PHOTONUCLEAR REACTIONS – A TUTORIAL

Andreas Zilges
University of Cologne

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für Bildung
und Forschung

(05P2015 ELI-NP)

PHOTONUCLEAR REACTIONS – A TUTORIAL

- **Light and the Nucleus**
- **A short history of photonuclear reactions**
- **Observables**
- **A selection of research highlights**

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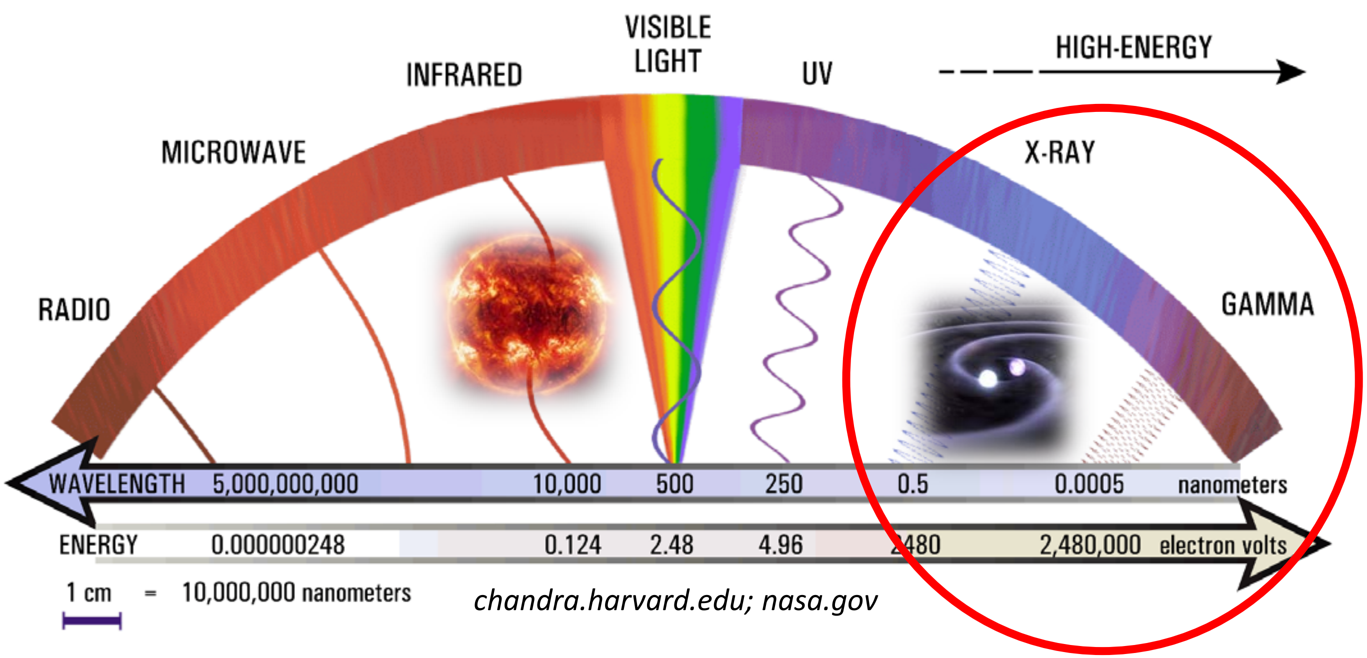
Photons in the MeV range



chandra.harvard.edu; nasa.gov

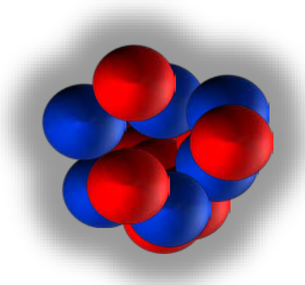
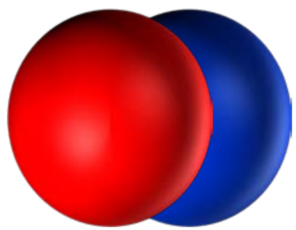
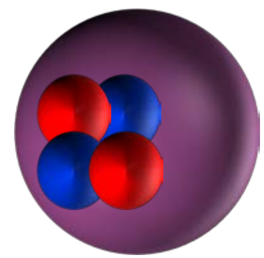
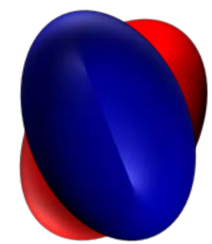
- MeV-photons are **abundant in the universe** (Planck photon bath, e.g., from supernovae, neutron star mergers)

→ photon-nucleus interaction important, e.g., for the synthesis of elements - „Nuclear Astrophysics“

Photons in the MeV range

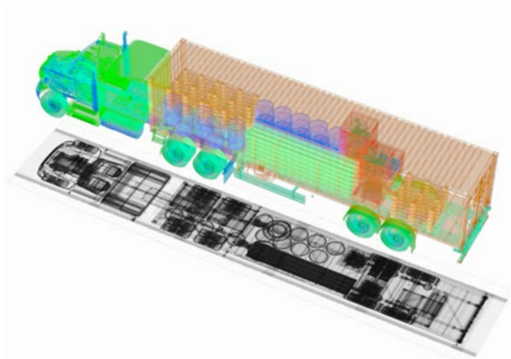
- MeV-photons are **complementary to „standard“ probes** in nuclear physics and excite nuclei very selectively

  → precision study of excitation modes in nuclei for Nuclear Structure and fundamental physics

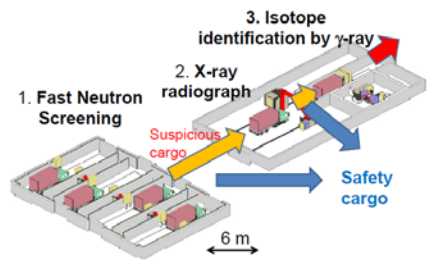





- MeV-photons are **very penetrative**

  → various applications (e.g. cargo inspection)

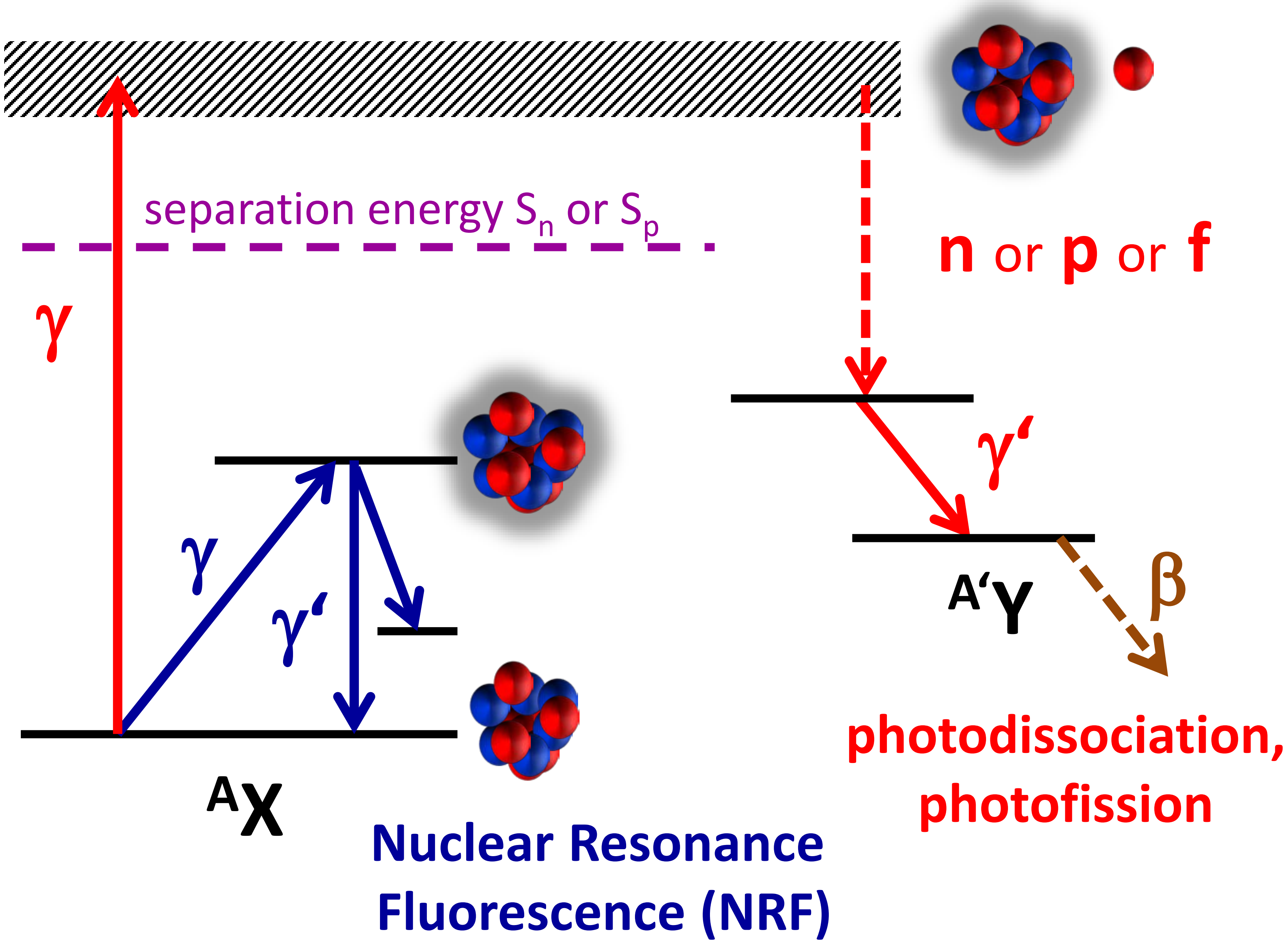


www.passportsystems.com



H. Ohgaki et al.

Photonuclear Reactions



Photonuclear Reactions

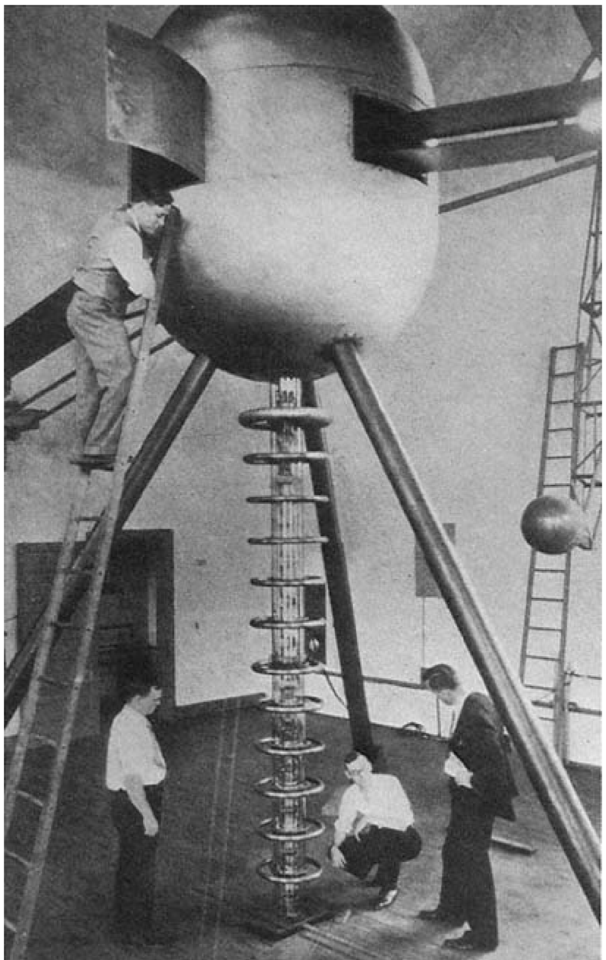
- pure EM interaction
- spin selectivity (mainly E1, M1, E2 transitions)
- strength selectivity

Photons produced in $^{7}Li(p,\gamma)$ reaction

1937:

Atomumwandlungen durch γ-Strahlen.

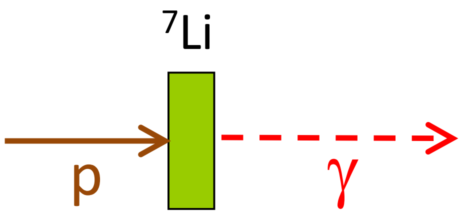
Von **W. Bothe** und **W. Gentner** in Heidelberg.



http://ark.cdlib.org/ark:/13030/ft5s200764/

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

Photon source:



$^{7}Li(p,\gamma)^{8}Be$ @ 600 kV van de Graaff generator

Subsequent (γ,n) reactions produced radioactive isotopes.

→ „Giant Resonance“

Giant Dipole Resonance (GDR)

1938:

Nuclear Photo-effects

THE beautiful experiments of Bothe and Gentner[1] on the ejection of neutrons from heavier nuclei by means of γ-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. ...

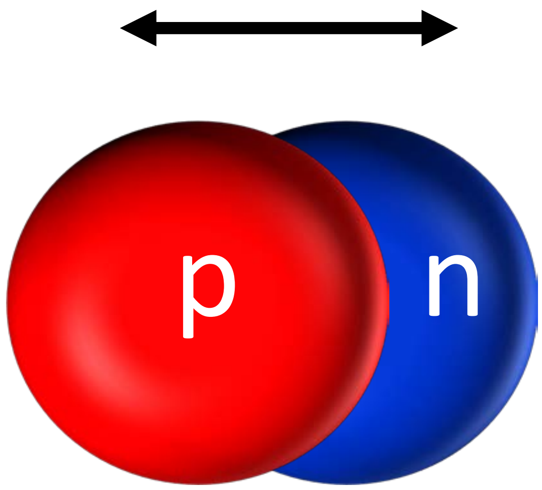
N. BOHR.

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

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

Giant Dipole Resonance (GDR)

Dynamic electric dipole (E1) moments in nuclei:
Separate center of mass and center of charge



Proton fluid oscillates against neutron fluid:
Giant Dipole Resonance (GDR)

A. Migdal, J. Phys. (USSR) ***8*** *(1944) 331*

Photons from Betatron Bremsstrahlung

1947:

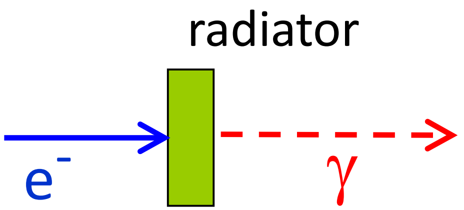
Photo-Fission in Heavy Elements*

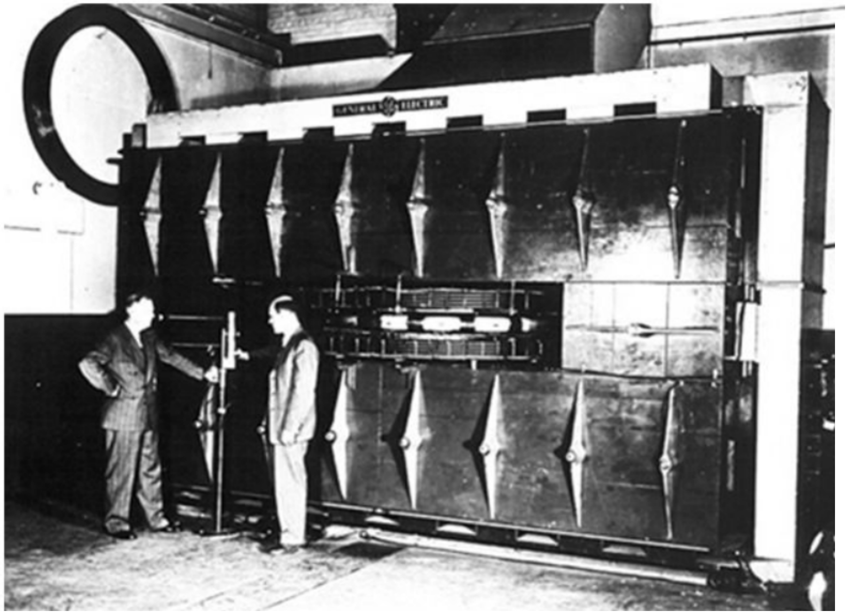
G. C. BALDWIN AND G. S. KLAIBER
Research Laboratory, General Electric Company, Schenectady, New York

Phys. Rev. ***71*** *(1947) 3*

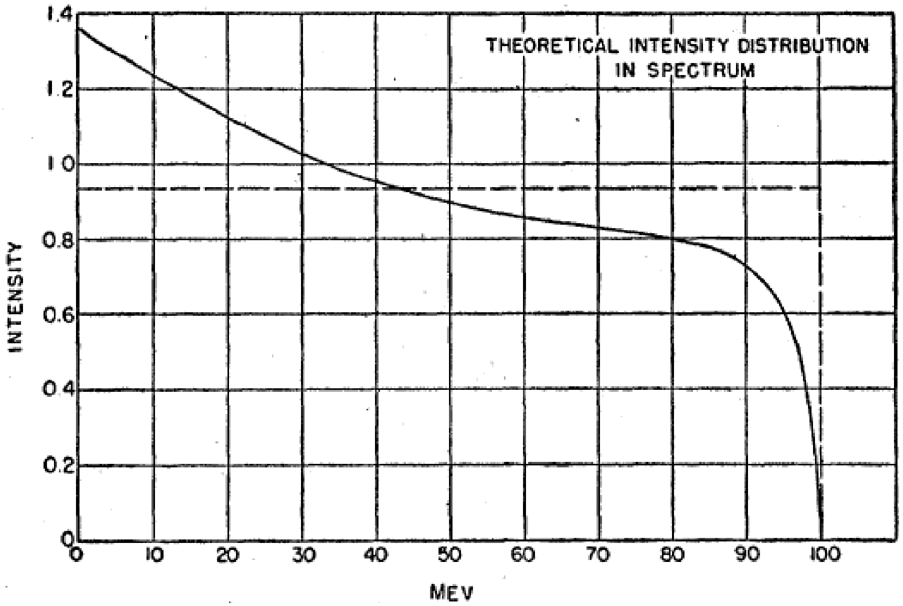
Photon source:

Bremsstrahlung from 100 MeV betatron





From: A.M. Sessler, LBNL



Giant Dipole Resonance (GDR)

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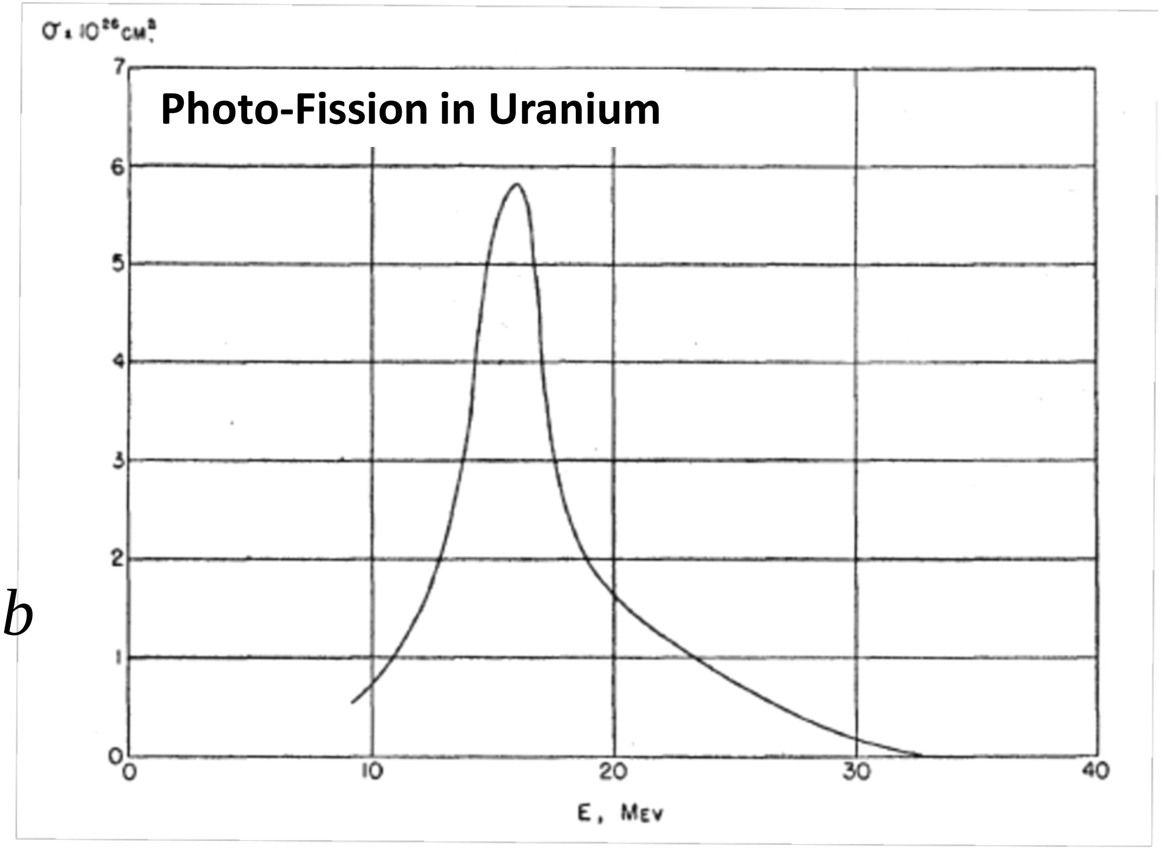
Phys. Rev. ***71*** *(1947) 3*

$E_x = 31\ A^{-1/3} + 21\ A^{-1/6}$

$$\int_0^{\infty} \sigma(E)dE = 60\frac{NZ}{A}MeV \cdot mb$$



Photons from van de Graaff accelerator for electrons

1969:

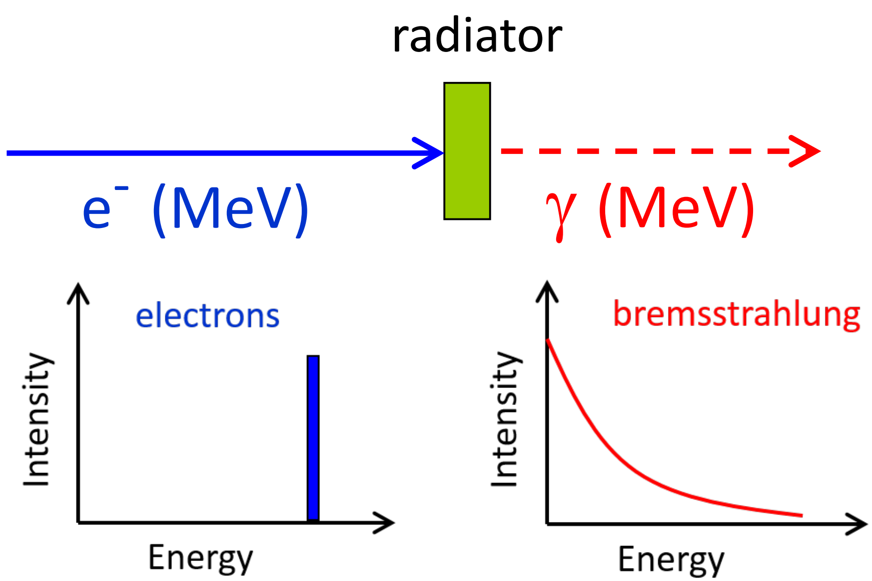
PHYSICAL REVIEW VOLUME 187, NUMBER 4 20 NOVEMBER 1969

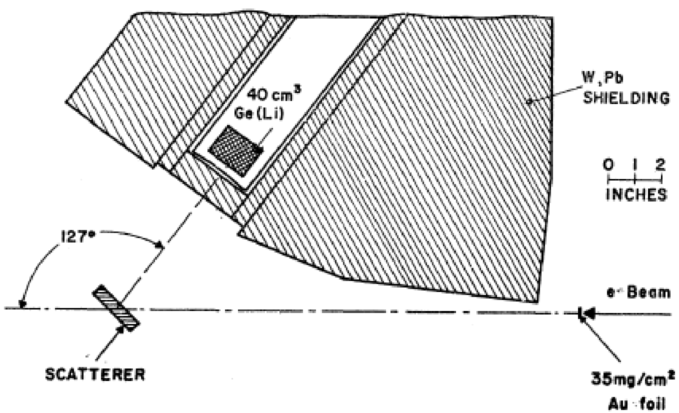
Electric Dipole Transitions from the 2.6-MeV Septuplet in Bi^{209}†

F. R. METZGER
Bartol Research Foundation of The Franklin Institute, Swarthmore, Pennsylvania 19081

(Received 25 June 1969)

Phys. Rev. ***187*** *(1969) 1680*

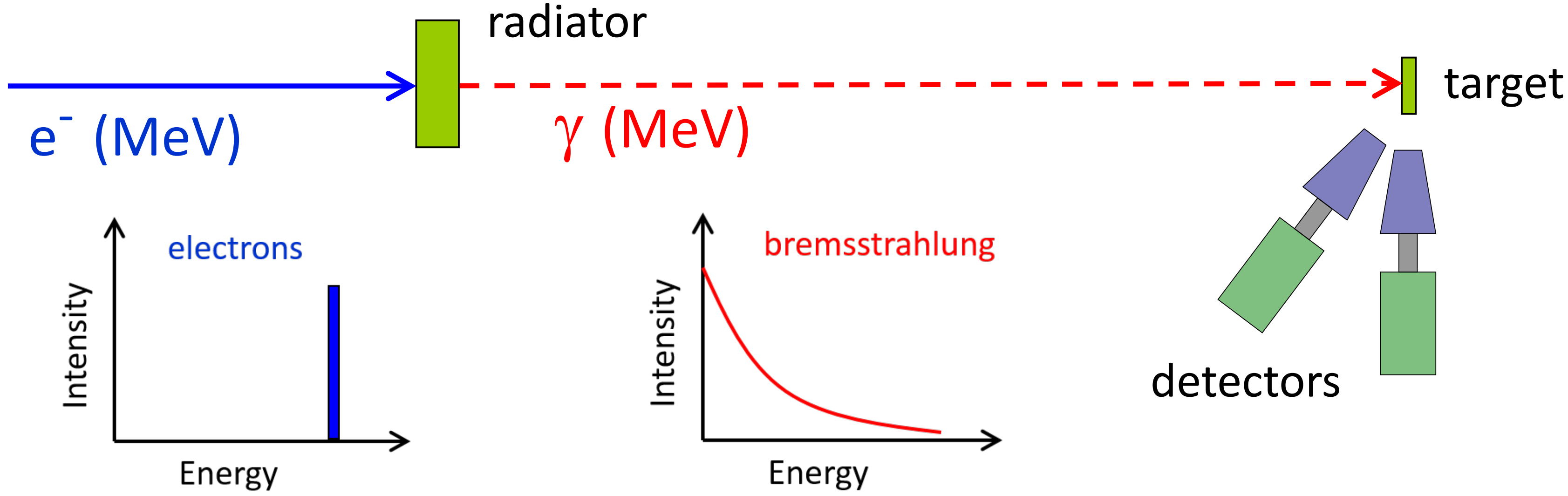


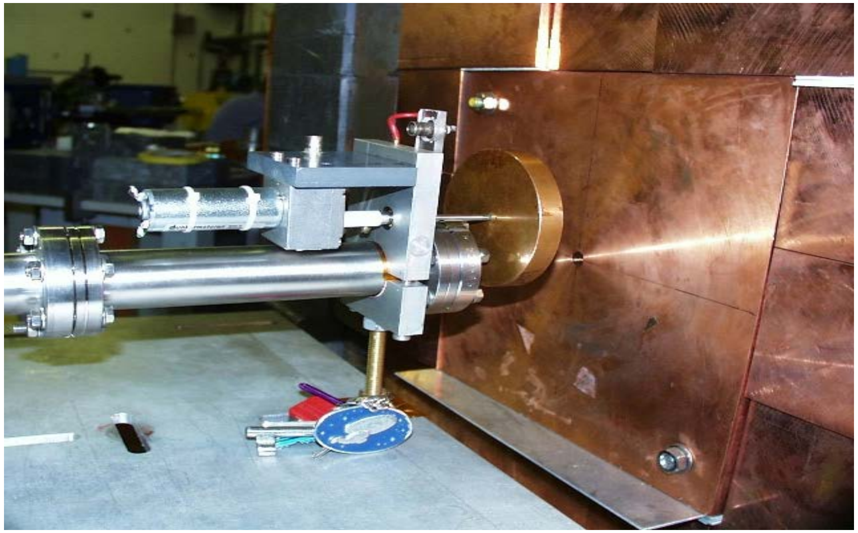


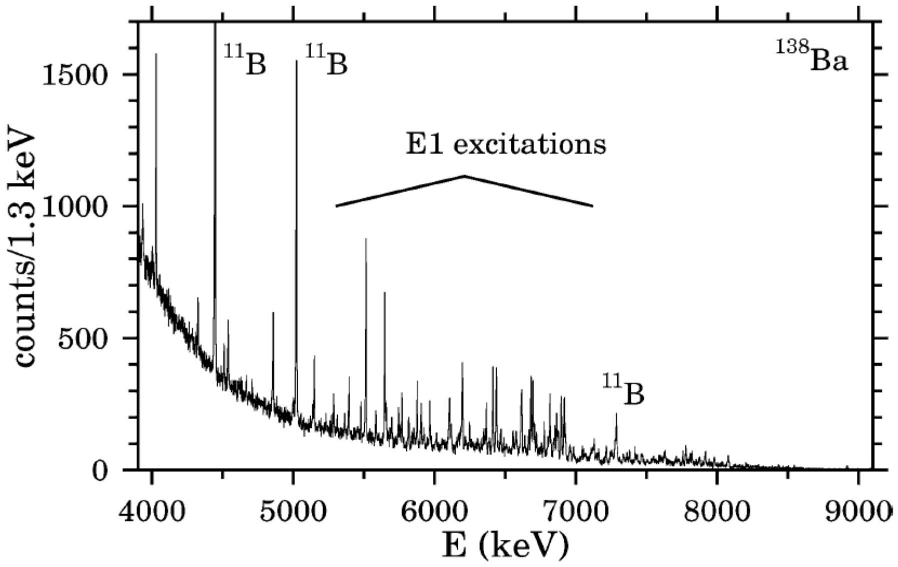
Adjustable bremsstrahlung endpoint energy up to a few MeV

High resolution Nuclear Resonance Fluorescence (NRF)

1980s, 1990s:



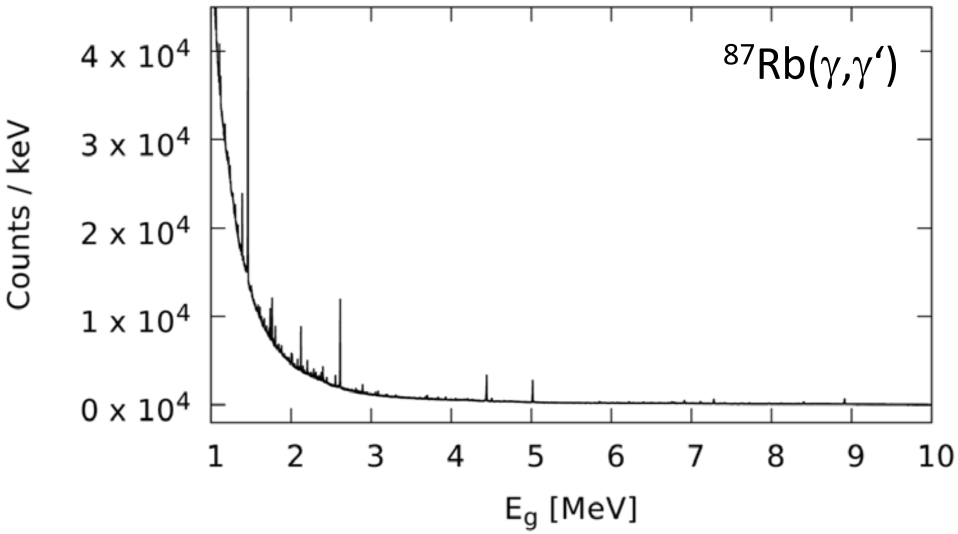


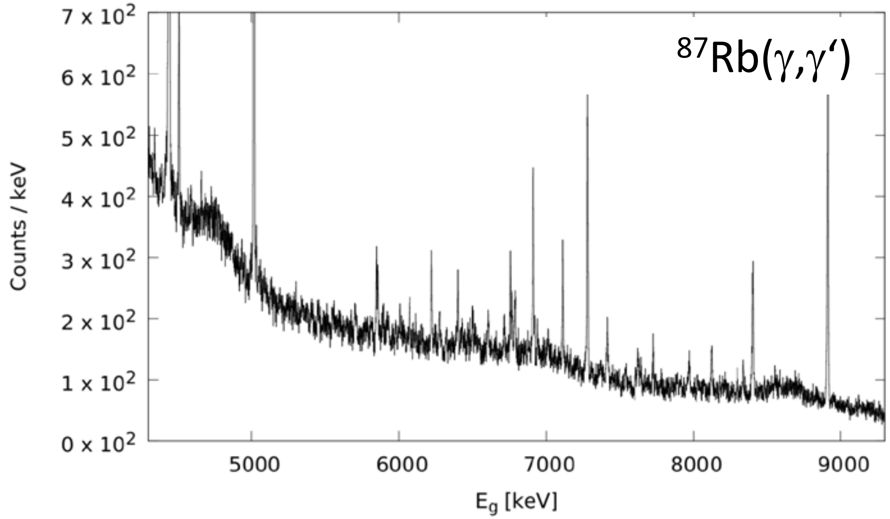


*Review: U. Kneissl, H.H. Pitz, and A.Z., PPNP **37** (1996) 349*

Limitations using bremsstrahlung

- no selectivity of excitation energy („white“ photon spectrum)
- strongly increasing continuous background at low energies
- background from higher lying states (e.g. detector response)
- beam only very weakly polarized (and only with thin radiator)
- large amount (100s of mg) of target material needed





→ tunable „mono“energetic photon sources !

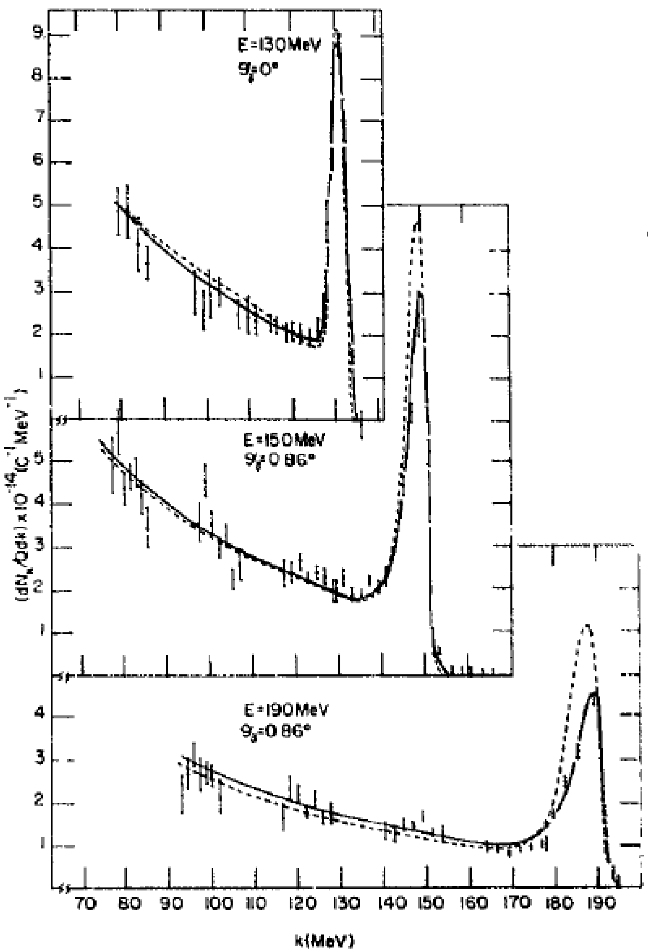
Photons from positron annihilation in flight

1953:

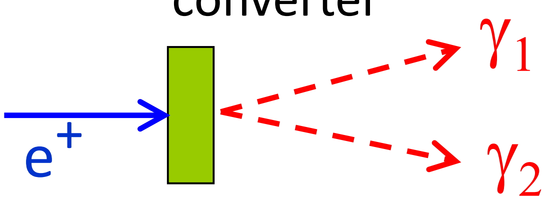
PHYSICAL REVIEW VOLUME 89, NUMBER 4 FEBRUARY 15, 1953

Electron-Positron Annihilation in Flight

S. A. COLGATE AND F. C. GILBERT
Radiation Laboratory, Department of Physics, University of California, Berkeley, California
(Received November 4, 1952)



Phys. Rev. ***89*** *(1953) 790*



Photon source:

e.g.: Saclay, Livermore, Gießen

but: rather low photon flux and high bremsstrahlung background

Tagged photons from electron bremsstrahlung

1982:

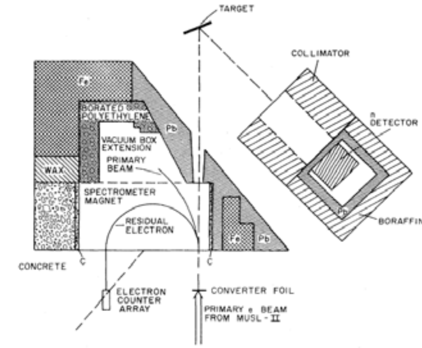
A HIGH RESOLUTION BREMSSTRAHLUNG MONOCHROMATOR FOR PHOTO-NUCLEAR EXPERIMENTS

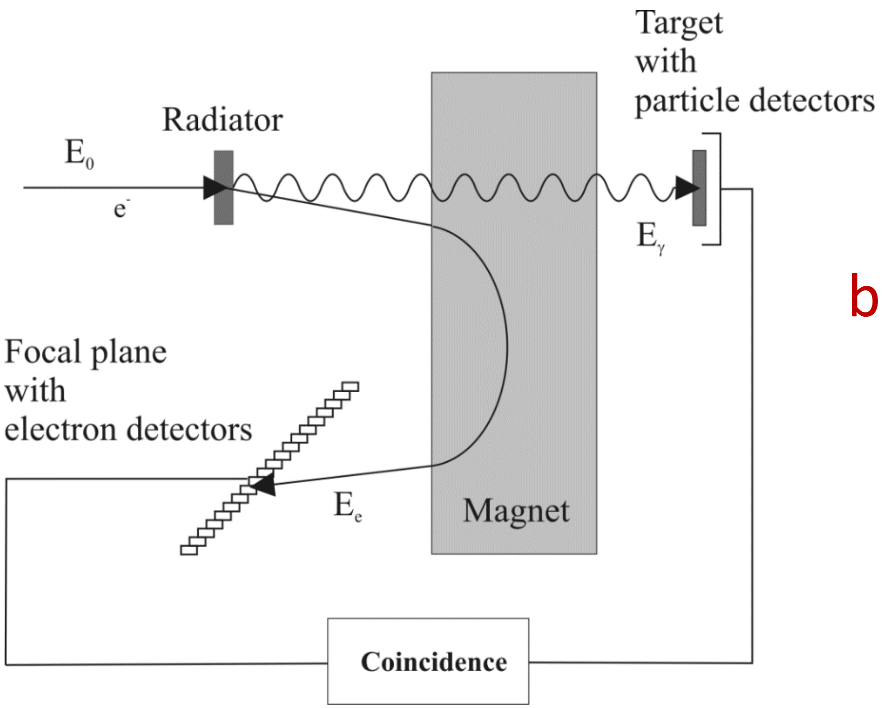
J.W. KNOWLES, W.F. MILLS, R.N. KING, G.E. LEE-WHITING
Atomic Energy of Canada Limited, Chalk River Nuclear Laboratories, Chalk River, Ontario, Canada K0J 1J0

S. YEN, B.O. PICH, J.C. KIM *, T.E. DRAKE
Physics Department, University of Toronto, Toronto, Ontario, Canada M5S 1A7

L.S. CARDMAN and R.L. GULBRANSON
Physics Department, University of Illinois, Urbana, Illinois, 61801 U.S.A.

Nucl. Inst. and Meth. Phys. Res. ***193*** *(1982) 463*



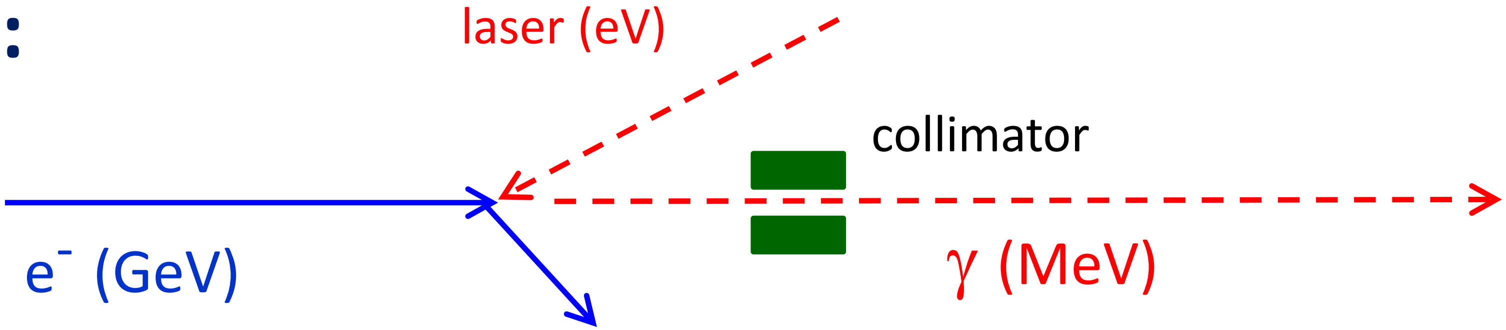


e.g.: JLAB, Frascati, Mainz, TU Darmstadt

but: rather low photon intensities

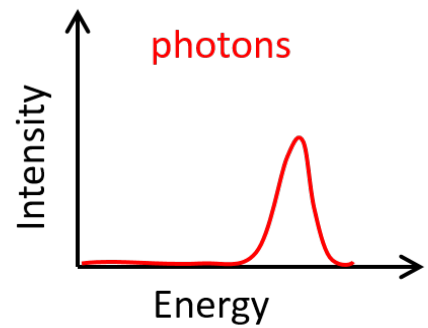
Photons from Laser Compton Backscattering (LCB)

1963:



$$E_{\gamma} \approx 4 \cdot \gamma_{e^-}^{2} \cdot E_{laser}$$

$$\left(\gamma_{e^-} = \frac{E_{e^-}^{kin}}{m_{e^-} c^2} + 1 \right)$$



PHYSICAL REVIEW LETTERS

VOLUME 10 | 1 FEBRUARY 1963 | NUMBER 3

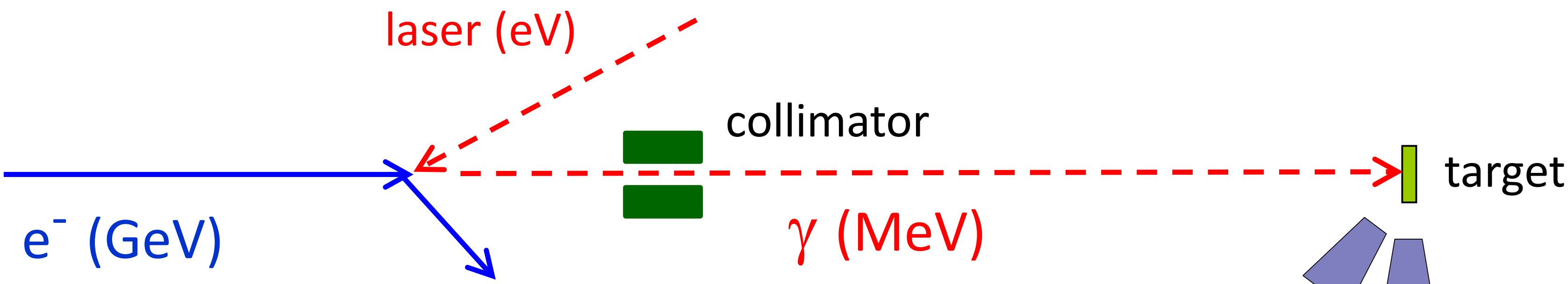
ELECTRON SCATTERING BY AN INTENSE POLARIZED PHOTON FIELD*

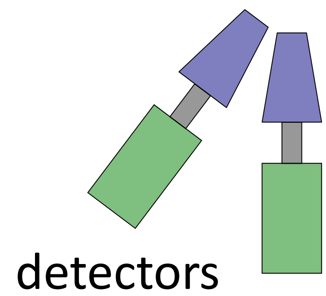
Richard H. Milburn
Department of Physics, Tufts University, Medford, Massachusetts

(Received 26 December 1962)

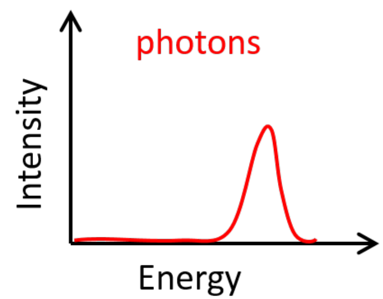
R.H. Milburn, PRL 10 (1963) 75

NRF and Laser Compton Backscattering





Examples:
HIGS at TUNL (USA)
NewSUBARU (Japan)
GBS at ELI-NP



- ”monoenergetic“ photon beam
- tunable energy
- polarized beam

→ Nuclear Photonics

*H.R. Weller et al., PPNP **62** (2009) 257*

Observables in NRF

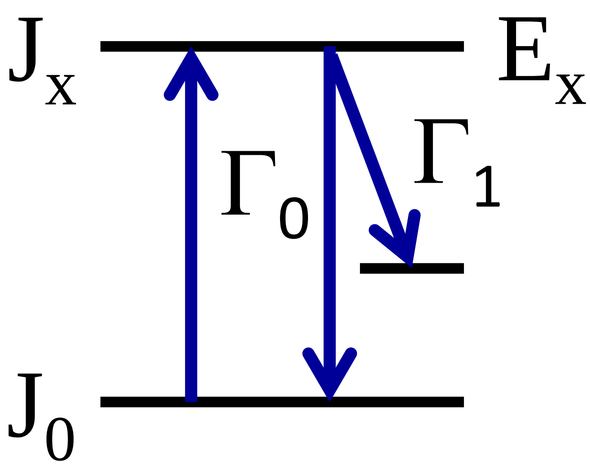
For a comparison with theory or for isotope identification one needs to know:

- **energy and distribution of E1/M1 strengths**
- **absolute transition strengths B(E1) or B(M1) (proportional to Γ_0 / E_x^3)**

Excitation of bound states by photons

- typical **natural level width** Γ: meV to eV (T$_{1/2}$ in ps-fs range)
- Γ < level spacing → **isolated resonances of Breit-Wigner shape**:

$$\sigma(E) = \frac{\pi}{2} \cdot \left(\frac{\hbar c}{E_x}\right)^2 \cdot \underbrace{\left(\frac{2J_x + 1}{2J_0 + 1}\right)}_{g} \cdot \frac{\Gamma_0 \cdot \Gamma}{(E - E_x)^2 + \Gamma^2 / 4}$$



$$\Gamma = \Gamma_0 + \Gamma_1$$

Γ_0: groundstate decay width

Γ_1: decay width to first excited state

Integrated cross section

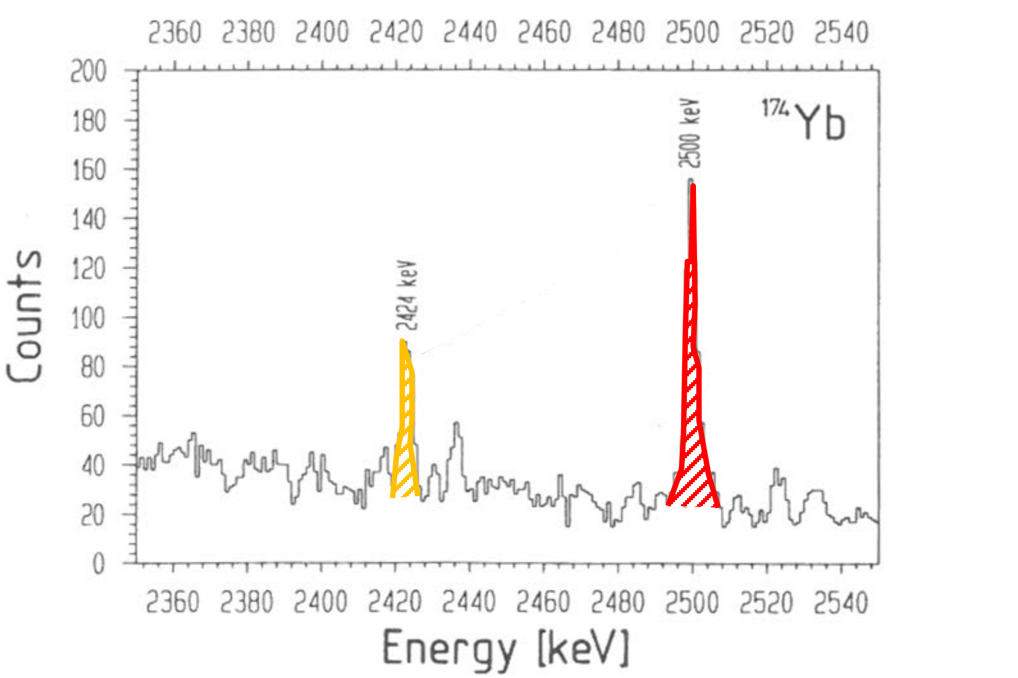
- additional **thermal Doppler broadening** in eV range
- photon flux usually constant within resonance range:
  → **integrated cross section** I is given by:

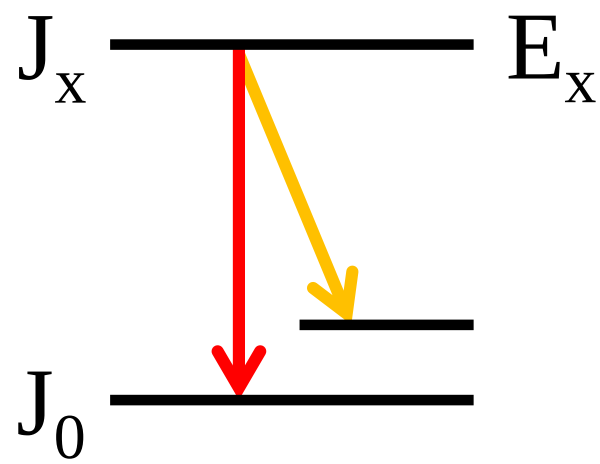
$$I_{0\to j\to k}(E) = \int \sigma(E)dE = \pi^2 \cdot \left(\frac{\hbar c}{E_x}\right)^2 \cdot \left(\frac{2J_j+1}{2J_0+1}\right) \cdot \frac{\Gamma_0 \cdot \Gamma_k}{\Gamma}$$

(peak area) (peak position) (angular distribution) (branching ratio)

→ Γ_0 can be derived from direct observables of the experiment!

Peak position, area, branching ratio





$$I_{0\to j\to k}(E) = \int \sigma(E)dE = \pi^2 \cdot \left(\frac{\hbar c}{E_x}\right)^2 \cdot \left(\frac{2J_j+1}{2J_0+1}\right) \cdot \frac{\Gamma_0 \cdot \Gamma_k}{\Gamma}$$

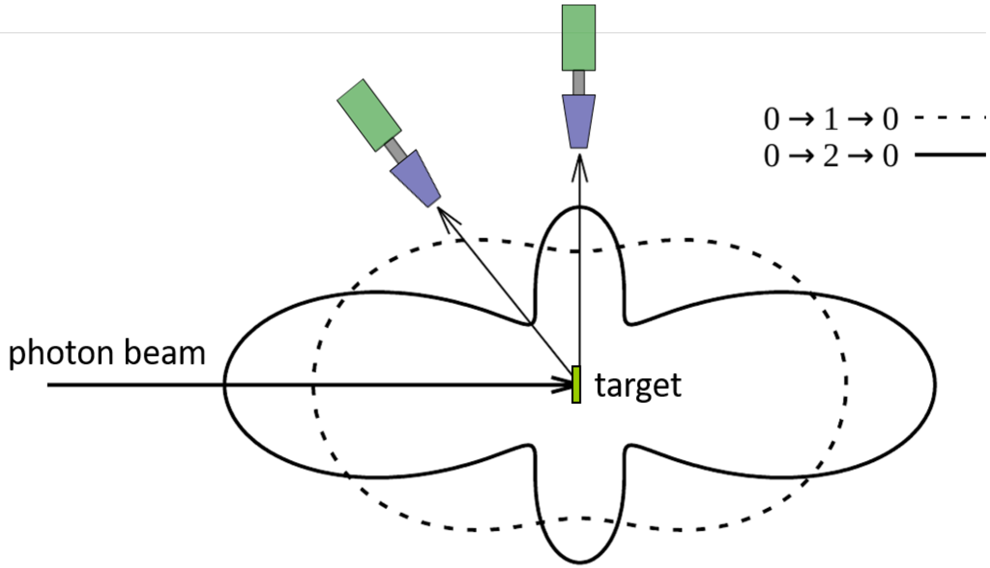
(peak area) ✓

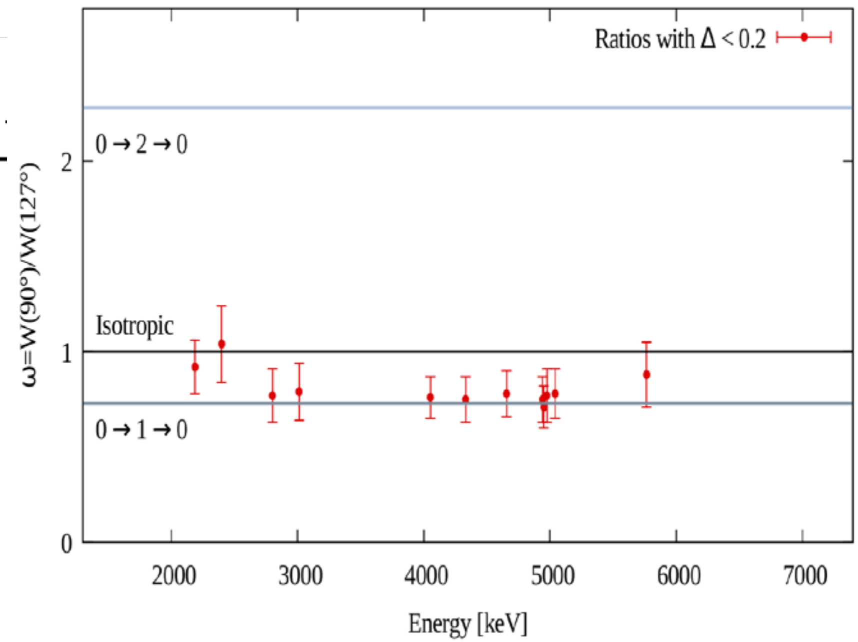
(peak position) ✓

(angular distribution)

(branching ratio) ✓

Angular distribution





$$I_{0\to j\to k}(E)=\int\sigma(E)dE=\pi^2\cdot\left(\frac{\hbar c}{E_x}\right)^2\cdot\left(\frac{2J_j+1}{2J_0+1}\right)\cdot\frac{\Gamma_0\cdot\Gamma_k}{\Gamma}$$

(peak area)

(peak position)

(angular distribution)

(branching ratio)

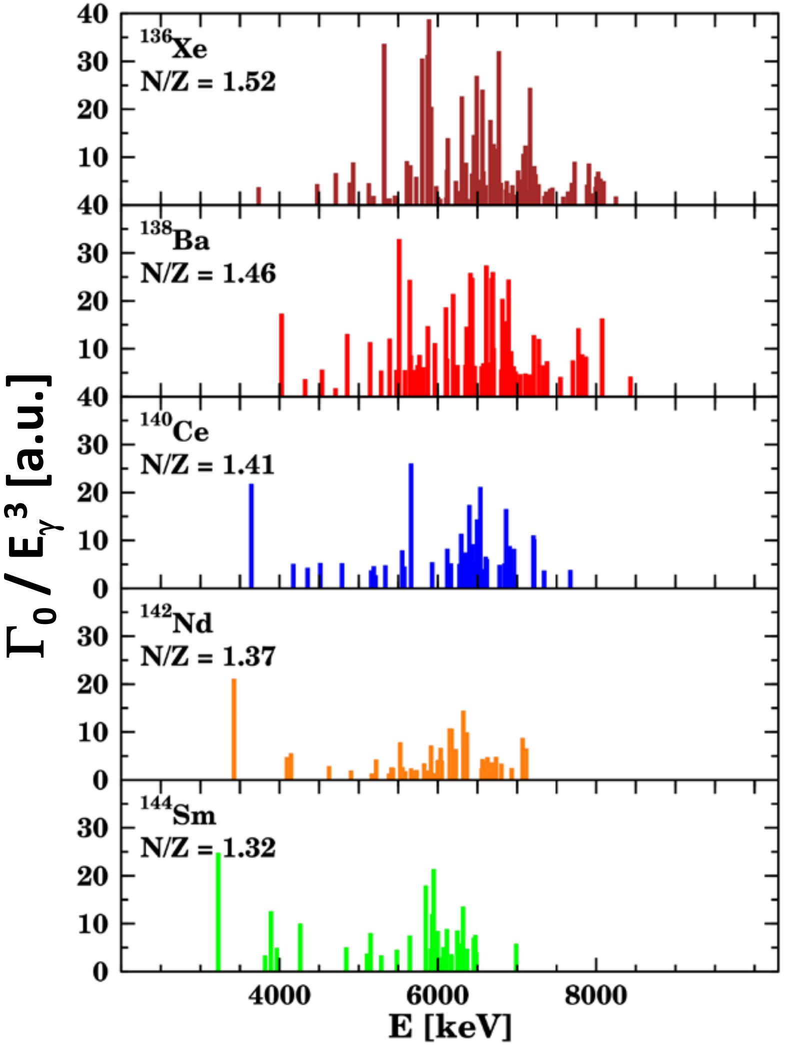
Γ_0 and absolute transition strength

- Crucial observables to be compared with theory are the **absolute transition strengths**:

$$B(E1)\uparrow = 9.554\times10^{-4}\cdot g\cdot\frac{\Gamma_0}{E_\gamma^3}$$

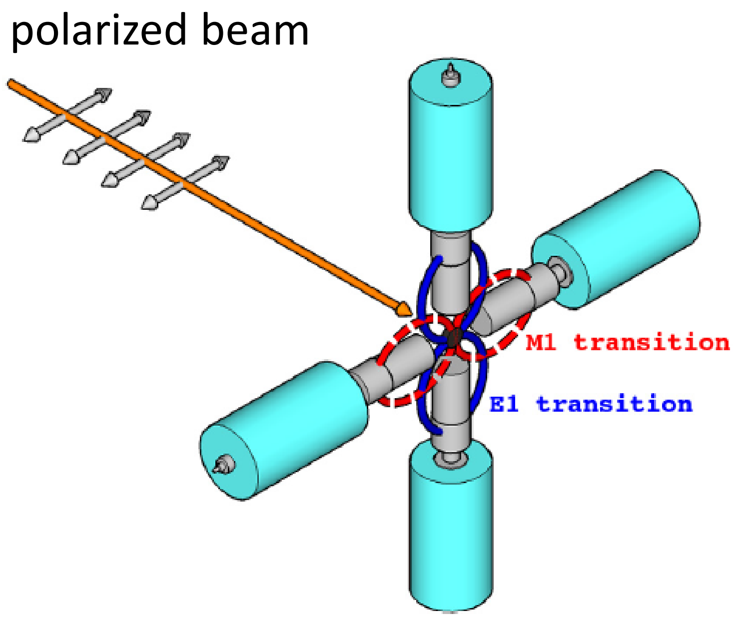
$$B(M1)\uparrow = 8.641\times10^{-2}\cdot g\cdot\frac{\Gamma_0}{E_\gamma^3}$$

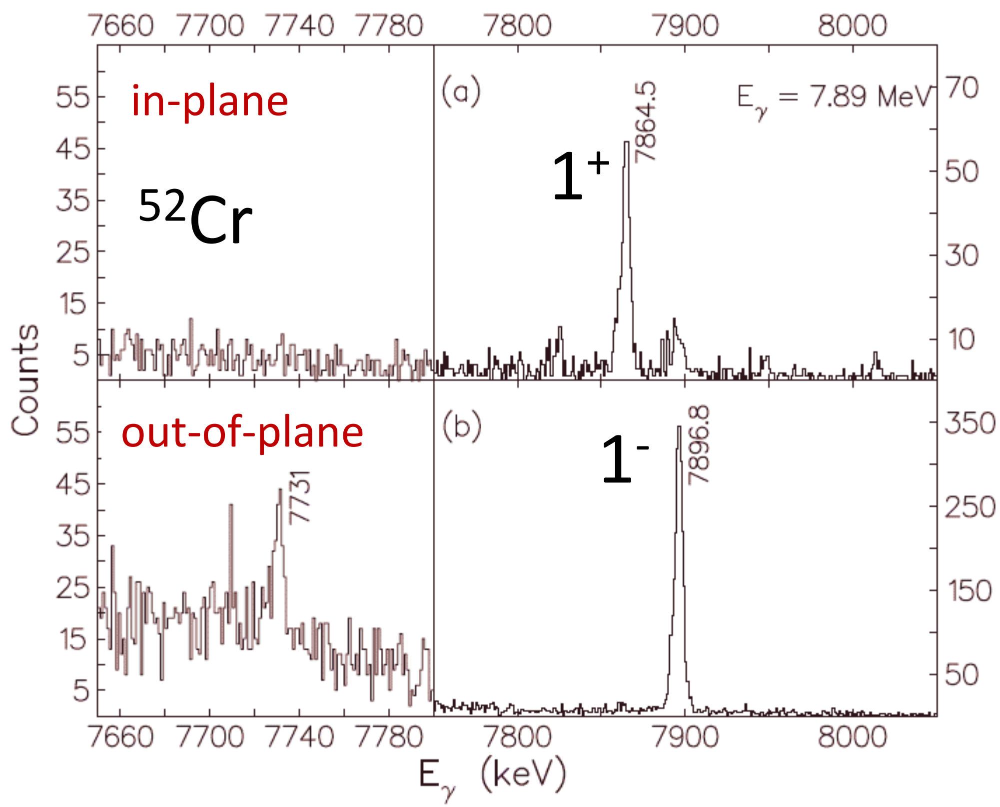
E1 or M1 transition?



Parity of excitations from polarized γ beam

Parity determination by measuring asymmetries

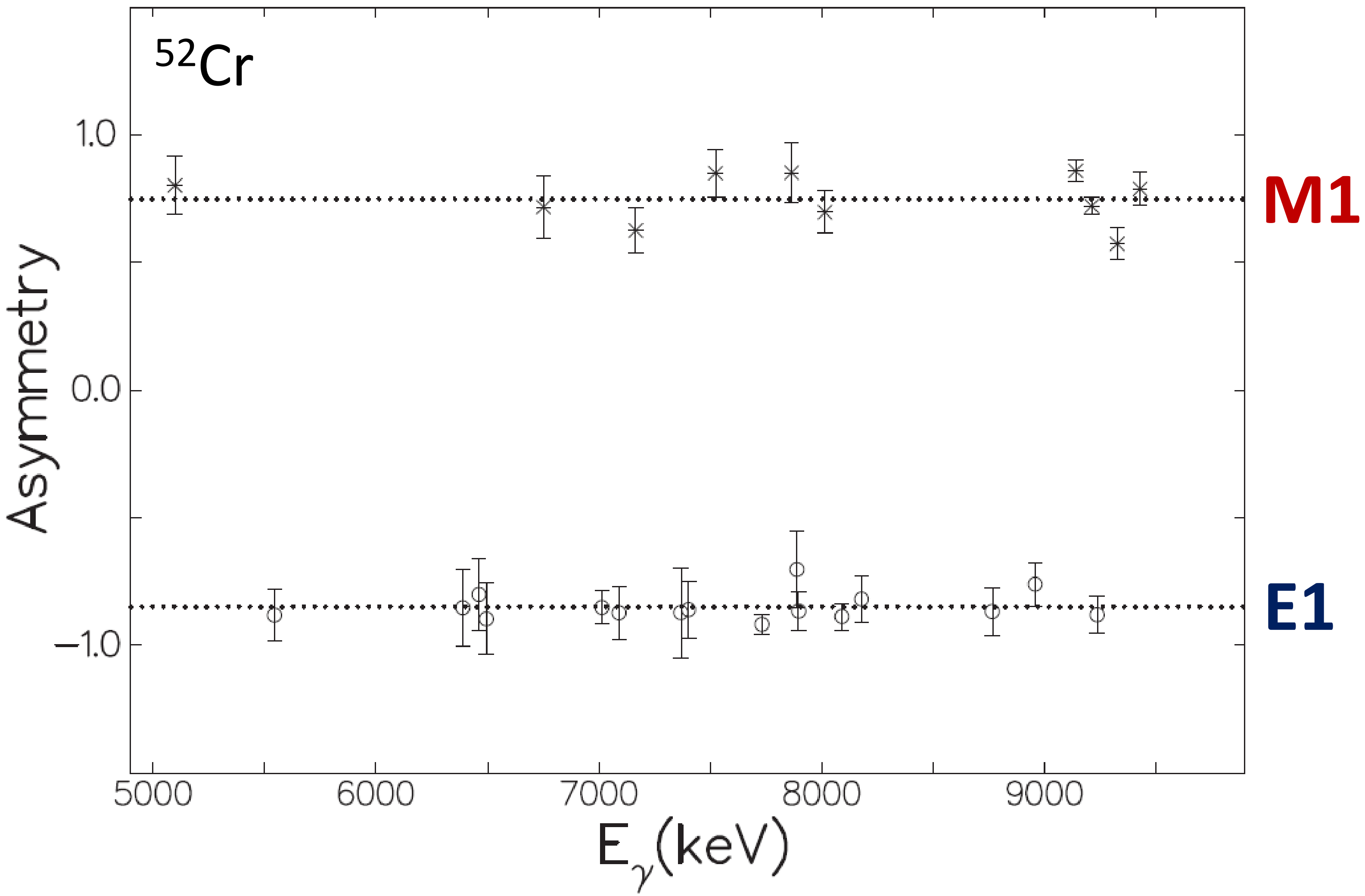




J. Beller et al., PLB ***741*** *(2015) 128*

Krishichayan et al., PRC ***91*** *(2015) 044328*

Parity determination



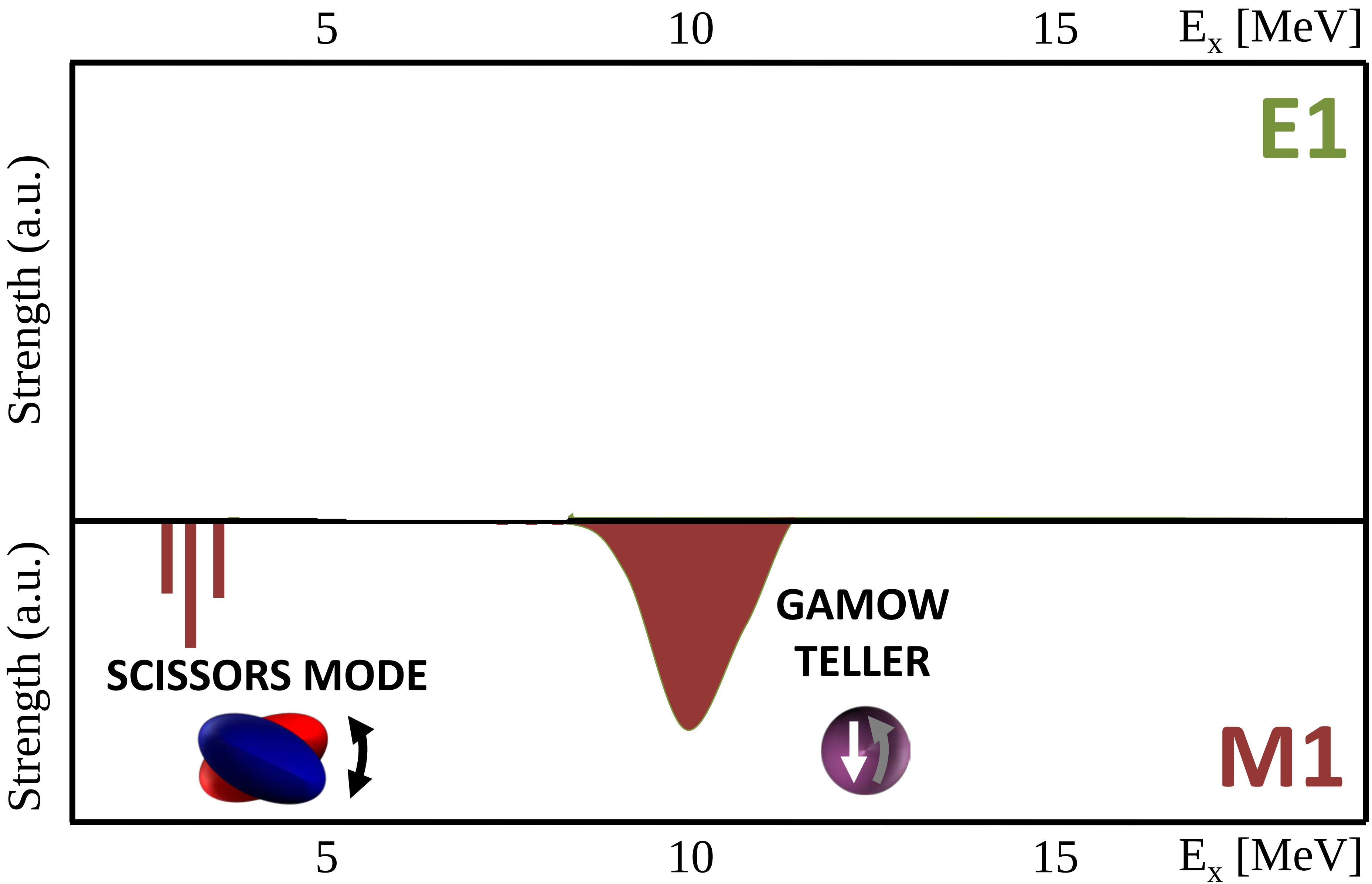
*Krishichayan et al., PRC **91** (2015) 044328*

Photonuclear Reactions

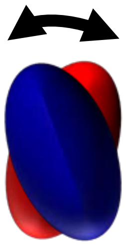
Nuclear Resonance Fluorescence:
derivation of excitation energies, spins, parities, decay energies, level widths, lifetimes, decay branchings, multipole mixing ratios, absolute transition strengths **with no model dependency!**

Two (out of many) research highlights

Dipole photoresponse of atomic nuclei



The scissors mode in deformed nuclei

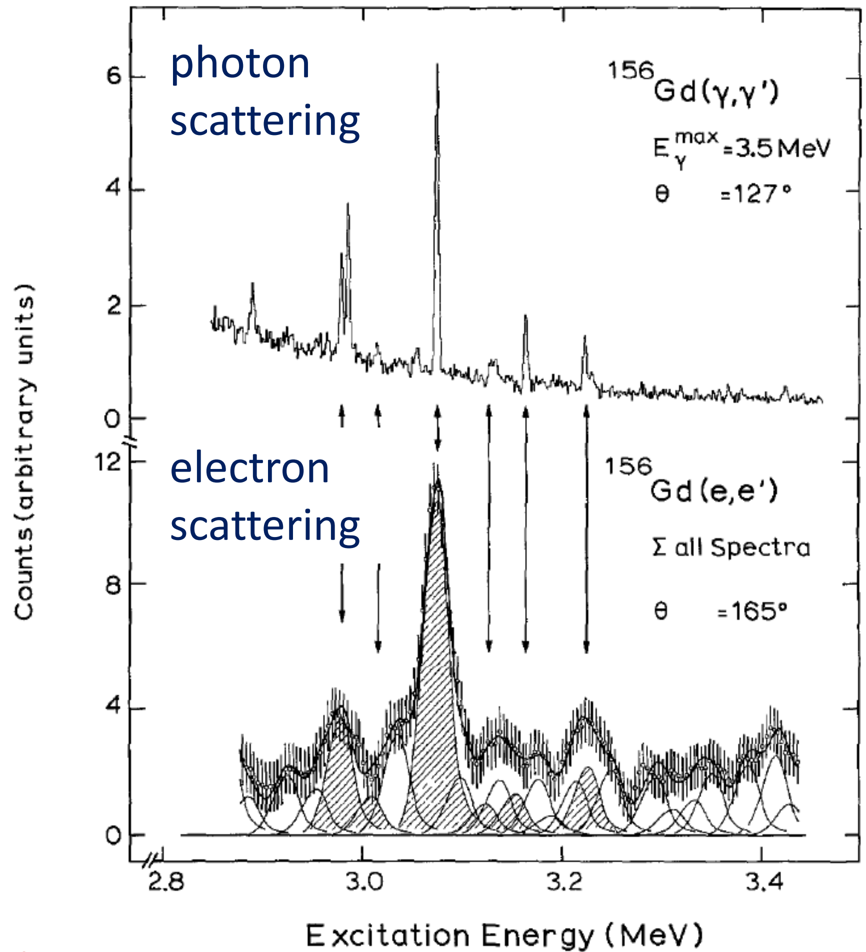


classically: current loop
→ M1 radiation
→ magnetic dipole excitation

Photonuclear experiments:

- detailed study of excitation mode

- systematic study of evolution

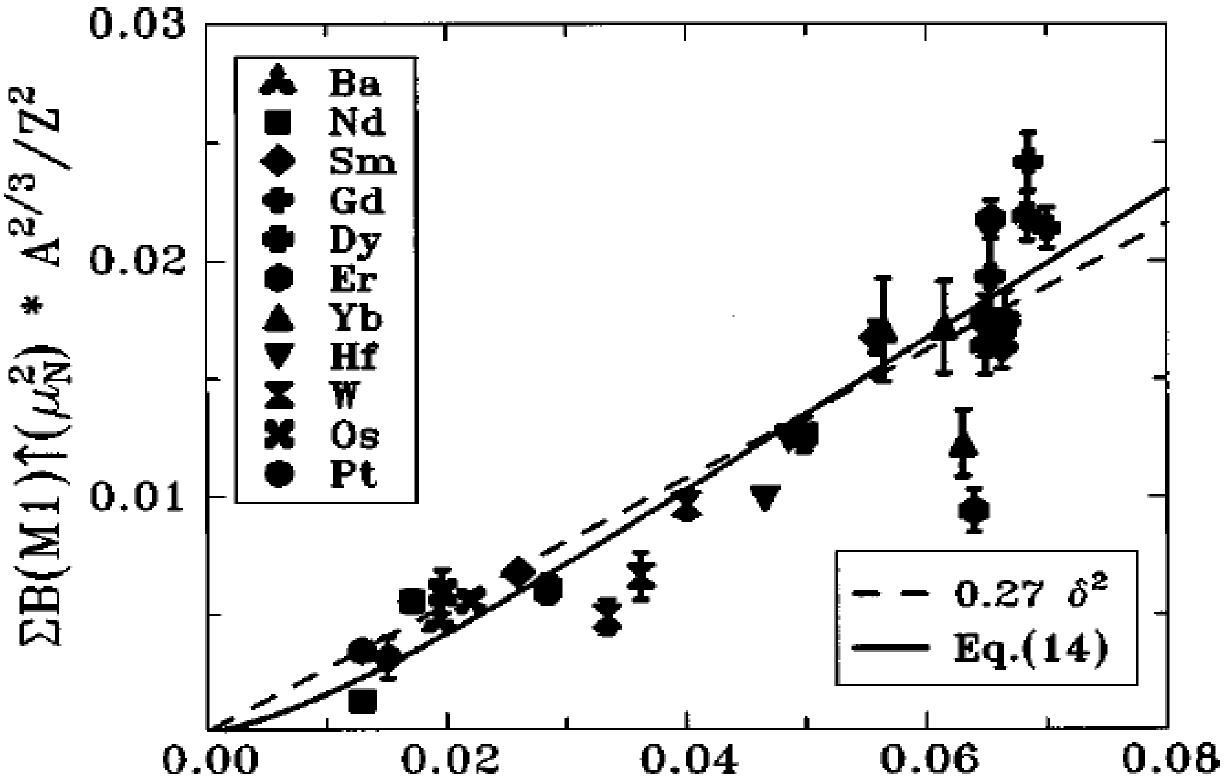


> 650 citations!

*D. Bohle et al., PLB **137** (1984) 27*
*D. Bohle et al., NPA **458** (1986) 205*
*H.H. Pitz et al., NPA **492** (1989) 411*

courtesy: Norbert Pietralla

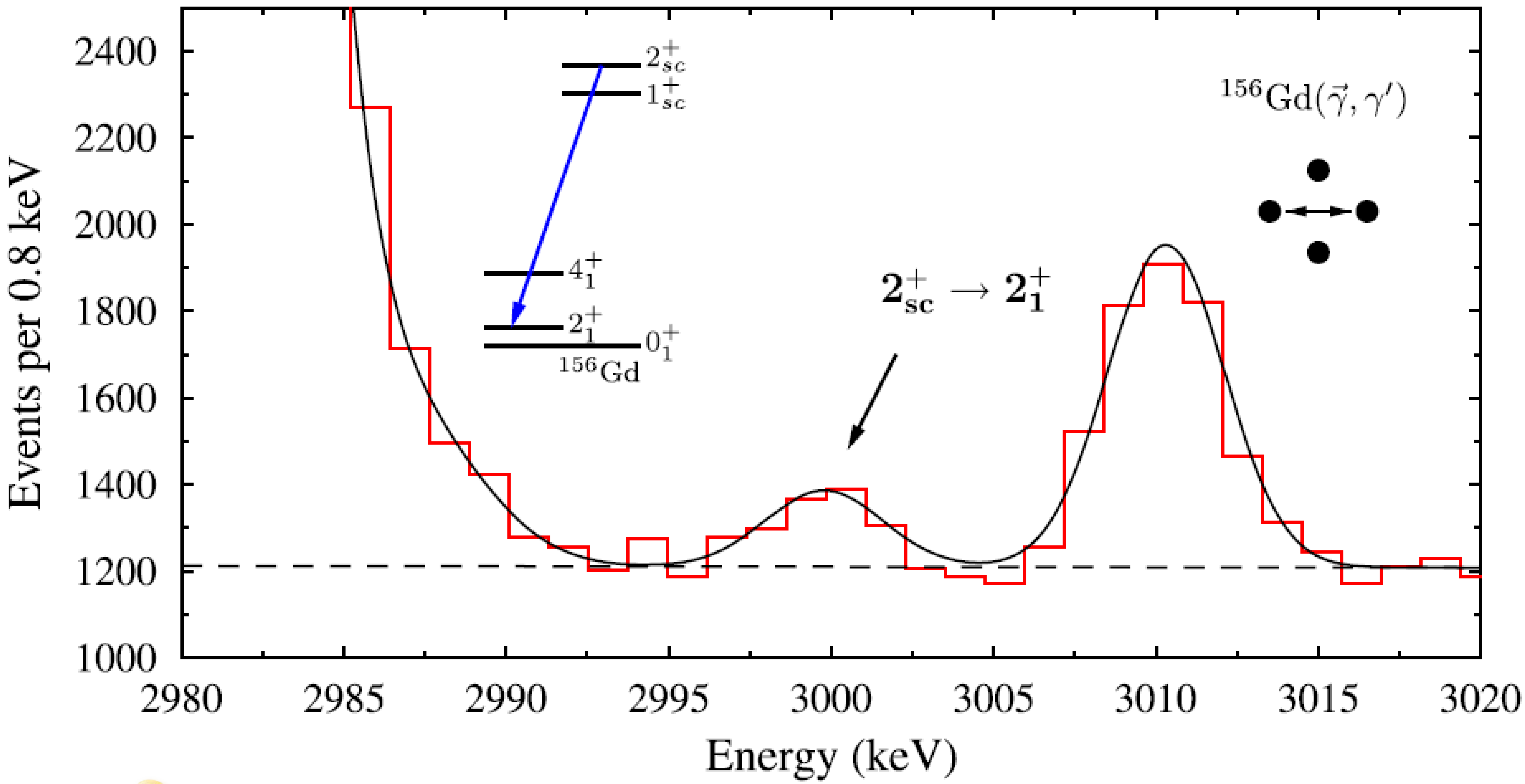
Collectivity of the scissors mode



(deformation δ)²

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

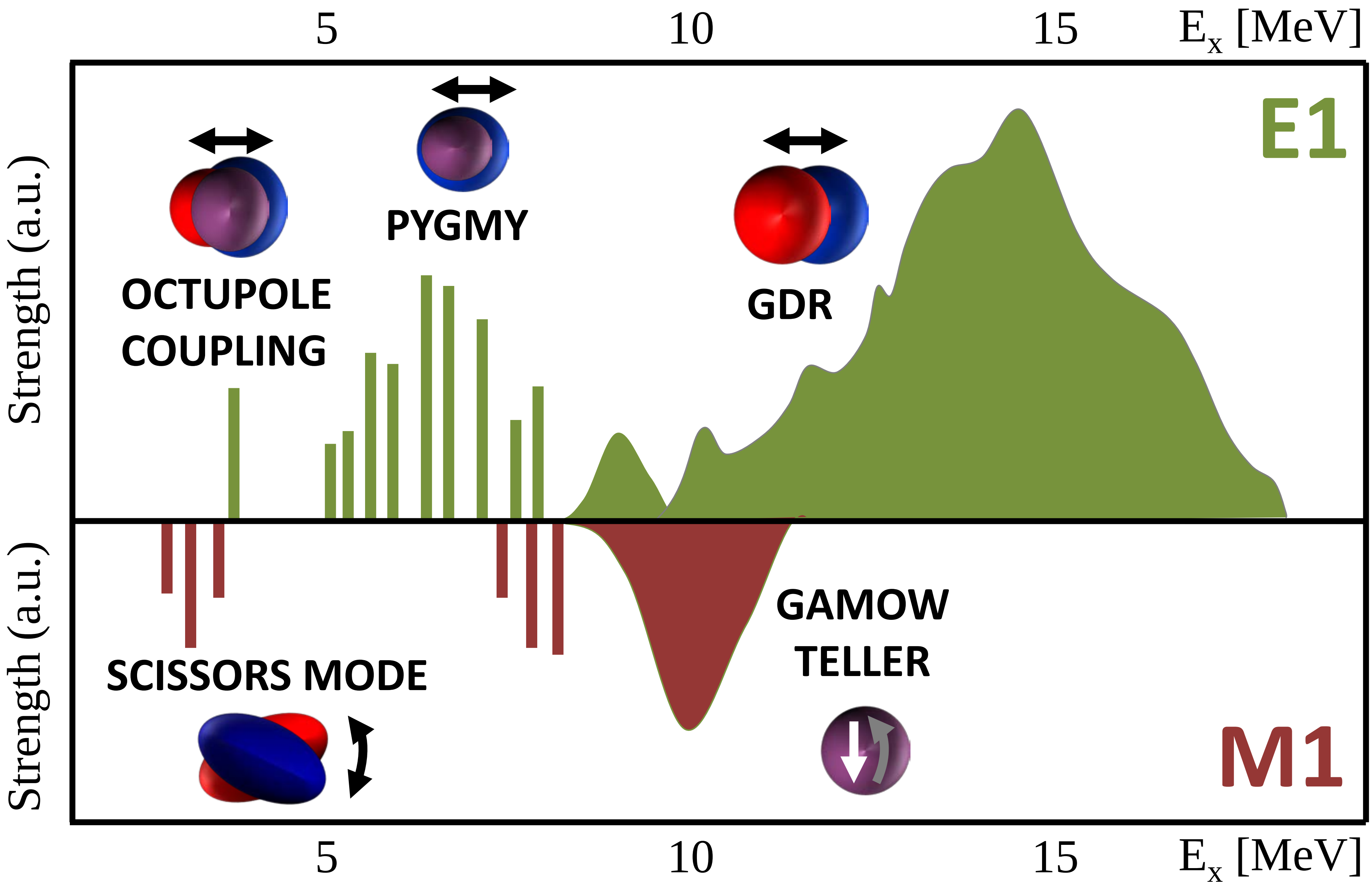
Rotational band on top of the scissors mode ?



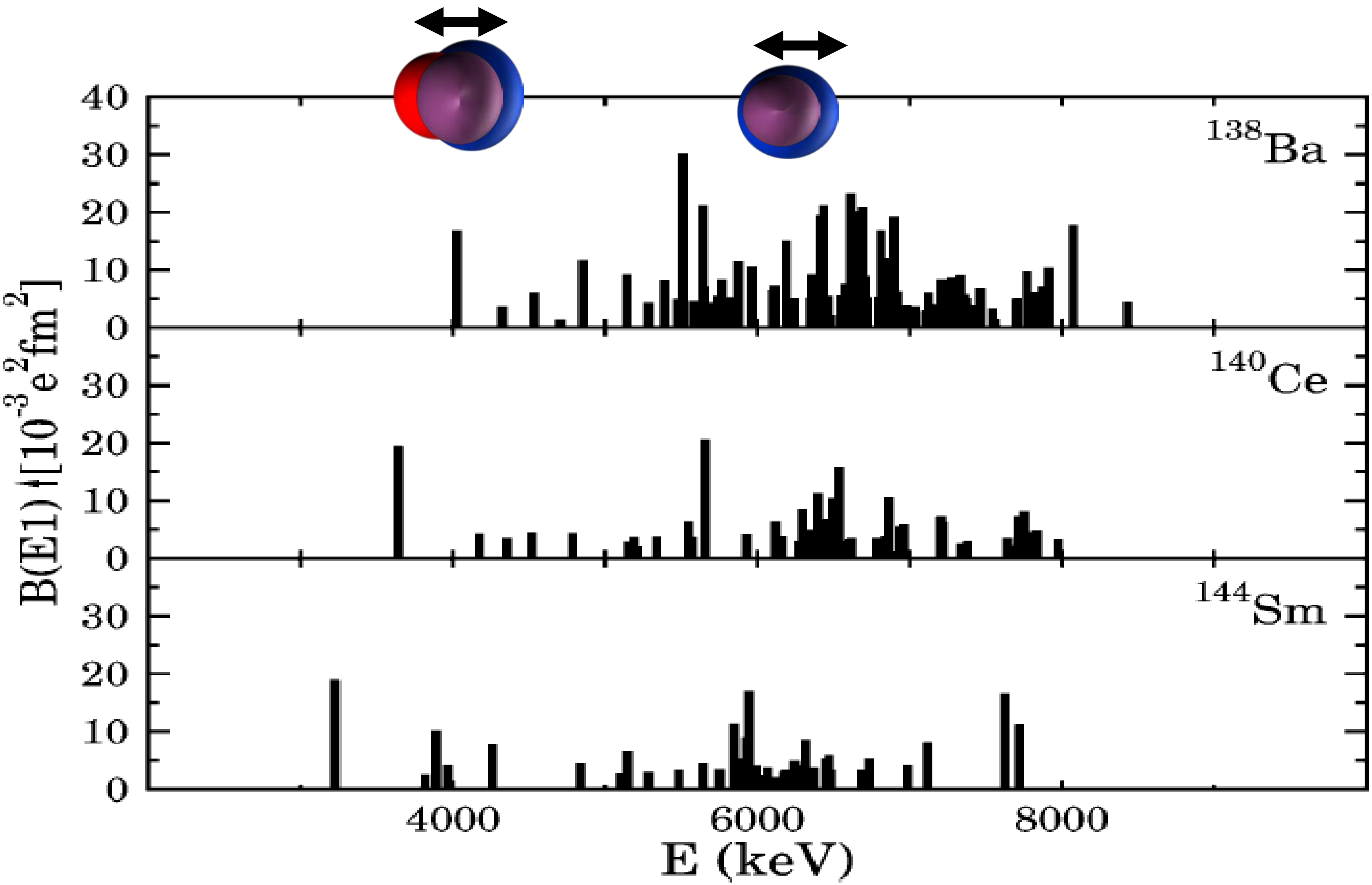
@HIGS (GSI/TUD/UoC/TUNL)

*T. Beck et al., PRL **118** (2017) 212502*

Dipole photoresponse of atomic nuclei

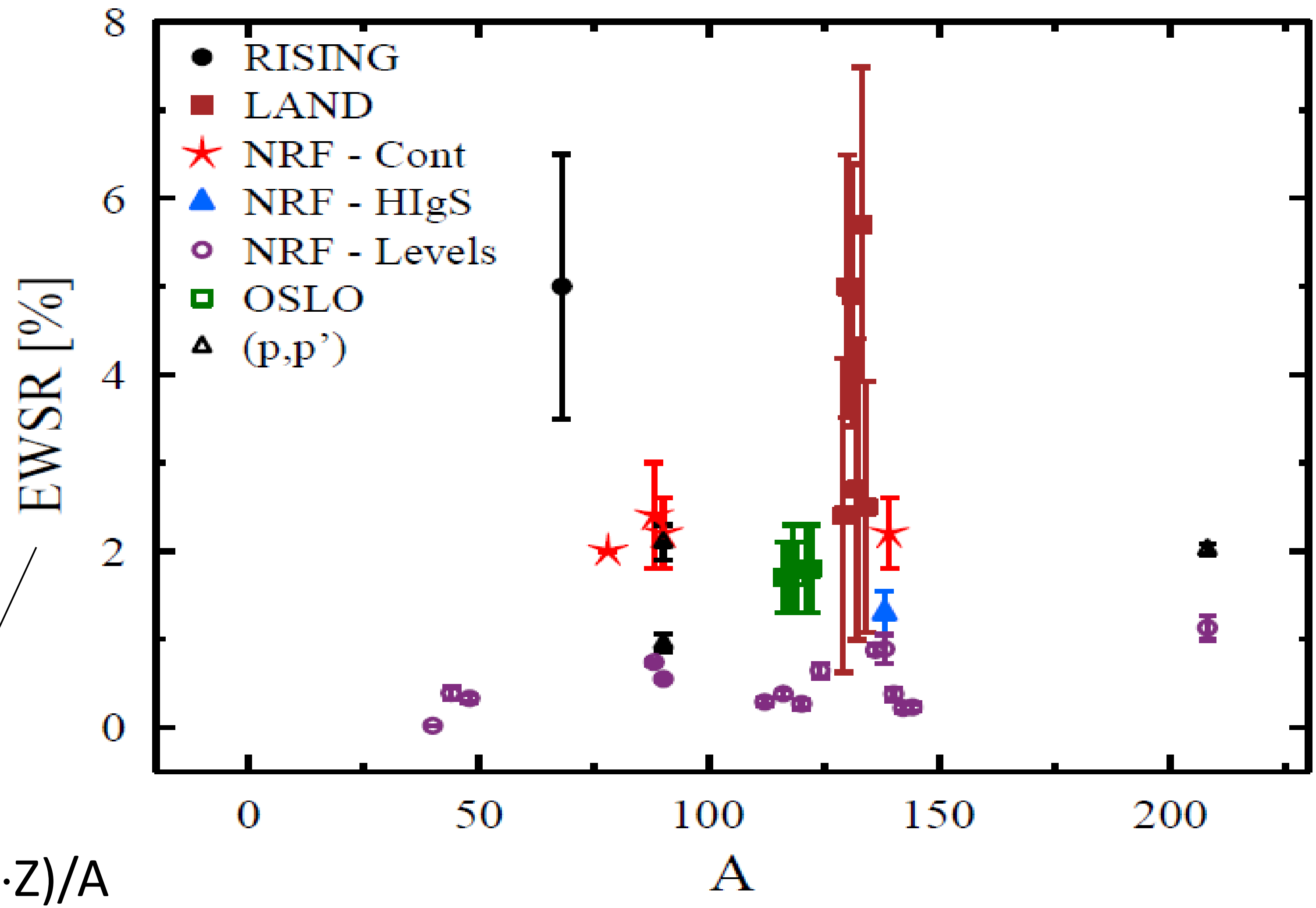


Electric dipole strength in nuclei



A. Zilges et al., Phys. Lett. B **542** (2002) 43

Summed electric dipole strength in nuclei

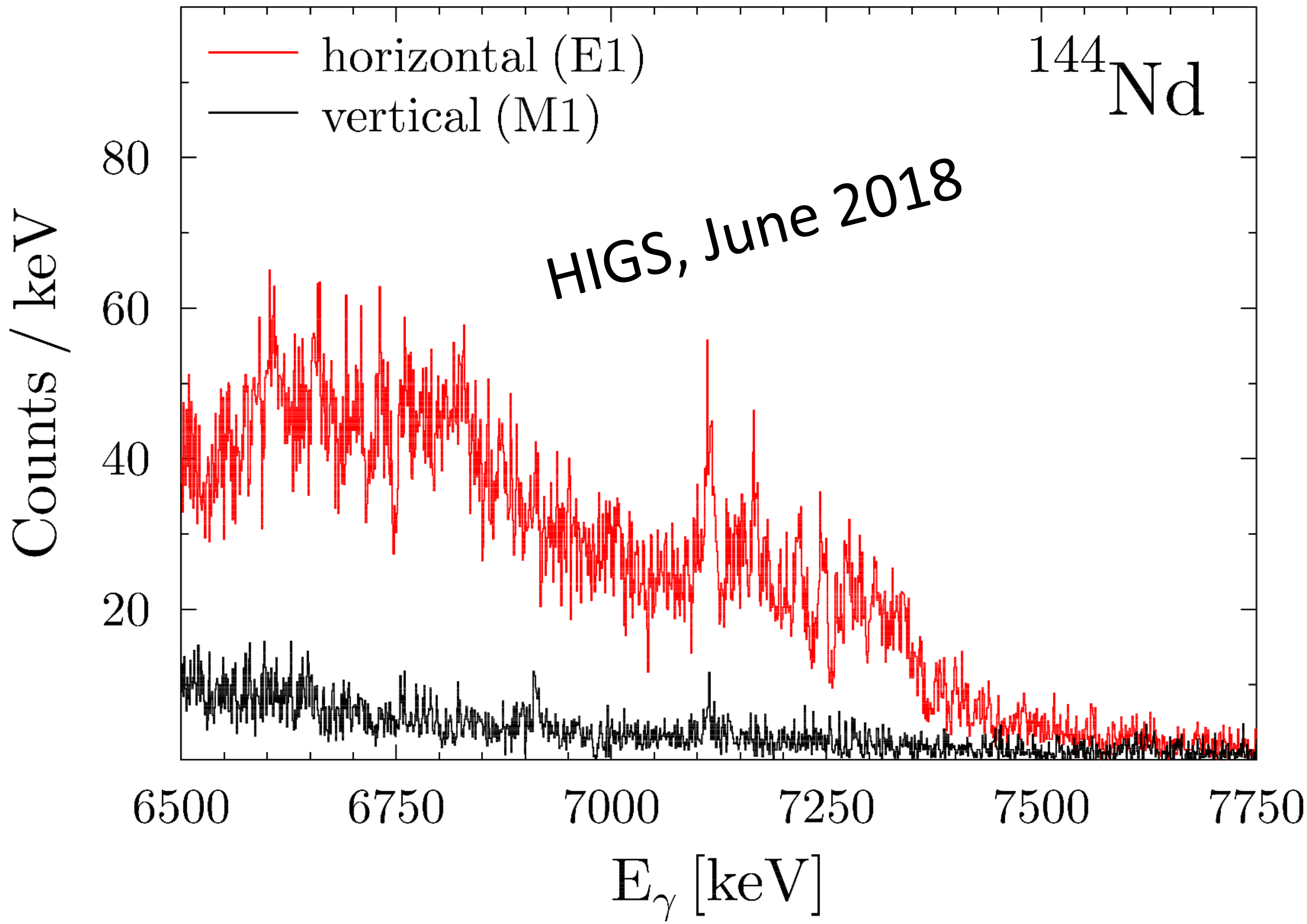


$\propto$ (N·Z)/A

*D. Savran et al., PPNP **70** (2013) 210*

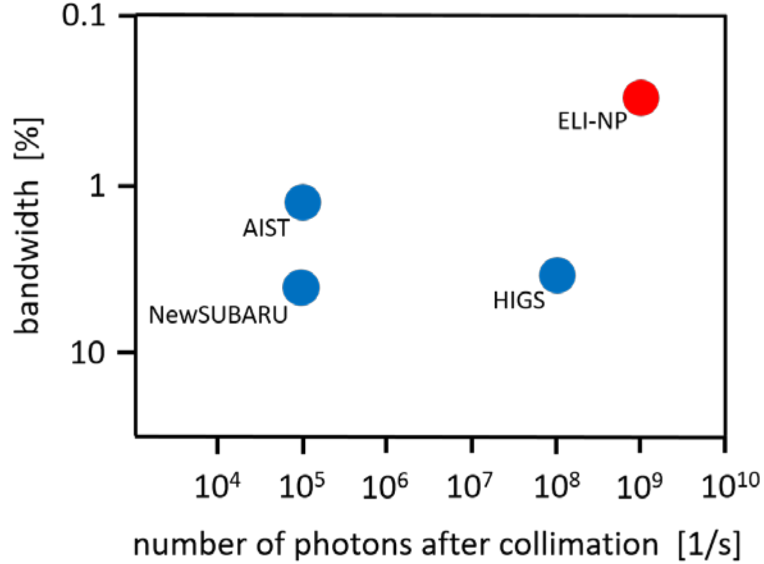
(highly cited paper, top 1% in physics)

PDR away from closed shells: NRF on ^{144}Nd

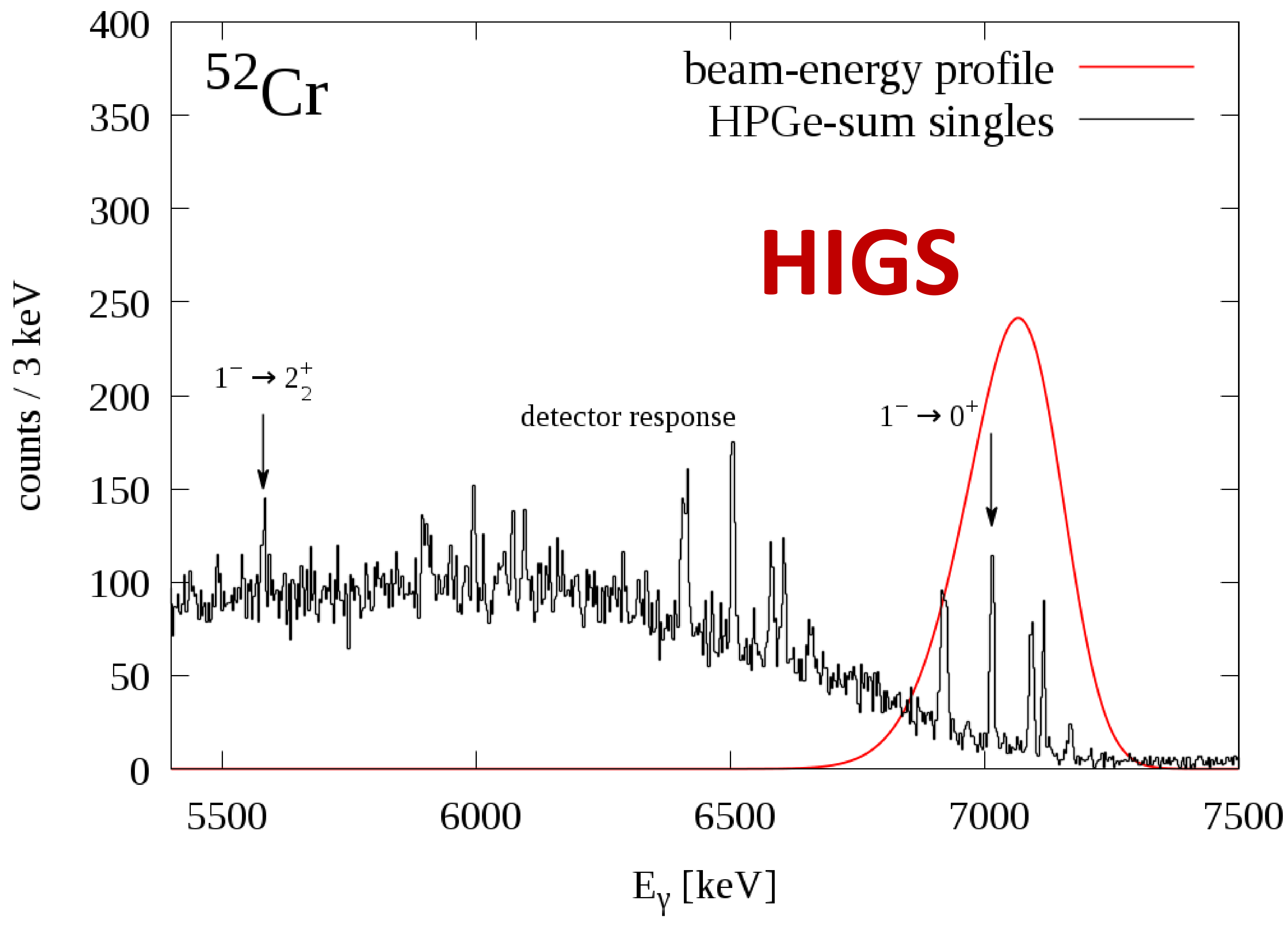


The future of MeV photon sources

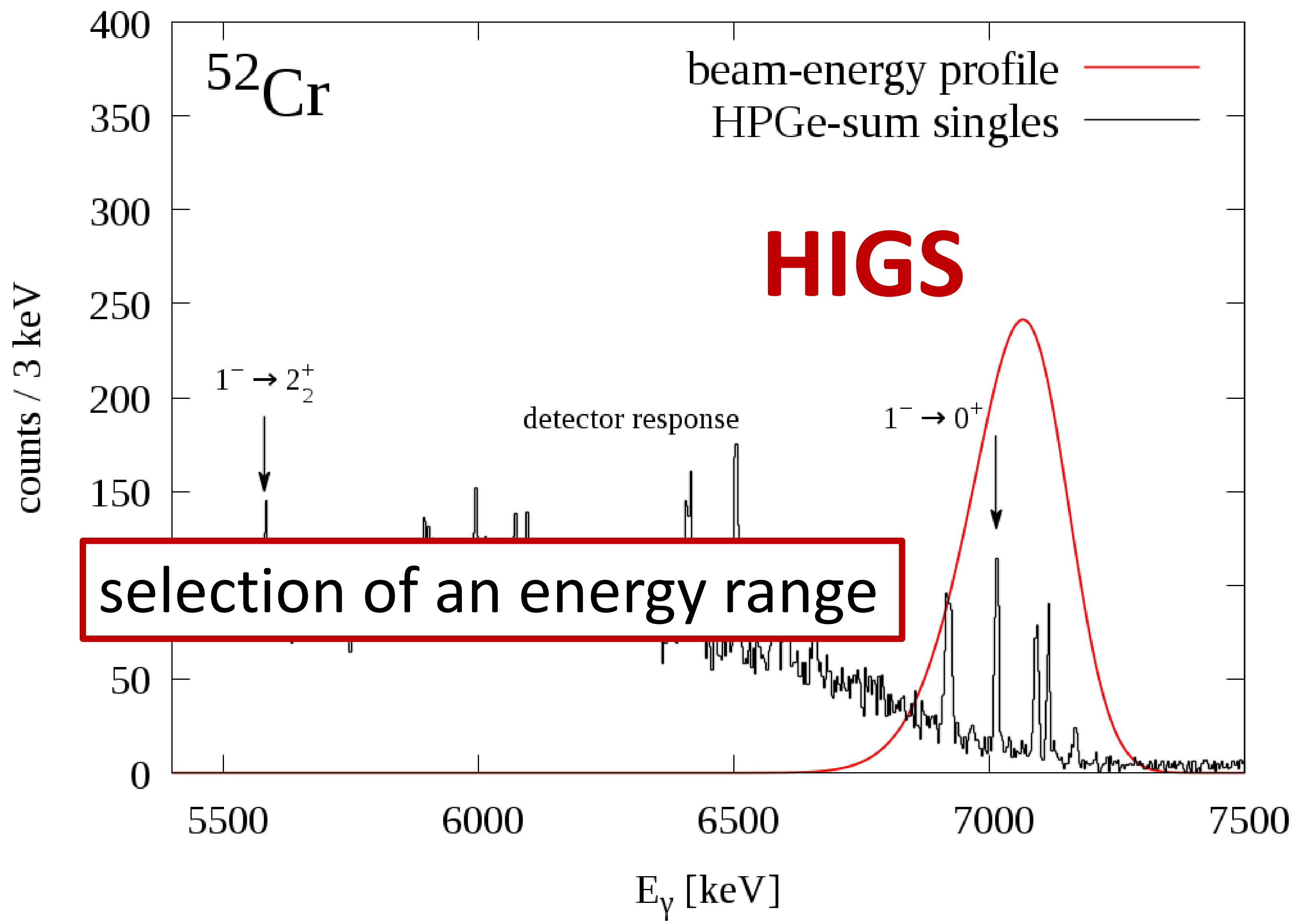
- higher intensity
- smaller bandwidth
- small beam diameter
- sensitive detection of ejectiles
- (tailored γ beams)



Energy profile: ELI-NP vs. HIGS

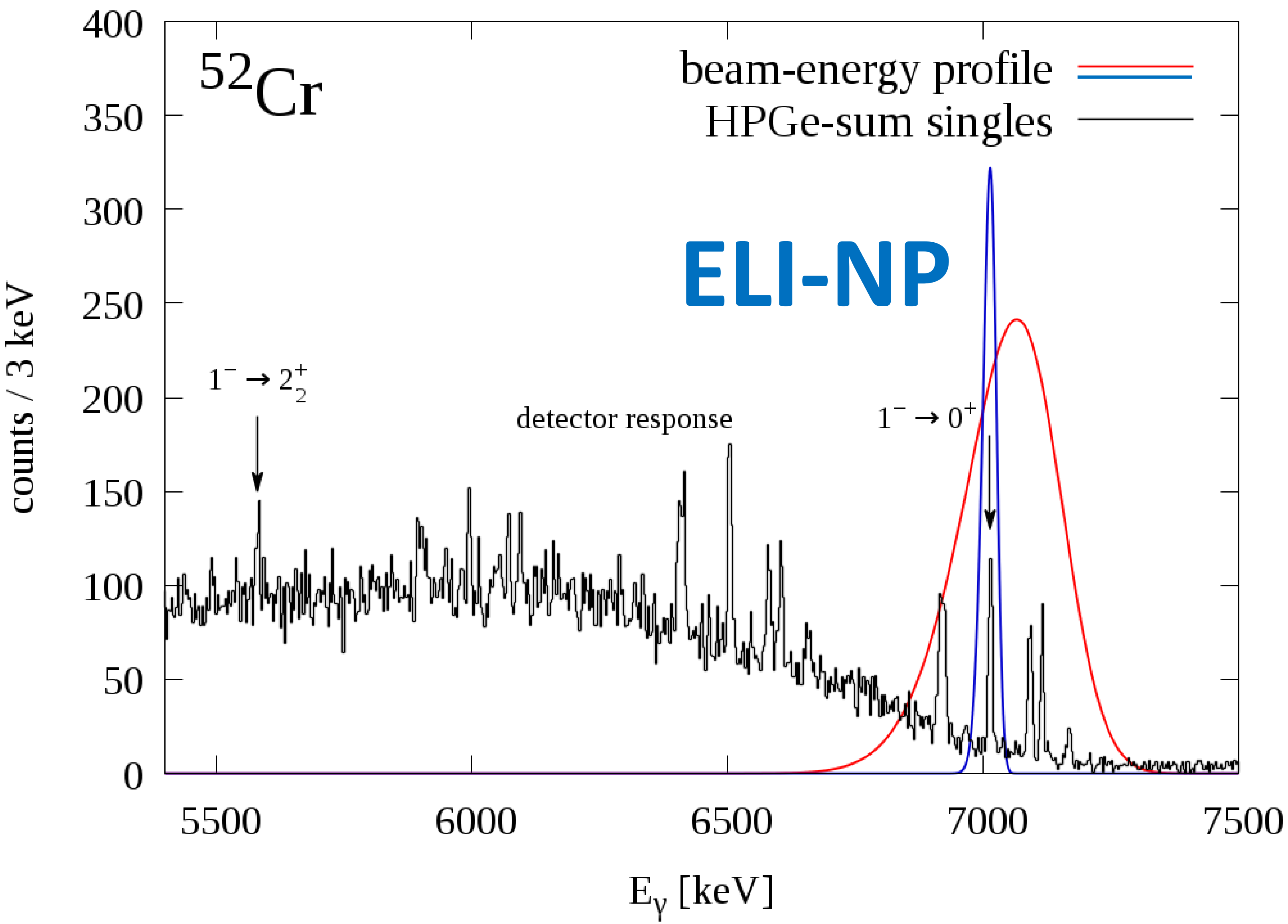


Energy profile: ELI-NP vs. HIGS

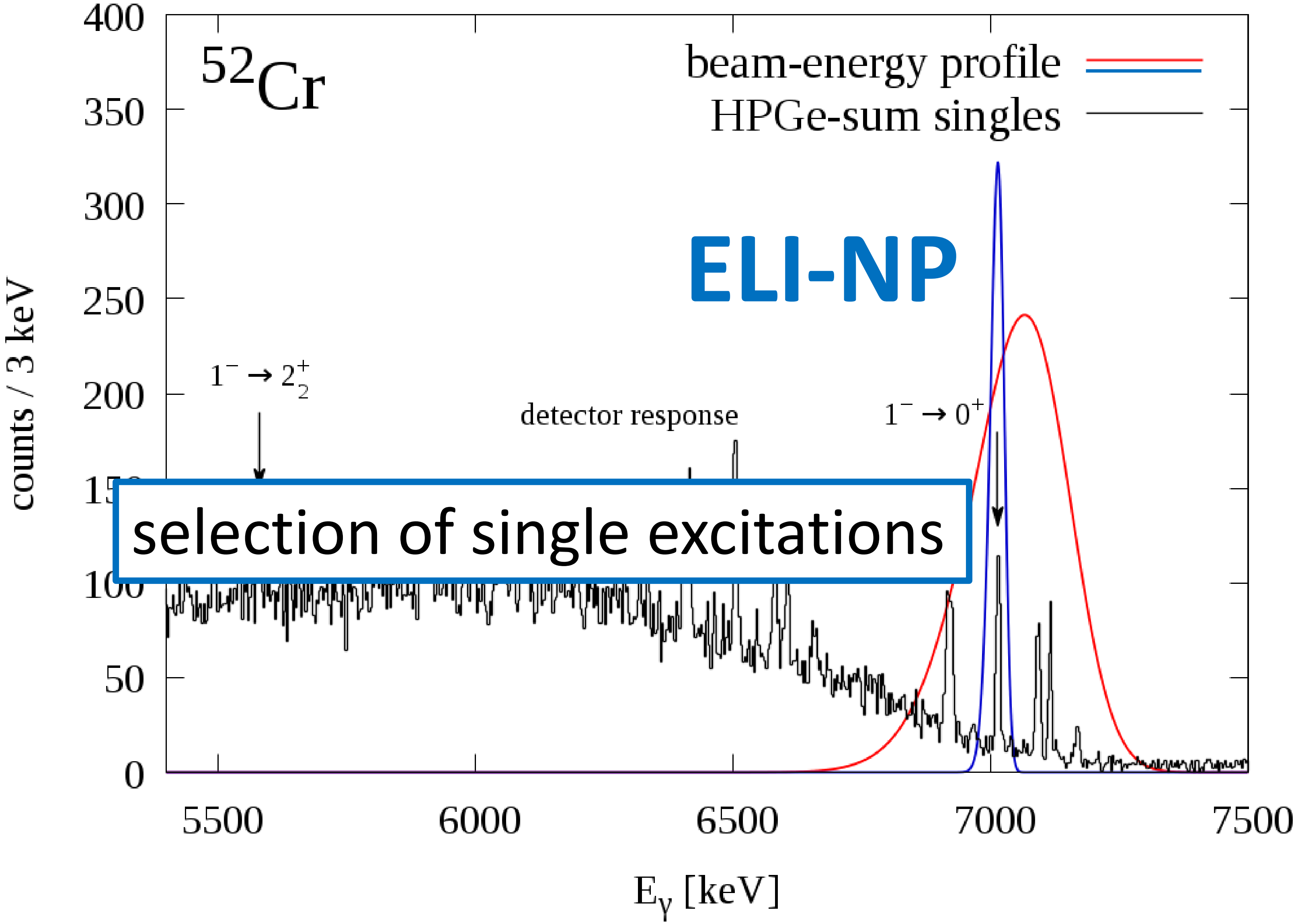


selection of an energy range

Energy profile: ELI-NP vs. HIGS



Energy profile: ELI-NP vs. HIGS



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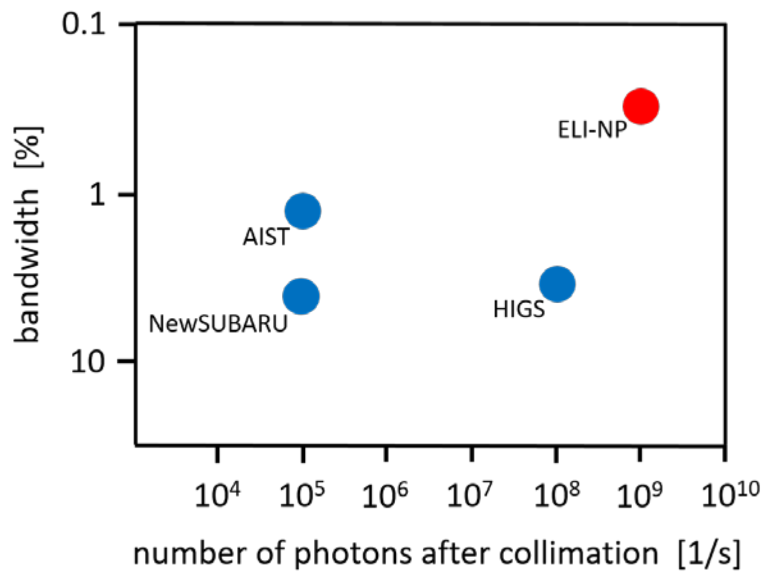

→ Selective manipulation and inspection of single excitations in atomic nuclei

Photonuclear reactions in Brasov

Session 04:
K. Tanaka

Session 05:
C. Howell, D. Savran, V. Werner, N. Tsoneva, J. Isaak

Session 07:
P. von Neumann-Cosel, F. Camara, M. Krzysiek,
O. Gorbachenko, I. Gheorghe

Session 15:
J. Wilhelmy, M. Müscher, U. Gayer, T. Beck

Session 16:
T. Ohgaki, I. Carter

Session 17:
M. Roth

Photonuclear Reactions

Elena Hoemann, Johann Isaak, Miriam Müscher, Simon Pickstone, Norbert Pietralla, **Deniz Savran**, Philipp Scholz, Werner Tornow, Volker Werner, **Julius Wilhelmy**, and A.Z.

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(05P2015 ELI-NP)