamma$ -ray beams, and their applications.“

„controlled“

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

„artificial gamma-ray beams“

- usage of artificially shaped  $\gamma$ -ray beams w.r.t. spectral intensity profile

„cross-disciplinary“

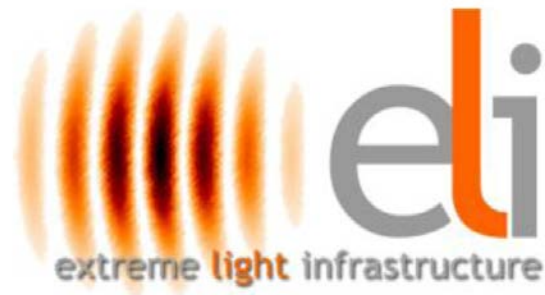
- integrates techniques from nuclear physics, quantum optics, accelerator science

ELI-NP will become THE major facility for Nuclear Photonics

Needs: **energy-tunable, high-flux, high-rep.rate, high-resolution, polarized  $\gamma$ -ray beam** from LASER-Compton backscattering

All this will be possible at ELI-NP !

Future w. high Brightness: ELI – Photonuclear Pillar



Thank you very much !

at  $10^3 - 10^6 \gamma / (\text{eV s})$  at VEGA@ELI-NP

