Nuclear Photonics – New horizons at ELI-NP

Nuclear Physics

Andreas Zilges
University of Cologne

ICEL • ELI-ALPS Szeged • November 2017

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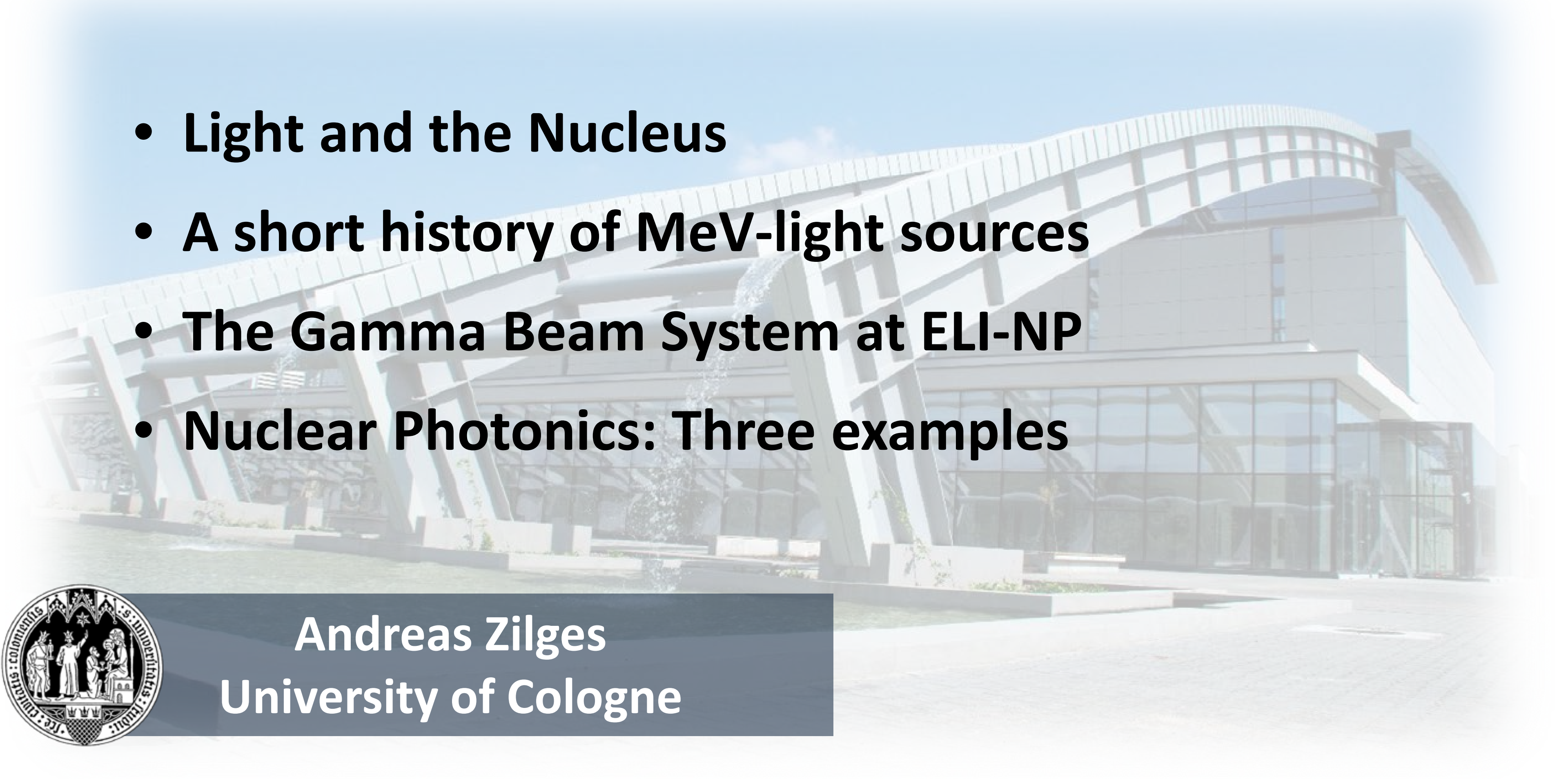

- **Light and the Nucleus**
- **A short history of MeV-light sources**
- **The Gamma Beam System at ELI-NP**
- **Nuclear Photonics: Three examples**

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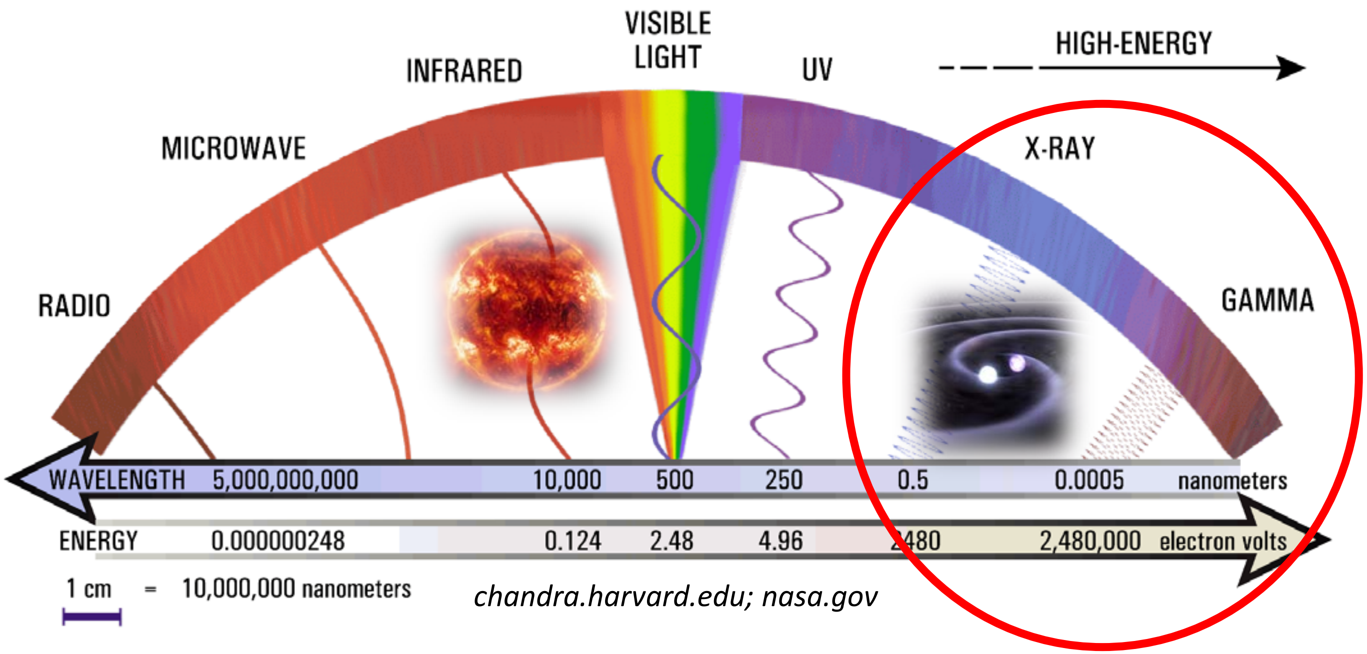
Photons in the MeV range



chandra.harvard.edu; nasa.gov

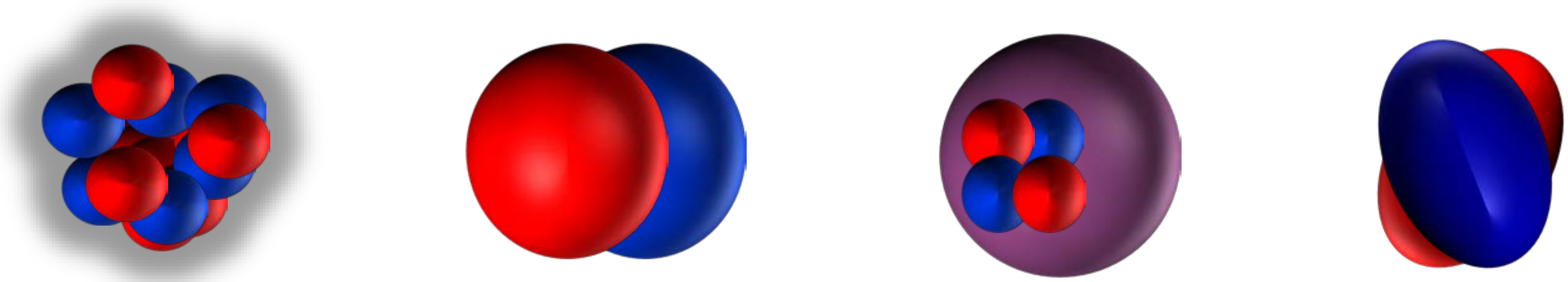
- MeV-photons are abundant in the universe
  (Planck photon bath, e.g., from supernovae, neutron star mergers)

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

Photons in the MeV range

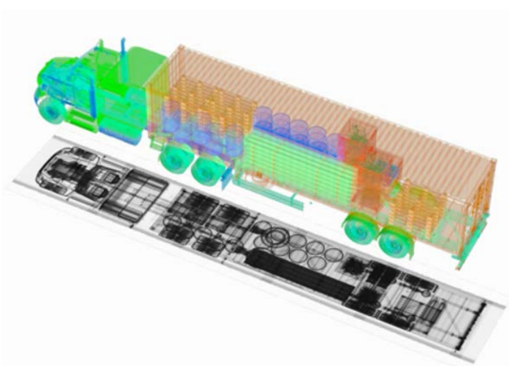
- MeV-photons are complementary to „standard“ probes in nuclear physics and excite nuclei very selectively

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



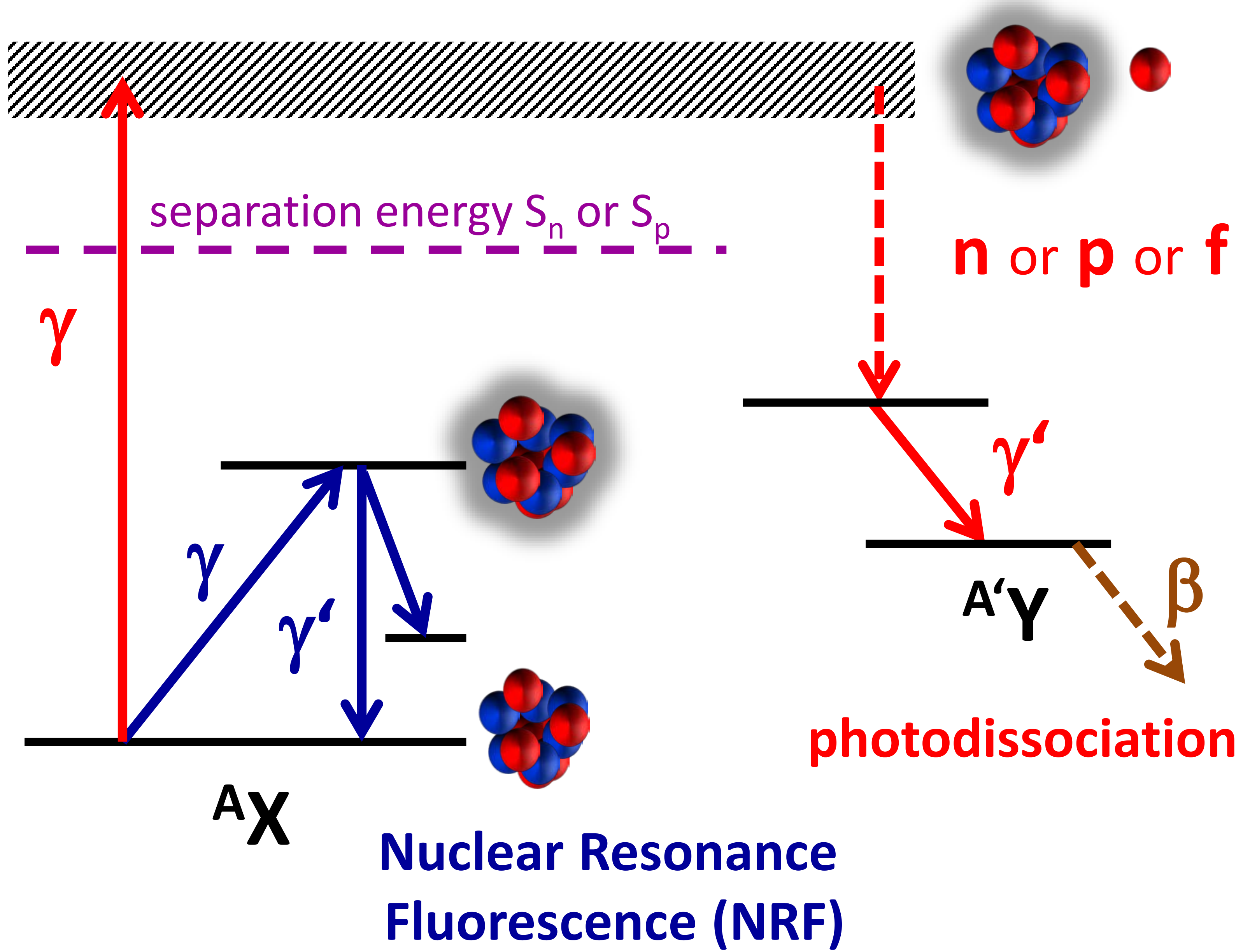
- MeV-photons are very penetrative

  → various applications (e.g. cargo inspection)



www.passportsystems.com

Photonuclear Reactions



Photonuclear Reactions

- pure EM interaction
- spin selectivity (mainly E1, M1, E2 transitions)
- strength selectivity
- **For $E_\gamma < S_n$ and S_p (NRF):**
  derivation of excitation energies, spins, parities, decay energies, level widths, lifetimes, decay branchings, multipole mixing ratios, absolute transition strengths
  completely model independent

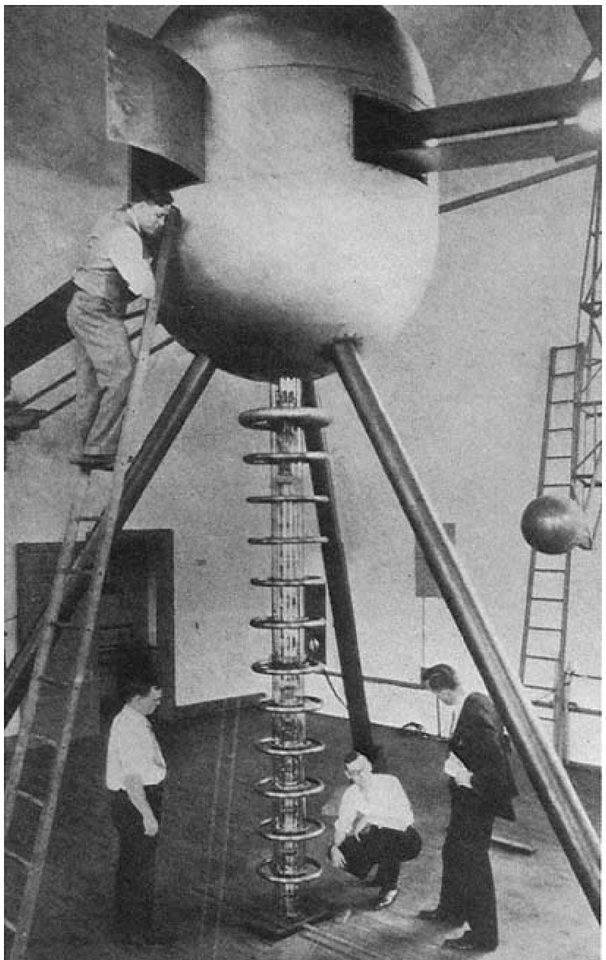
Photons produced in $^{7}Li(p,\gamma)$ reaction

1937:

Atomumwandlungen durch γ-Strahlen.

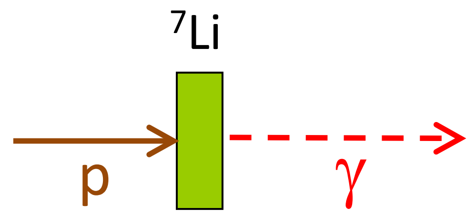
Von **W. Bothe** und **W. Gentner** in Heidelberg.

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



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

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)

1937:

Atomumwandlungen durch γ-Strahlen.

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

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

1944:

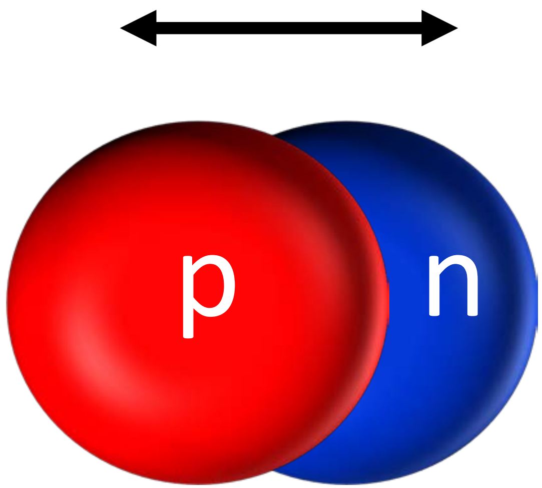
QUADRUPOLE AND DIPOLE γ-RADIATION OF NUCLEI

By **A. MIGDAL**

J. Phys. (USSR) ***8*** *(1944) 331*

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:

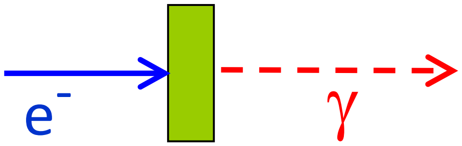
Photo-Fission in Heavy Elements*

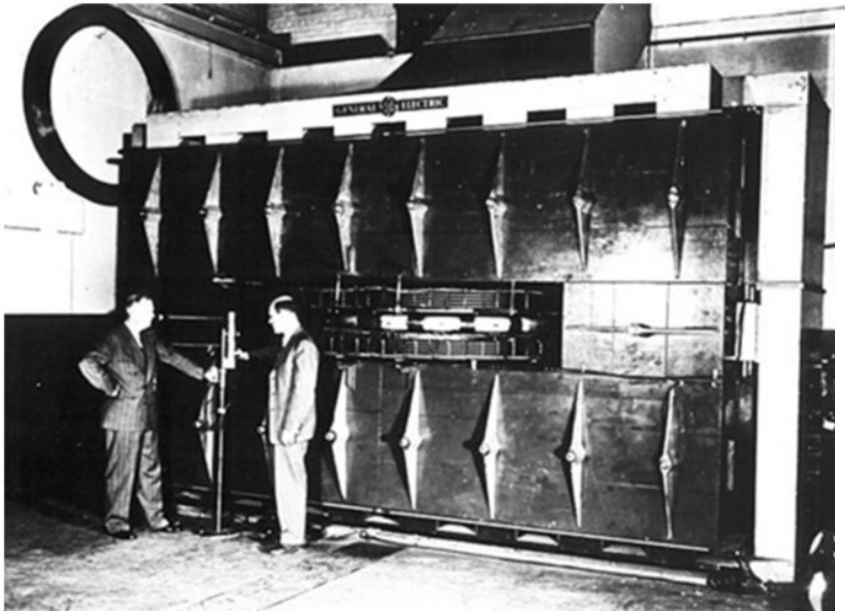
G. C. Baldwin and G. S. Klaiber
Research Laboratory, General Electric Company, Schenectady, New York

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

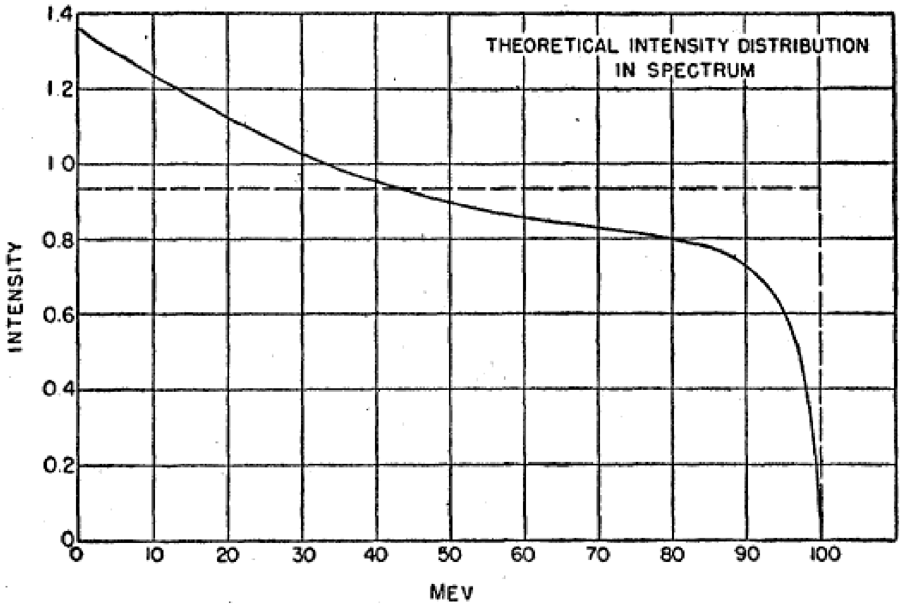
Photon source:

Bremsstrahlung from 100 MeV betatron





From: A.M. Sessler, LBNL



Giant Dipole Resonance (GDR)

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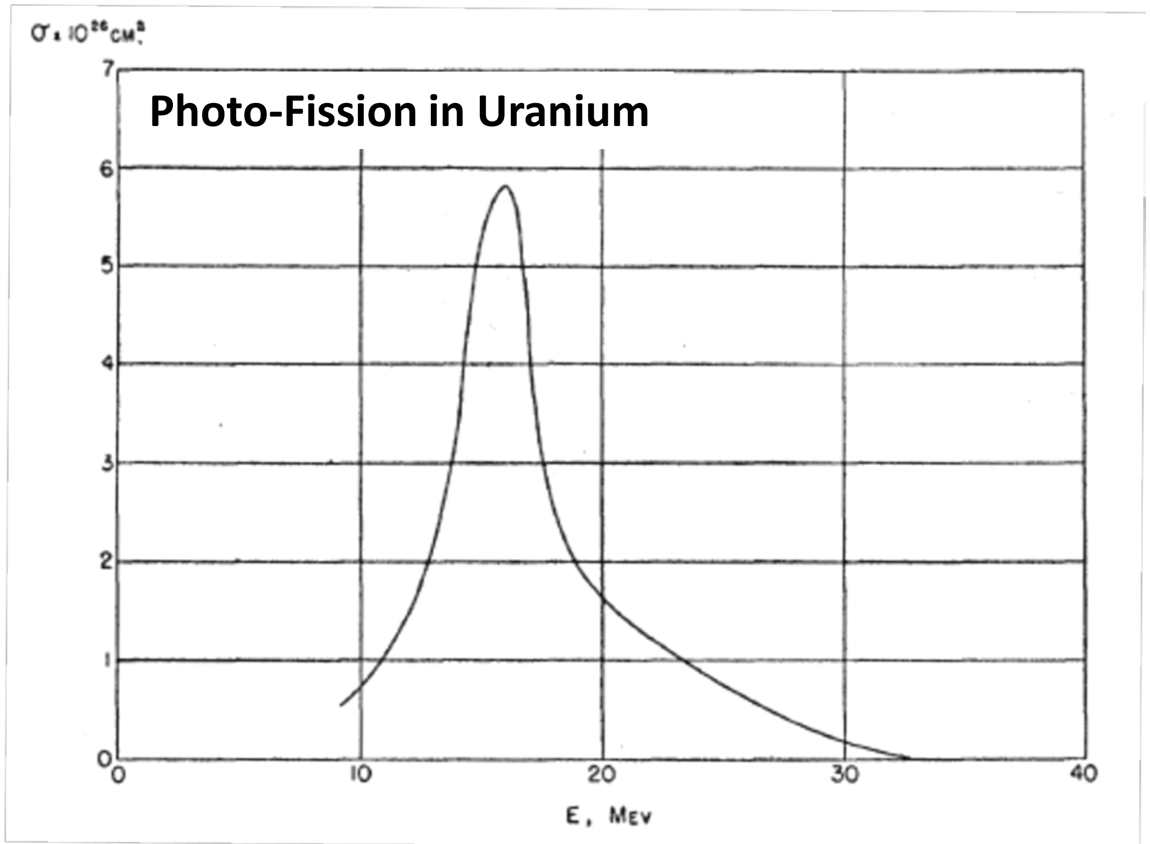
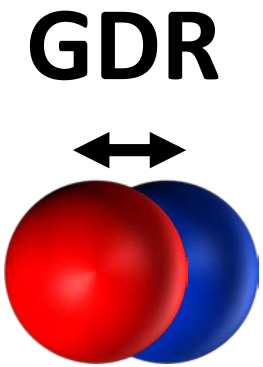
Phys. Rev. ***71*** *(1947) 3*

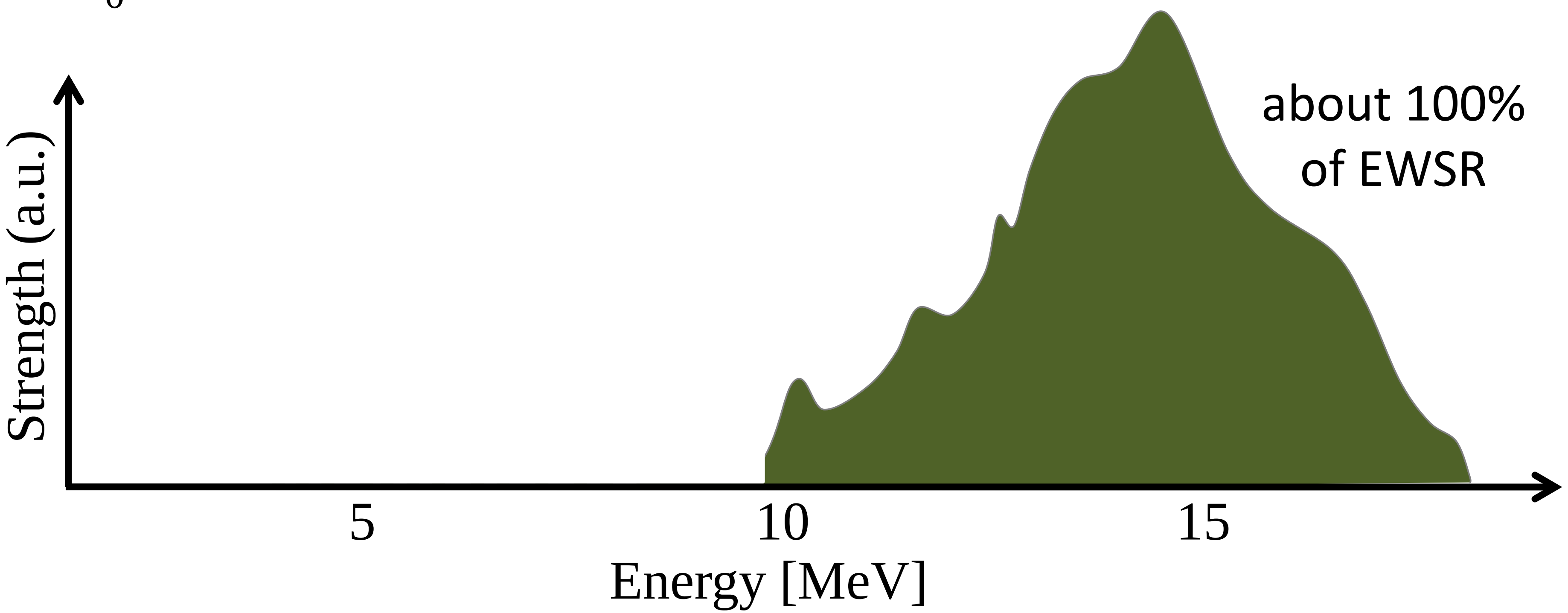


Giant Dipole Resonance (GDR)

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

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





Photons from van de Graaff accelerator for electrons

1969:

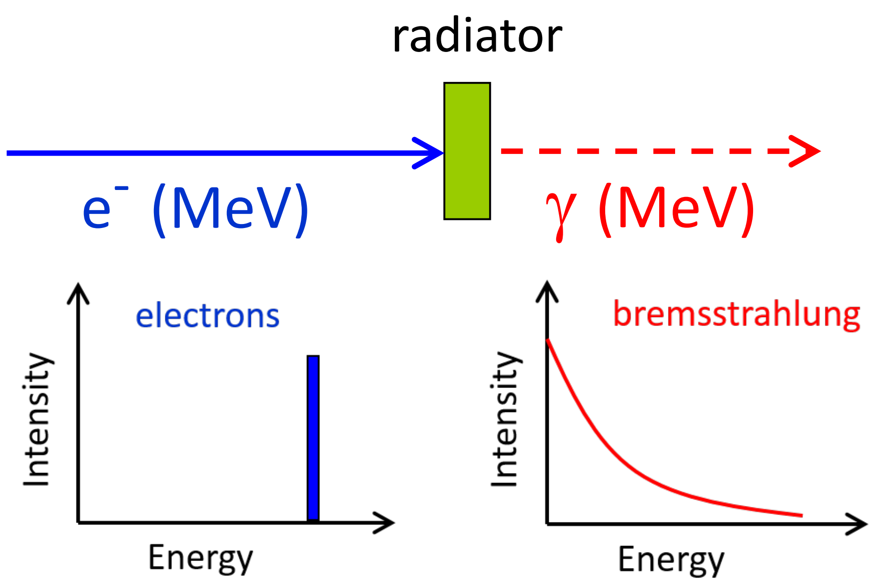
PHYSICAL REVIEW VOLUME 187, NUMBER 4 20 NOVEMBER 1969

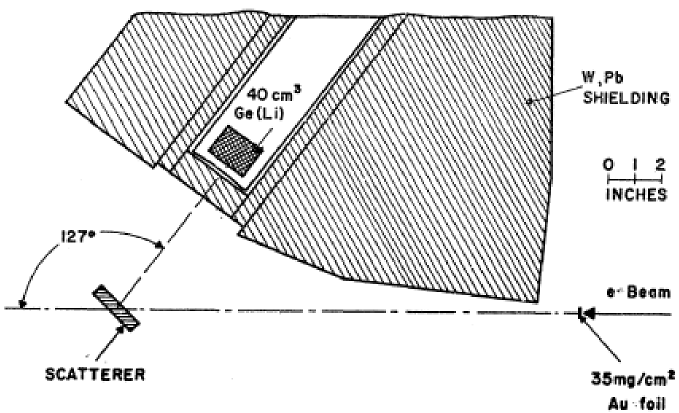
Electric Dipole Transitions from the 2.6-MeV Septuplet in Bi^{209} †

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

(Received 25 June 1969)

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

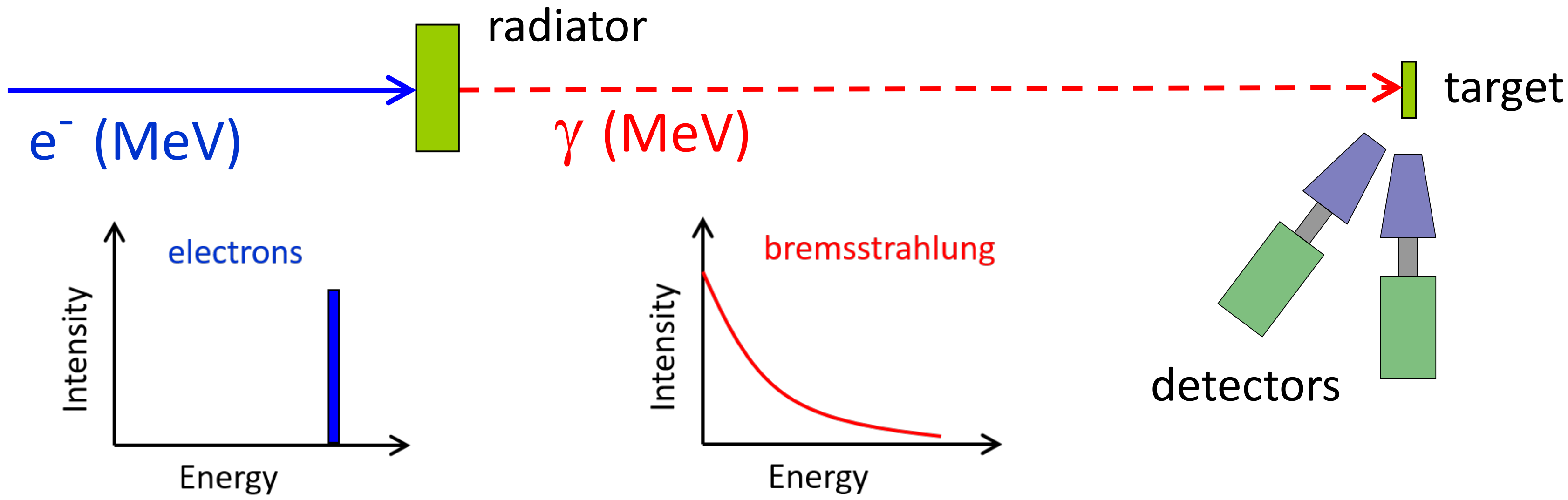


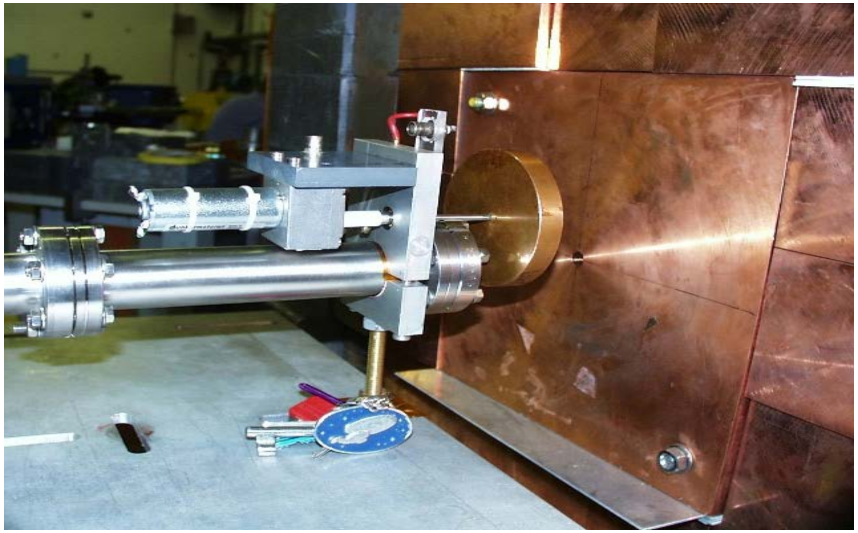


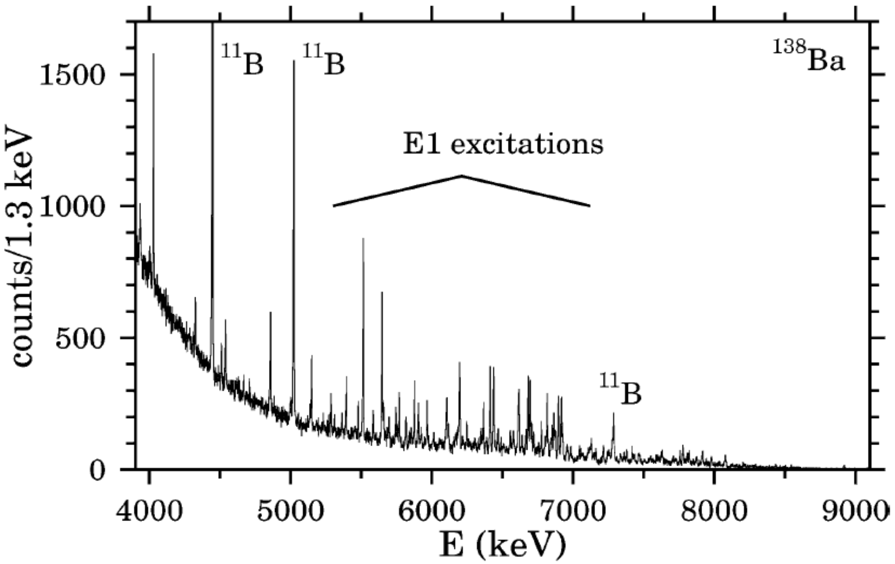
Adjustable bremsstrahlung endpoint energy up to a few MeV

High resolution Nuclear Resonance Fluorescence (NRF)

1980s, 1990s:

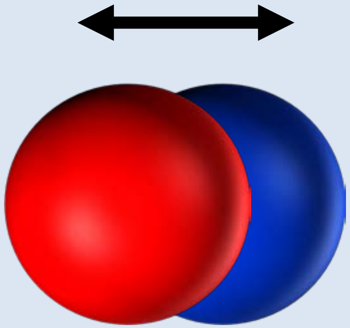




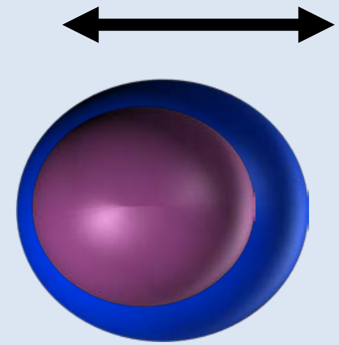


*Review: U. Kneissl, H.H. Pitz, and A.Z., PPNP **37** (1996) 349*

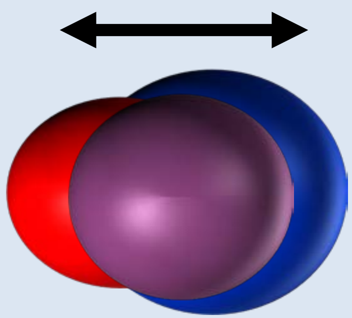
Sources for E1 moments in nuclei



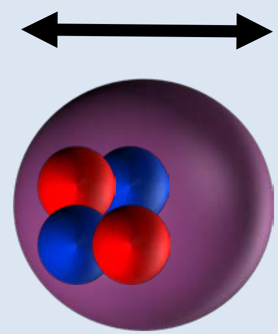
Giant Dipole Resonance (GDR)



Pygmy Dipole Resonance (PDR)

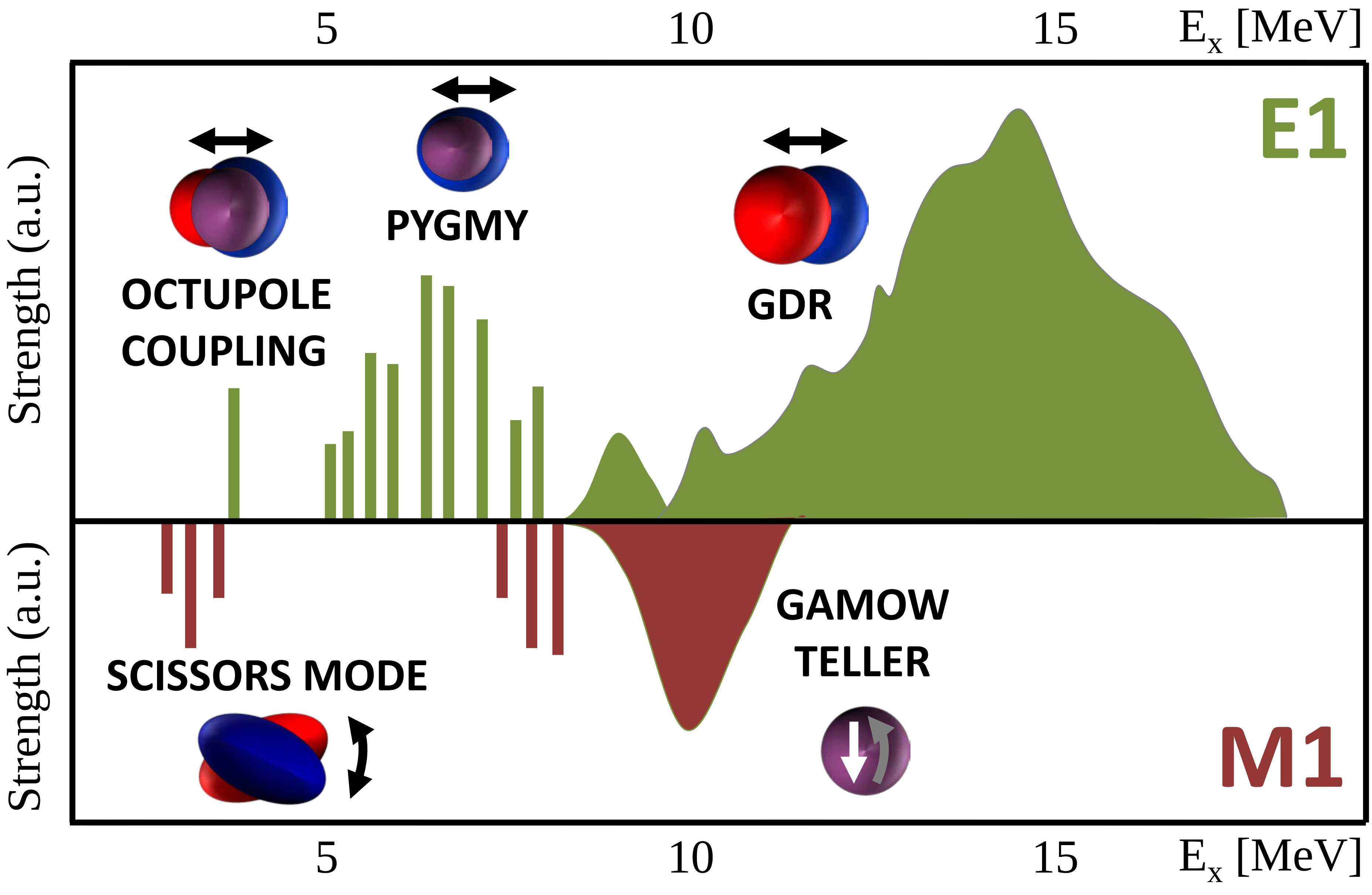


Octupole Coupling



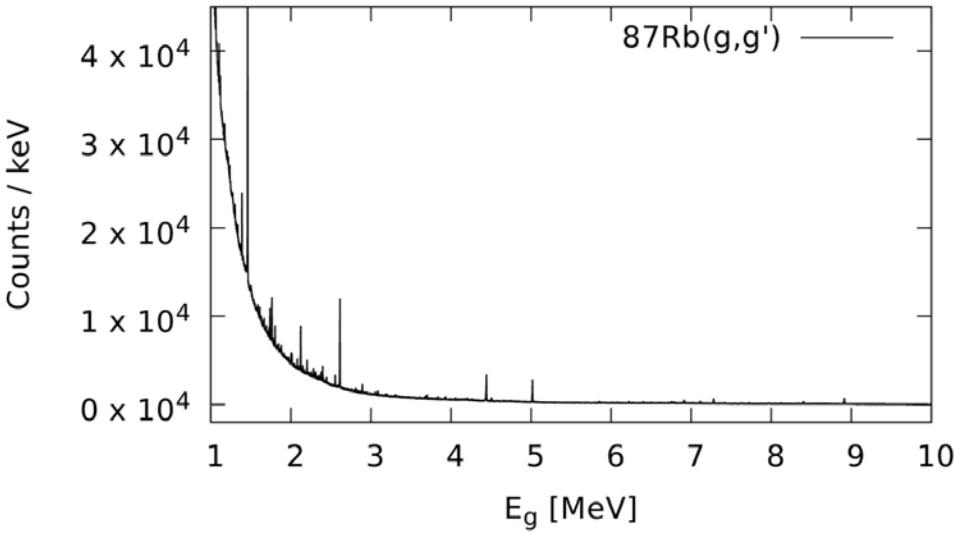
Alpha-Clustering

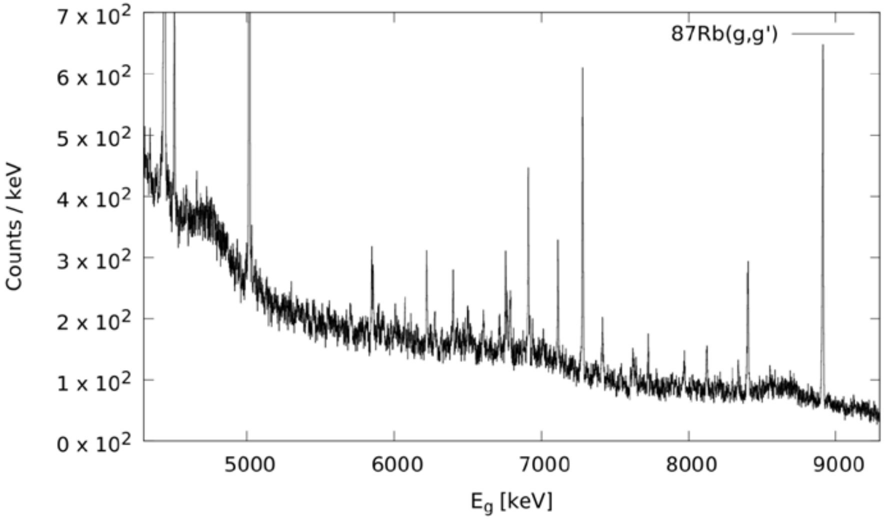
Dipole photoresponse of atomic nuclei



Limitations using bremsstrahlung

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





Photons from positron annihilation in flight

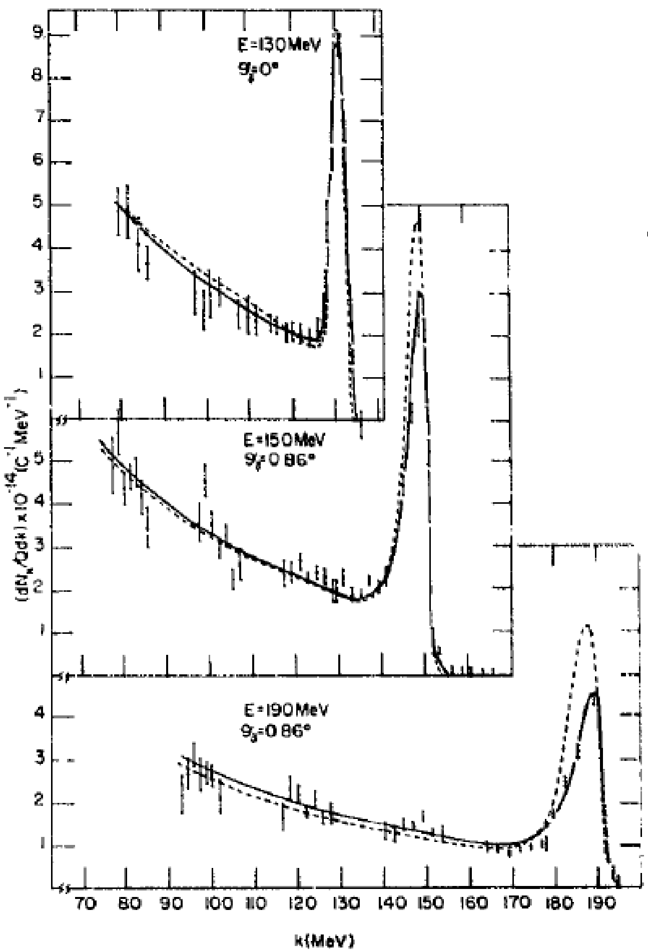
1953:

PHYSICAL REVIEW VOLUME 89, NUMBER 4 FEBRUARY 15, 1953

Electron-Positron Annihilation in Flight

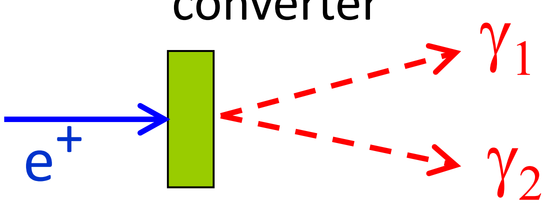
S. A. Colgate and F. C. Gilbert
Radiation Laboratory, Department of Physics, University of California, Berkeley, California

(Received November 4, 1952)



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

Photon source:



but: rather small cross section and background by bremsstrahlung

Tagged photons from electron bremsstrahlung

1982:

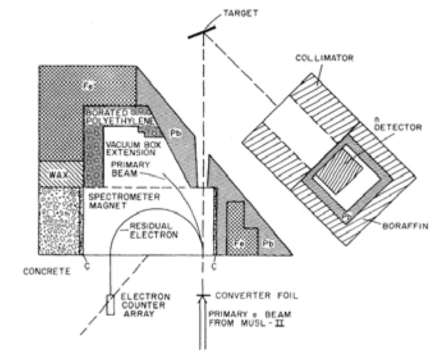
A HIGH RESOLUTION BREMSSTRAHLUNG MONOCHROMATOR FOR PHOTO-NUCLEAR EXPERIMENTS

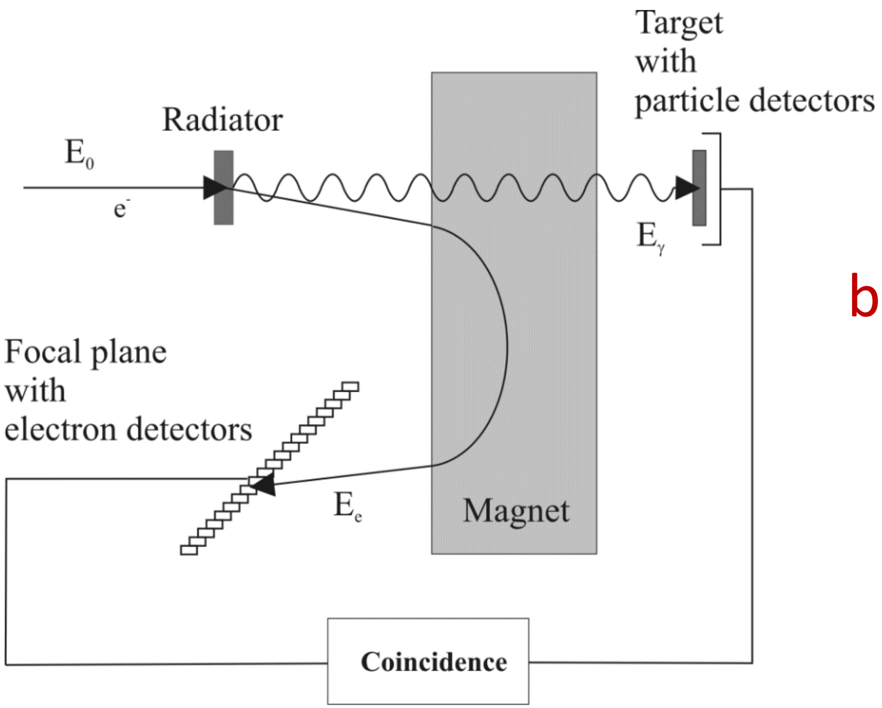
J.W. KNOWLES, W.F. MILLS, R.N. KING, G.E. LEE-WHITING
Atomic Energy of Canada Limited, Chalk River Nuclear Laboratories, Chalk River, Ontario, Canada K0J 1J0

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*

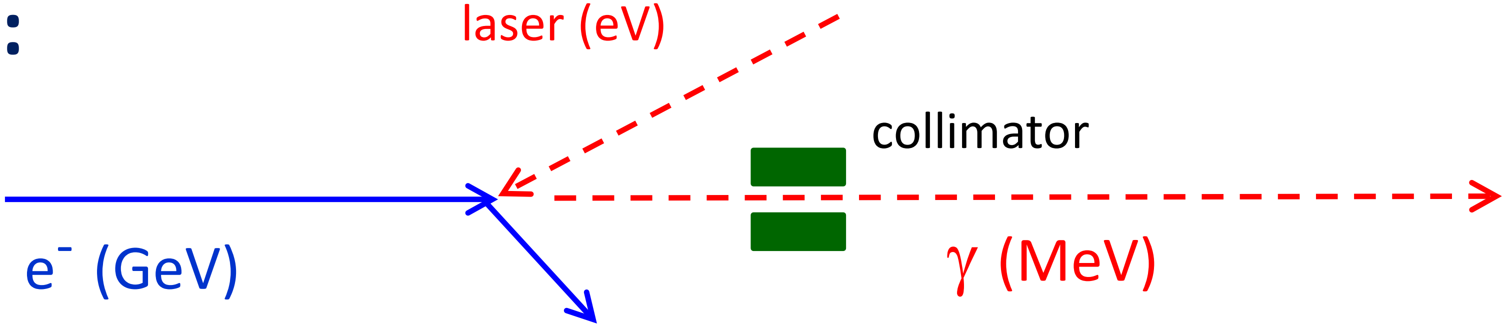




but: rather low photon intensities

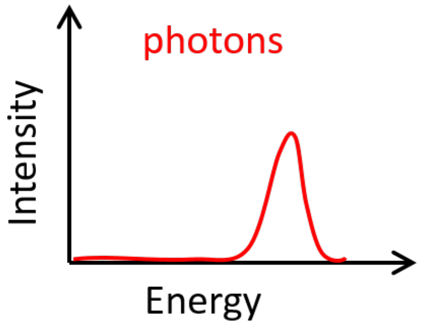
Photons from Laser Compton Backscattering (LCB)

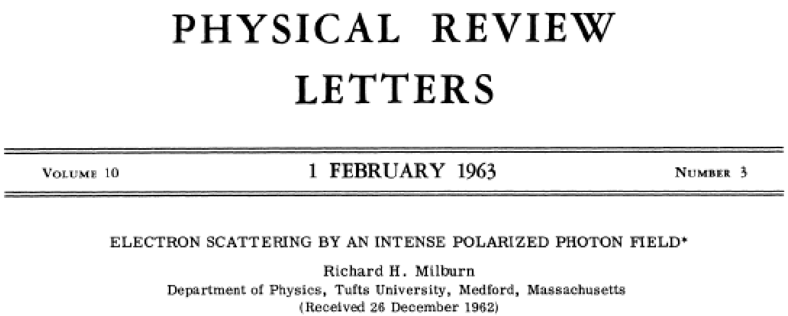
1963:



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

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





PHYSICAL REVIEW LETTERS

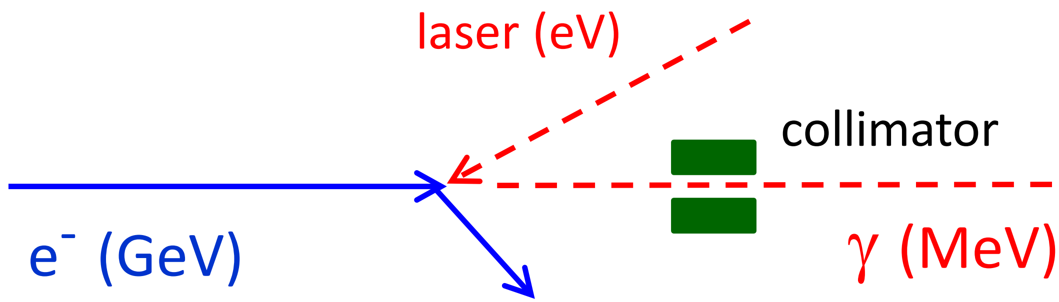
VOLUME 10 | 1 FEBRUARY 1963 | NUMBER 3

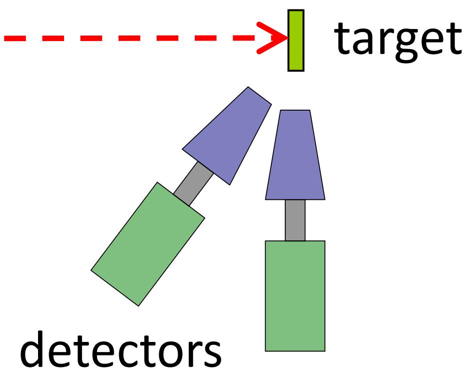
ELECTRON SCATTERING BY AN INTENSE POLARIZED PHOTON FIELD*

Richard H. Milburn
Department of Physics, Tufts University, Medford, Massachusetts
(Received 26 December 1962)

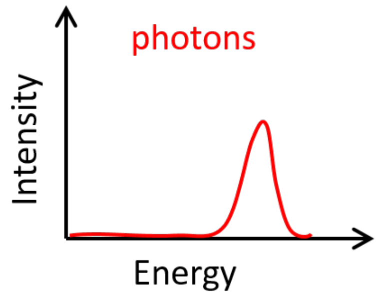
R.H. Milburn, PRL 10 (1963) 75

NRF and Laser Compton Backscattering





Examples:
HIGS at TUNL (USA)
NewSUBARU (Japan)



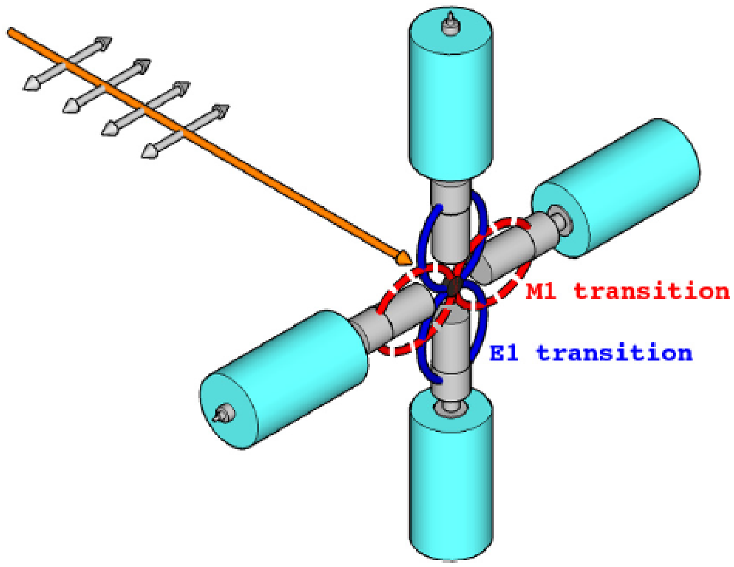
- ”monoenergetic“ photon beam
- tunable energy
- polarized beam

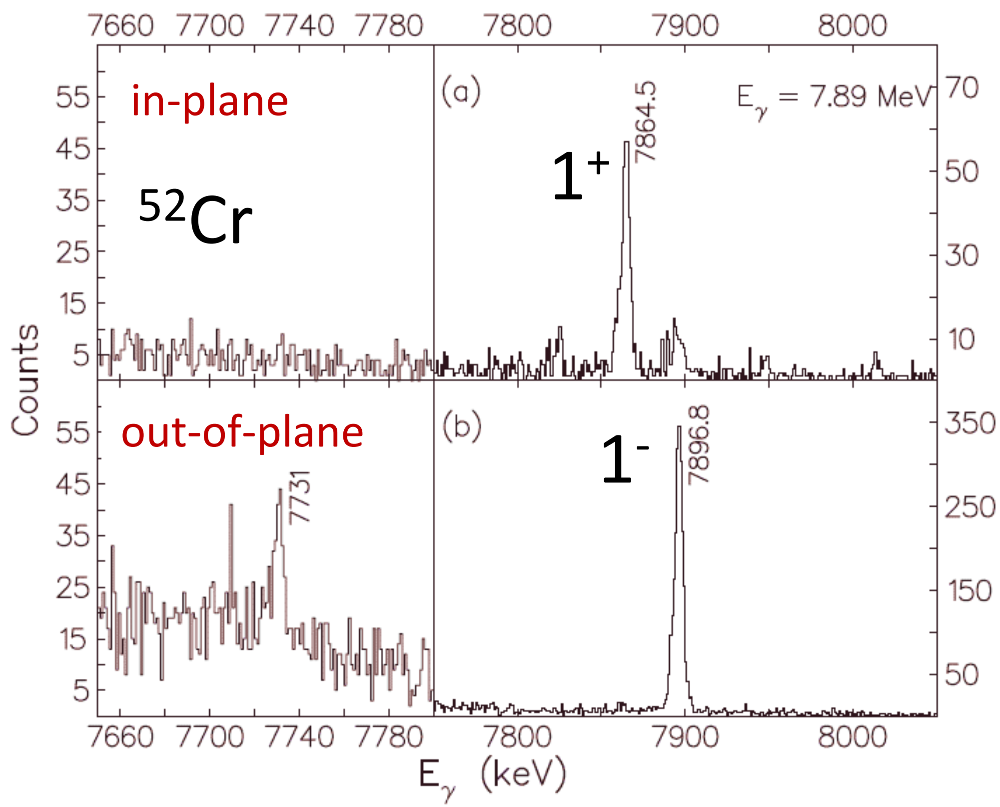
→ Nuclear Photonics

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

A polarized MeV photon beam

Parity determination by measuring asymmetries

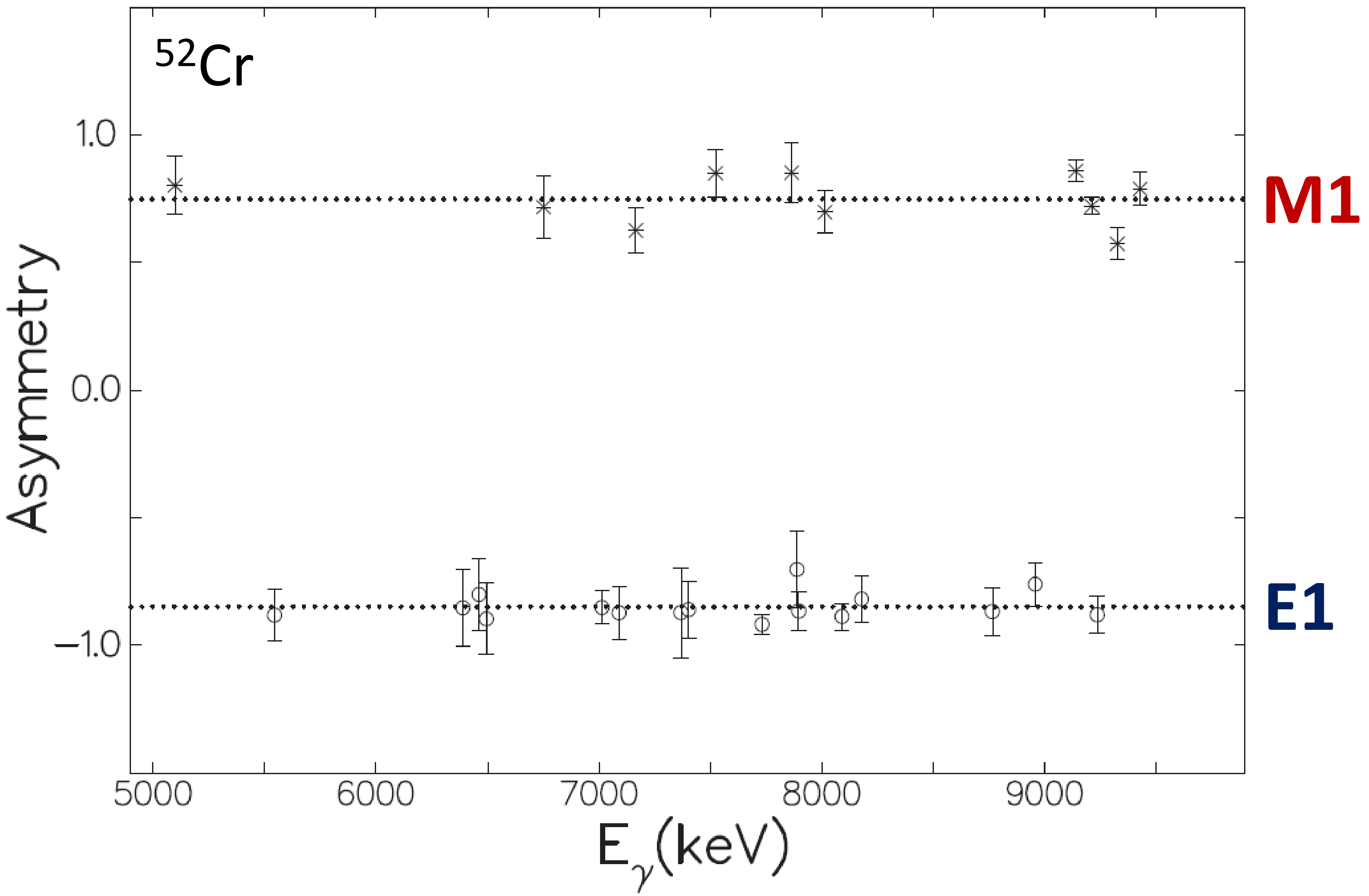




*J. Beller et al., PLB **741** (2015) 128*

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

A polarized MeV photon beam



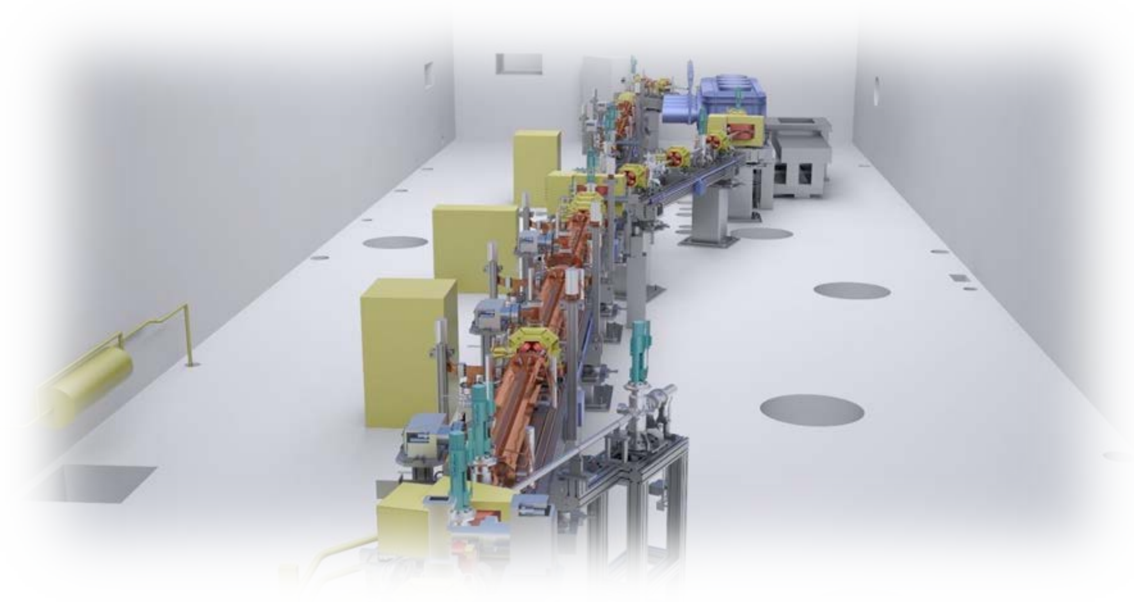
*Krishichayan et al., PRC **91** (2015) 044328*

The MeV photon beam at ELI-NP

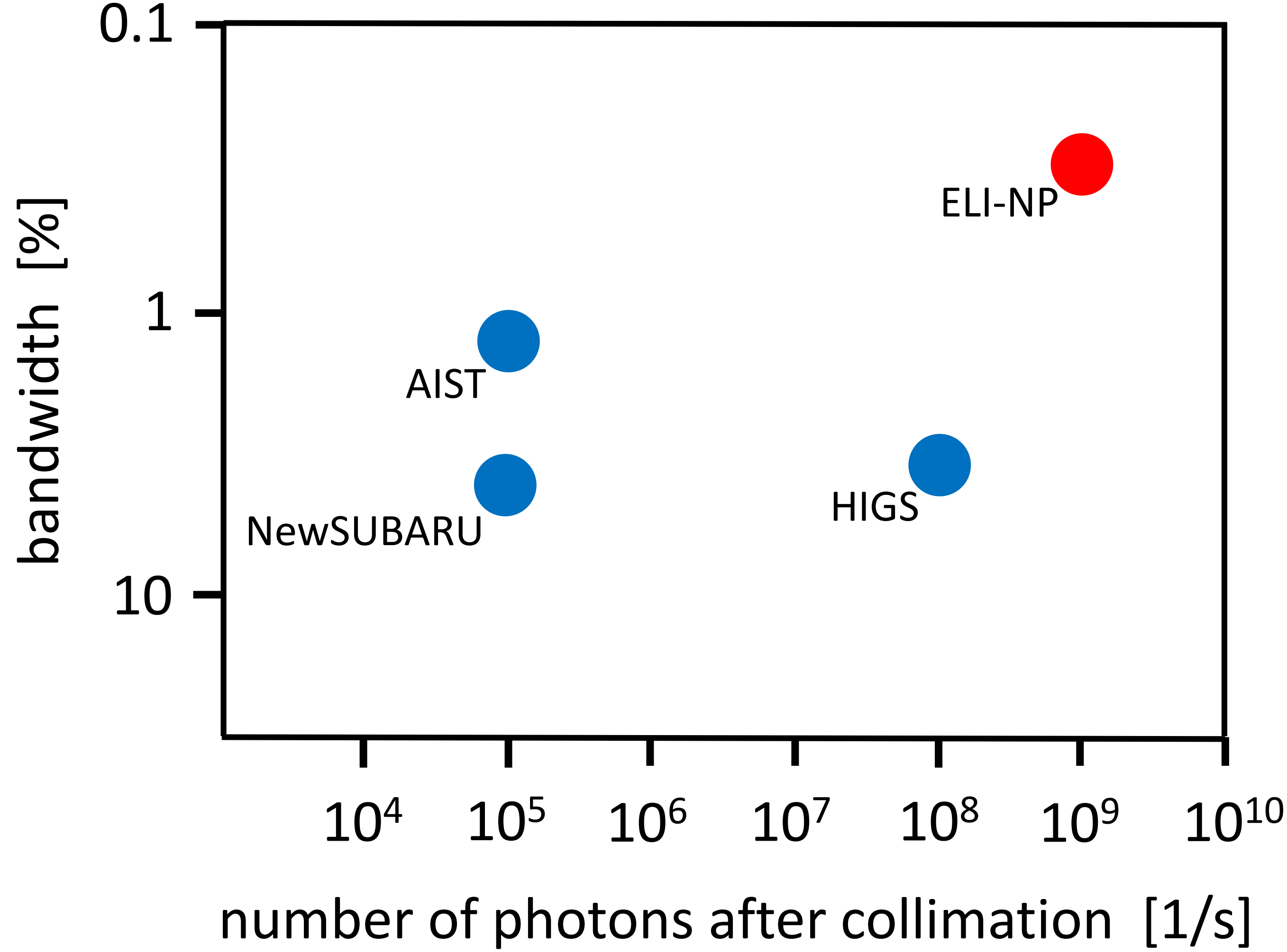
status report ELI-NP:
Kazuo Tanaka, 16:30

The MeV photon beam at ELI-NP

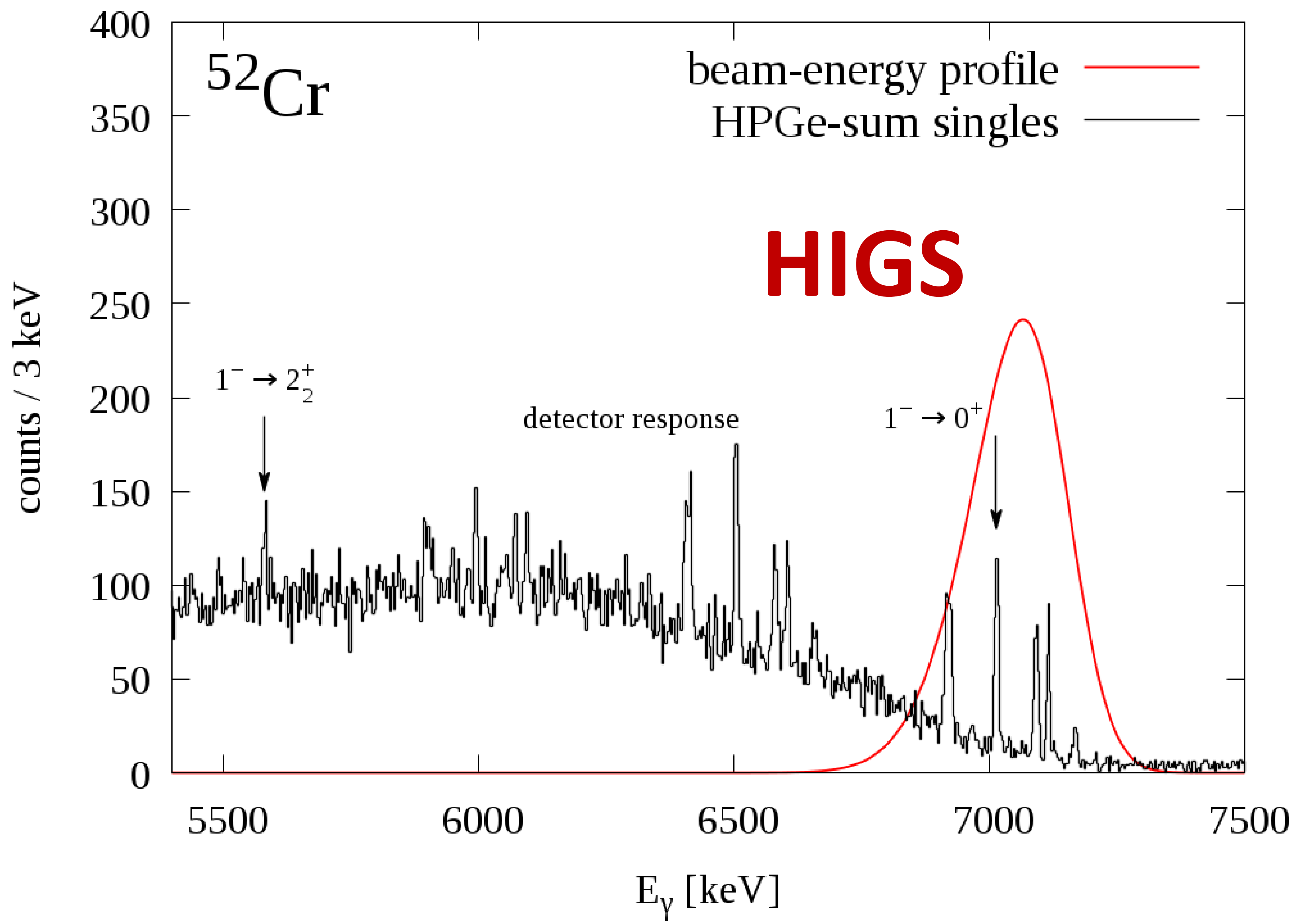
- energy range 0.2 - 19.5 MeV (HIGS: 1 - 95 MeV)
- very high intensity > 10^4 γ/(s·eV) (HIGS: 10^2 γ/(s·eV))
- narrow bandwidth down to 0.5% (HIGS: 3%)
- small beam diameter in mm range (HIGS: cm range)
- high degree of polarization > 95% (HIGS: > 99%)



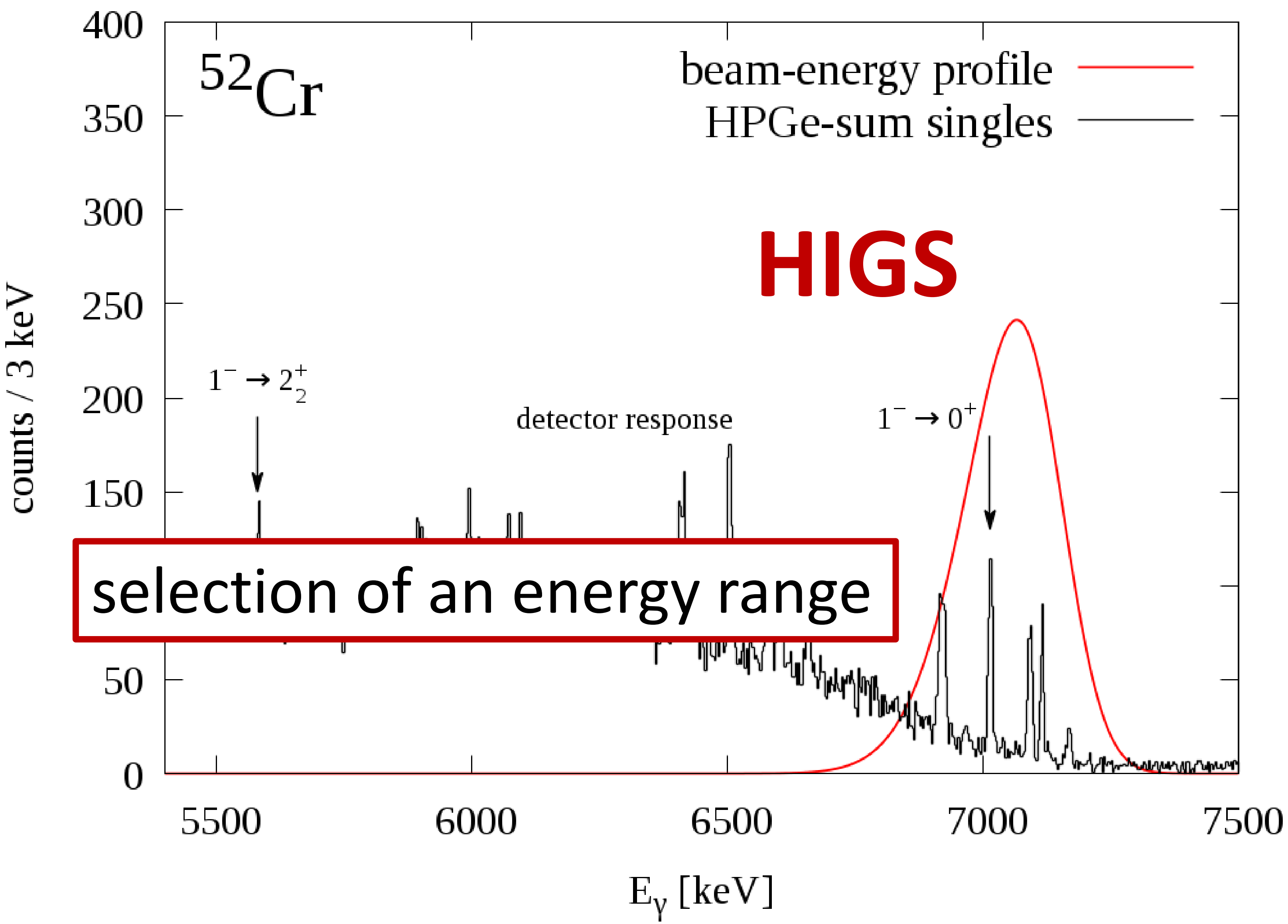
MeV photon beams worldwide



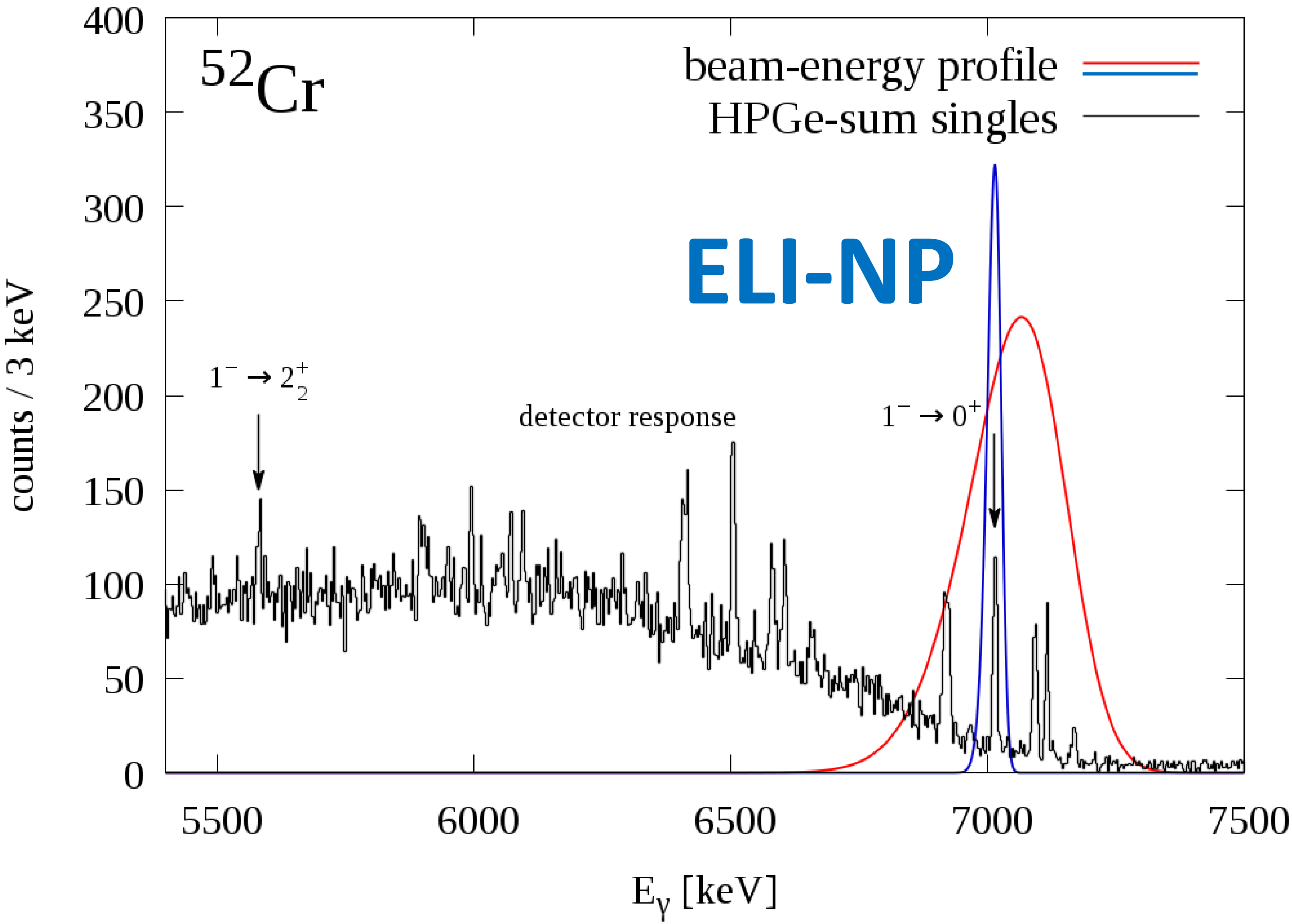
Energy profile: ELI-NP vs. HIGS



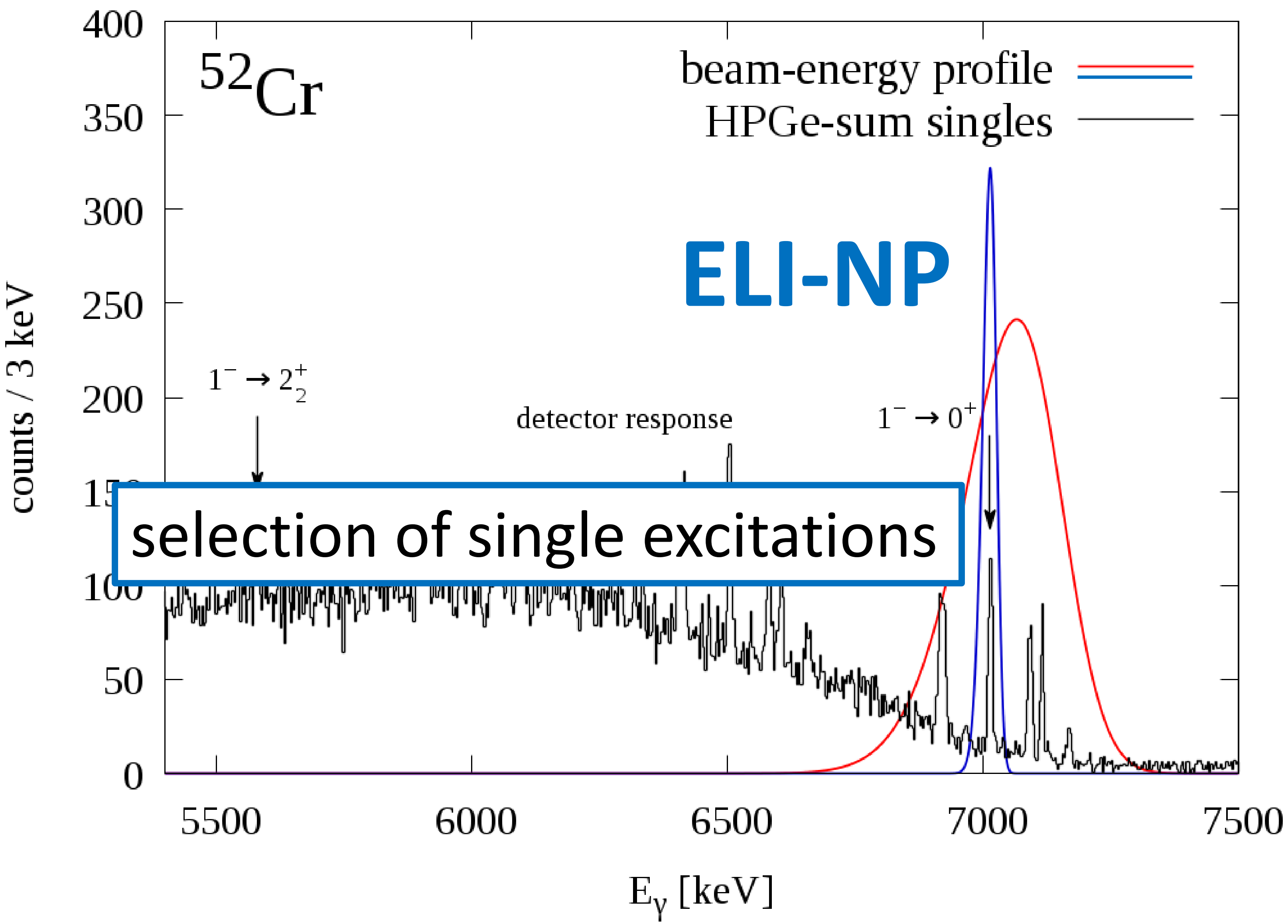
Energy profile: ELI-NP vs. HIGS



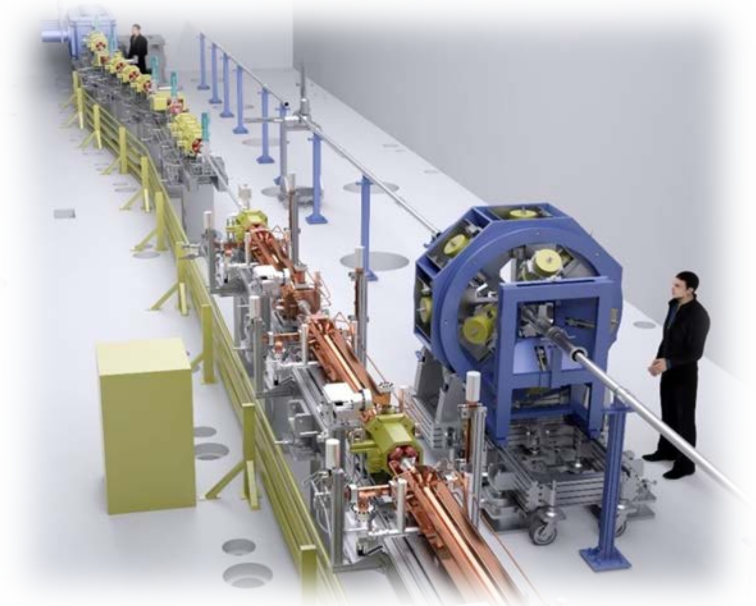
Energy profile: ELI-NP vs. HIGS



Energy profile: ELI-NP vs. HIGS



Nuclear Resonance Fluorescence at ELI-NP: Sensitive γ detection with ELIADE



- 8 segmented HPGe Clover detectors @ 90° and 135°, $\varepsilon_{total} \cong 6\%$ @ 1.3 MeV
- 4 $LaBr_3$ detectors @ 90° or 4 additional HPGe Clover

→ Selective excitation

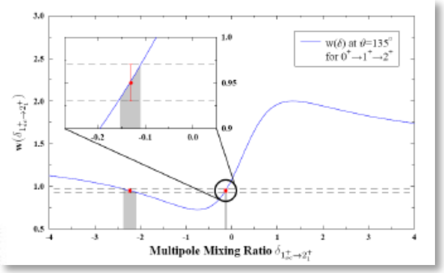
plus

sensitive detection

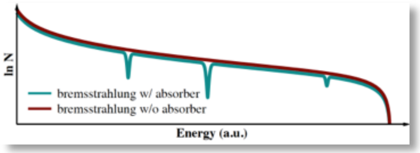
Discovery frontiers for NRF at ELI-NP

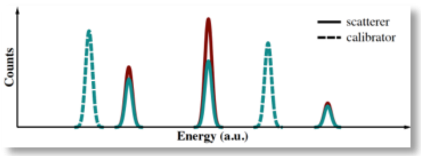
Availability frontier
(access to rare isotopes)

Sensitivity frontier
(weak channels)

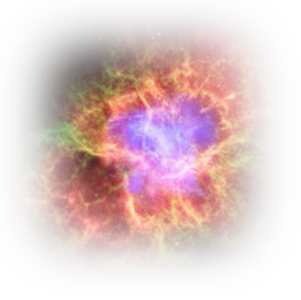


Precision frontier
(high statistics)

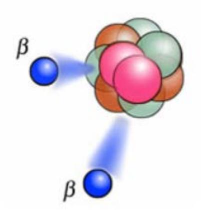




Three physics cases for day-one experiments



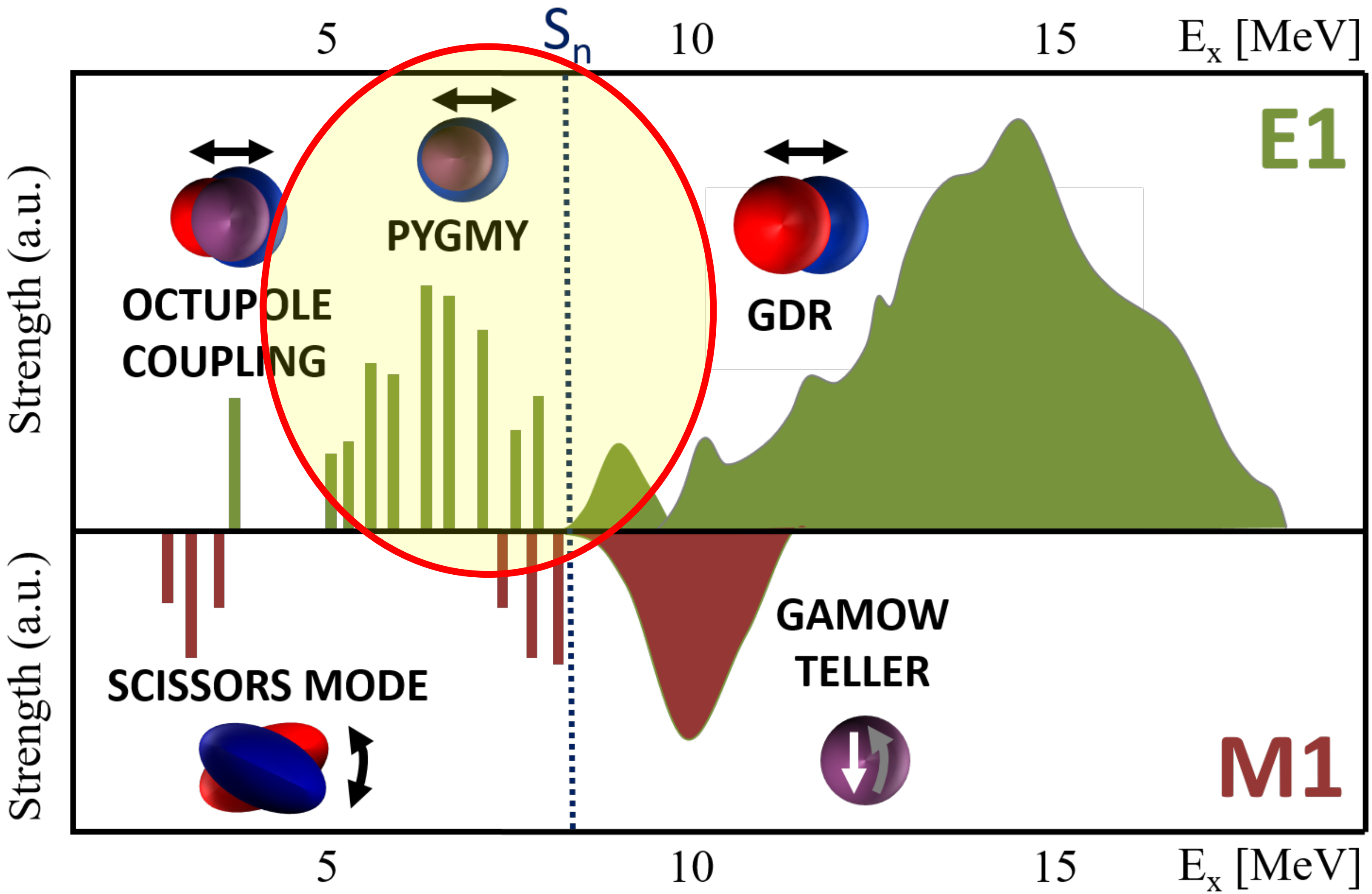
What is the equation of state of nuclear matter and of neutron stars?



Are there new boundary conditions to the neutrinoless double-beta decay?

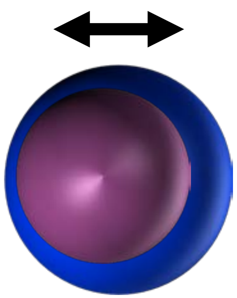
How do nuclear excitations violate parity?

An access to the equation of state and to neutron-rich matter: The Pygmy Dipole Resonance



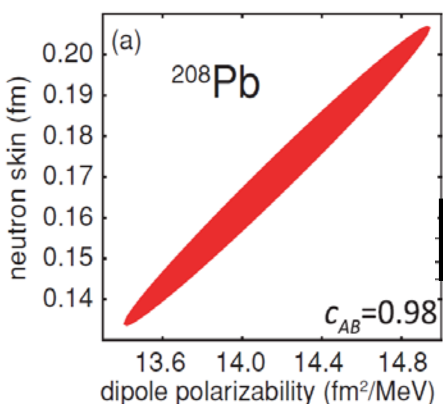
D. Savran, T. Aumann, and A. Zilges, Prog. Part. Nucl Phys. ***70*** *(2013) 210*

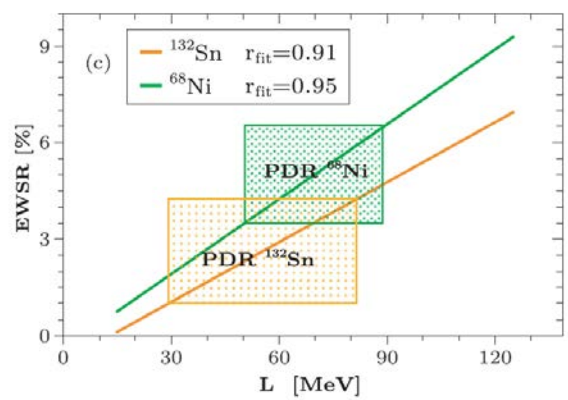
An access to the equation of state and to neutron-rich matter: The Pygmy Dipole Resonance

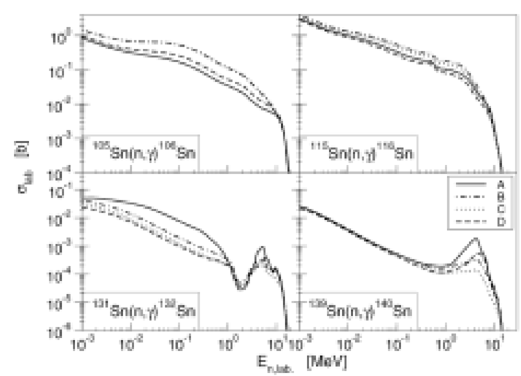


A detailed understanding of the PDR helps to:

- confine the symmetry energy in the EOS;
- extract the thickness of the neutron skin;
- understand the synthesis of heavy elements.





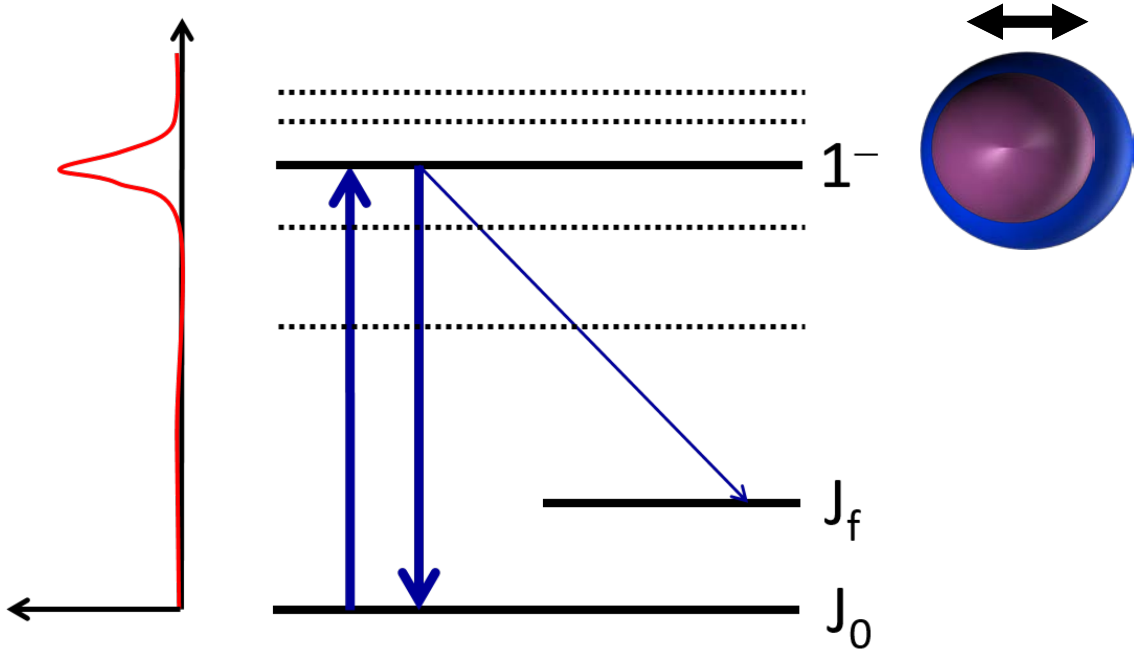


D. Savran, T. Aumann, and A. Zilges, Prog. Part. Nucl Phys. ***70*** *(2013) 210*

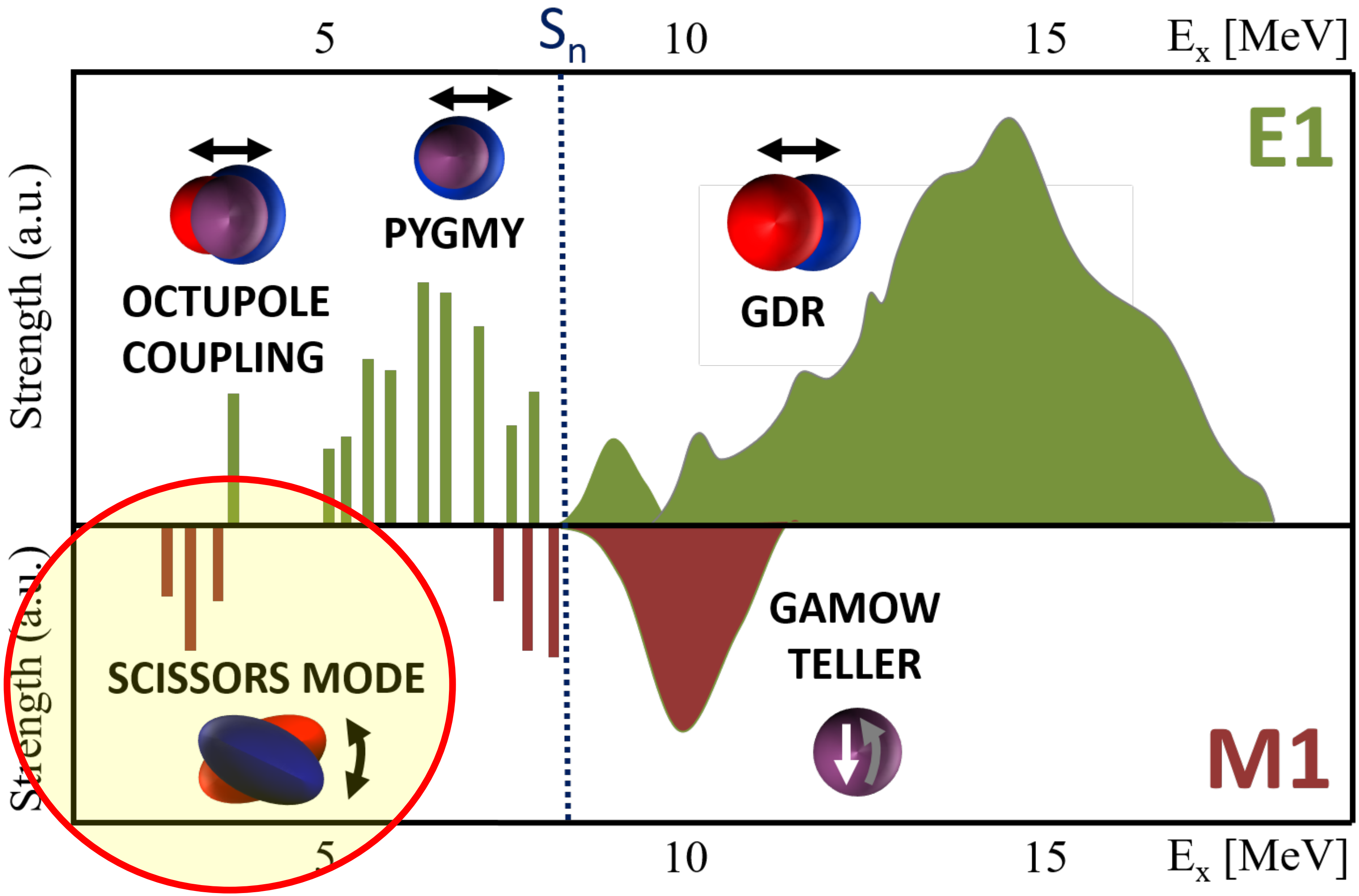
An access to the equation of state and to neutron-rich matter: The Pygmy Dipole Resonance

ELI-NP:

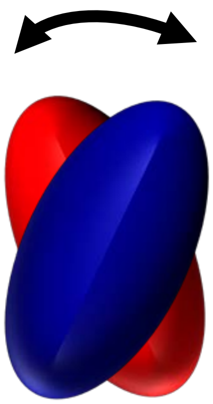
- narrow bandwidth allows single state excitation
  → measure, e.g., branching ratios to excited states
- high intensity and small beam diameter
  → study E1 distribution in rare isotopes



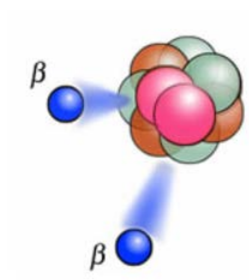
Constraints on neutrinoless double-beta decay matrix elements: Decay channels of the scissors mode



Constraints on neutrinoless double-beta decay matrix elements: Decay channels of the scissors mode



- Branching ratios of the 1^+ scissors mode are very sensitive to important parameters in certain nuclear structure models.
- The same models are used to calculate the nuclear matrix element in $0\nu\beta\beta$ decays.



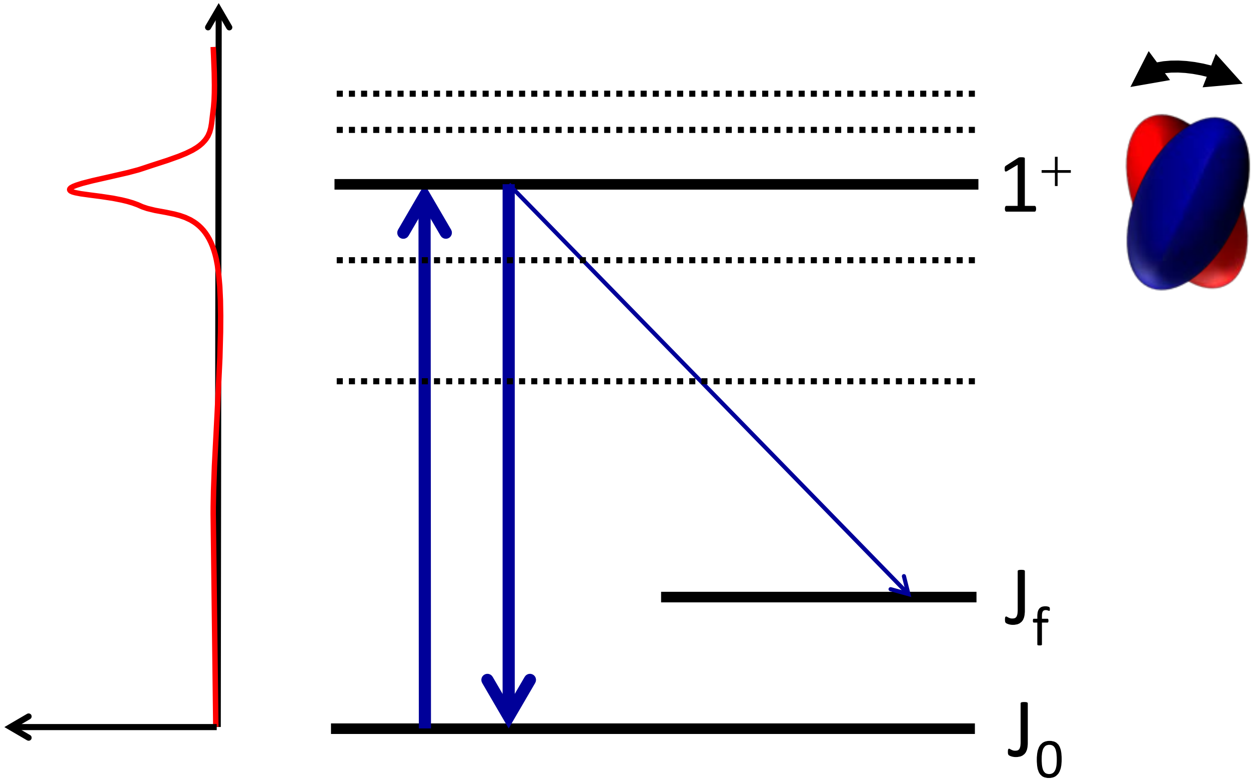
$\rightarrow$ constrain nuclear matrix element in $0\nu\beta\beta$ transition rate

$$\lambda_{0\nu\beta\beta} = G_{0\upsilon} \left|M^{(0\nu)}\right|^2 \left(\frac{\langle m_\nu \rangle}{m_e}\right)^2$$

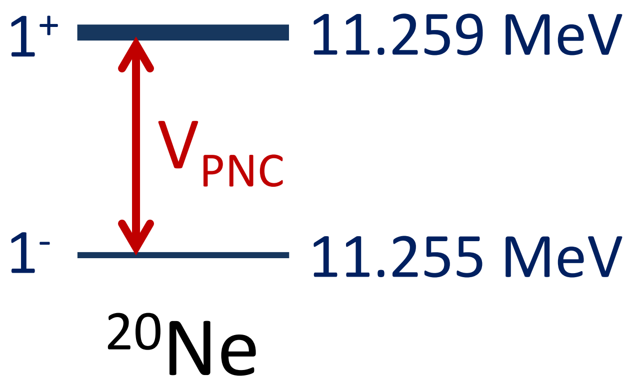
Constraints on neutrinoless double-beta decay matrix elements: Decay channels of the scissors mode

ELI-NP:

- narrow bandwidth allows selective excitation and detection of weak decay channels
- polarization allows to distinguish 1^+ and 1^- states



Parity violation in nuclear excitations



V_{PNC} ≡ parity non-conserving interaction (about 1 eV)

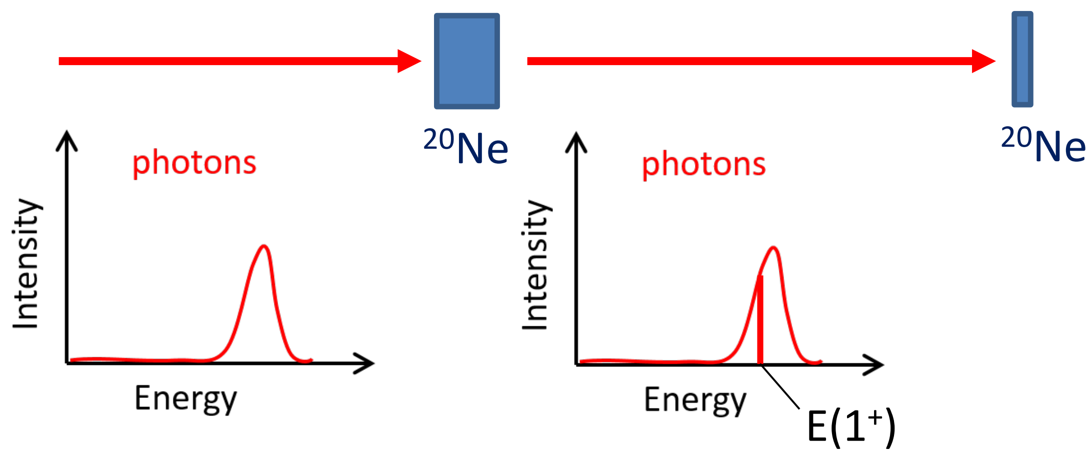
Study level mixing in $1^+/1^-$ parity doublets

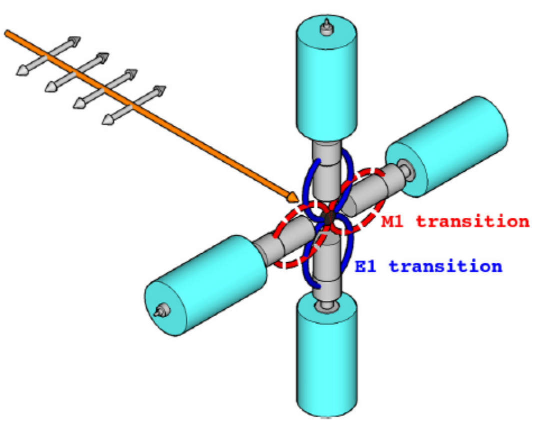
$\rightarrow$ constrain weak meson-nucleon coupling

Parity violation in nuclear excitations

ELI-NP:

- nearly 100% polarized γ beam
- thick ^{20}Ne absorber in front of target removes photons to excite broad 1^+ state, because $\sigma(1^+) \approx 30 \bullet \sigma(1^-)$
- only 1^- state of doublet is excited by remaining photons
- measure M1 admixture to E1 excitation by analyzing NRF events in detector perpendicular to beam axis





Nuclear Photonics at ELI-NP - summary

- The GBS will provide unique MeV photon beam properties:
  high intensity, small bandwidth, polarization, small spatial dimensions
- Excellent detection setups: ELIADE γ array, ELIGANT neutron array, ELITPC charged particles detector

→ Selective manipulation and inspection of excitations in atomic nuclei

Many challenging questions in nuclear physics can be addressed for the first time

Nuclear Photonics – New horizons at ELI-NP

Nuclear Physics

D. Balabanski, J. Beller, B. Boisdeffre, V. Buznea, F. Camera, M. Cernaianu, D. Filipescu, I. Kojouharov, B. Löher, C. Matei, C. Mihai, M. Müscher, G. Pascovici, C. Petcu, N. Pietralla, C. Romig, D. Savran, G. Suliman, P. Thirolf, E. Udup, C.A. Ur, H. Utsunomiya, V. Werner, J. Wilhelmy, N.V. Zamfir, A.Z.

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