ERL for photonuclear reactions

Tobias Beck
Facility for Rare Isotope Beams,
Michigan State University,
East Lansing, MI 48824, USA

This material is based upon work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661, the State of Michigan and Michigan State University. Michigan State University designs and establishes FRIB as a DOE Office of Science National User Facility in support of the mission of the Office of Nuclear Physics.

Outline

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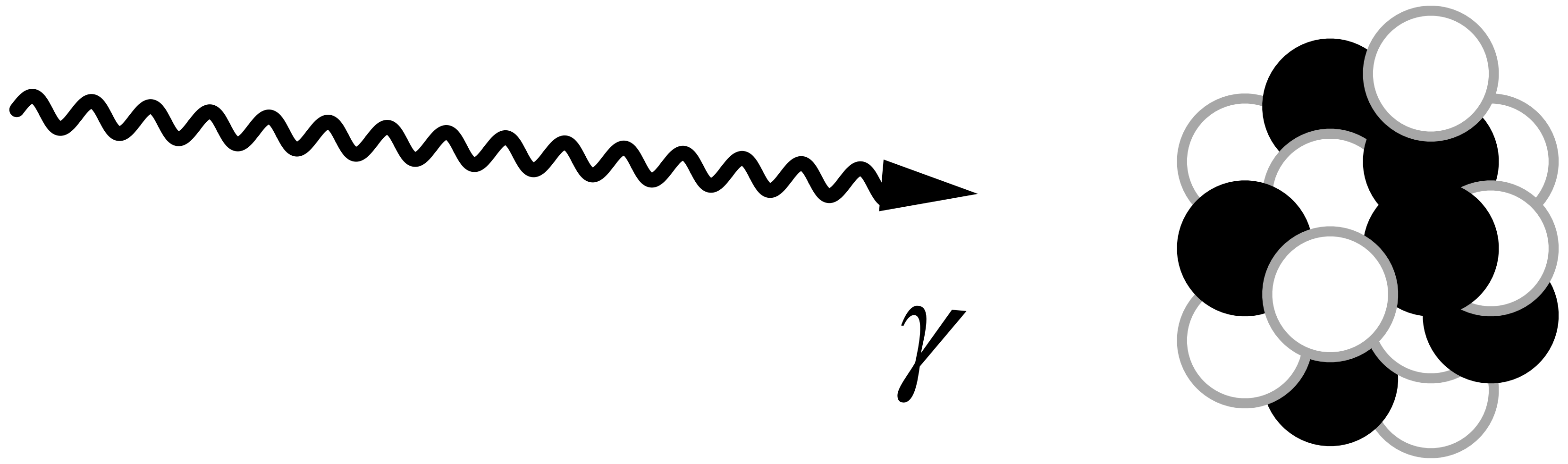


- interactions of photons with nuclei
- experiments
- observables

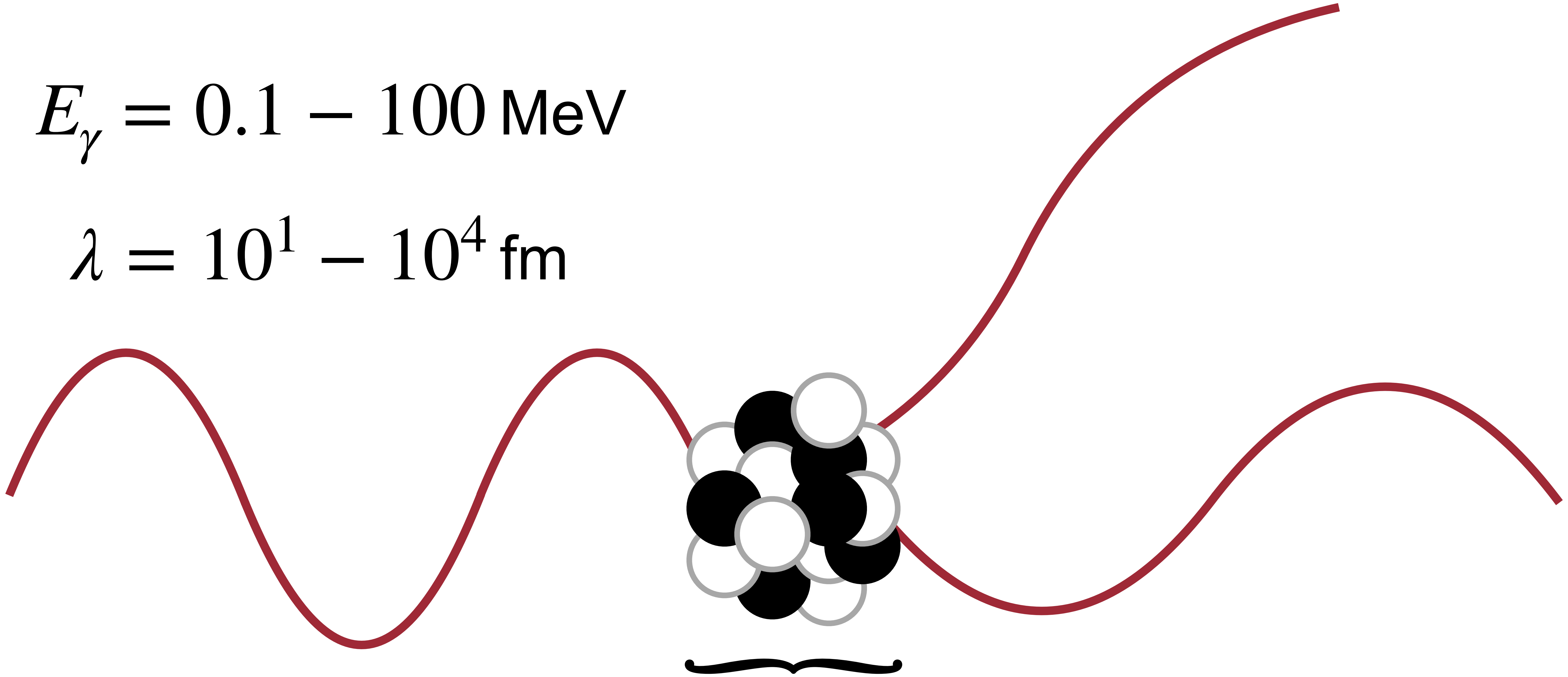
Outline

- historic overview
- photon sources and facilities
- “wishes” from the user side
- interactions of photons with nuclei
- experiments
- observables

Interaction of photons with nuclei

$E_\gamma = 0.1 - 100$ MeV

$\lambda = 10^1 - 10^4$ fm



$\lambda \gg D$

$D \approx 10^{-15}$ m

$\lambda \gg D$:

Thomson, Rayleigh, and Compton scattering

➨ size, charge, polarizability

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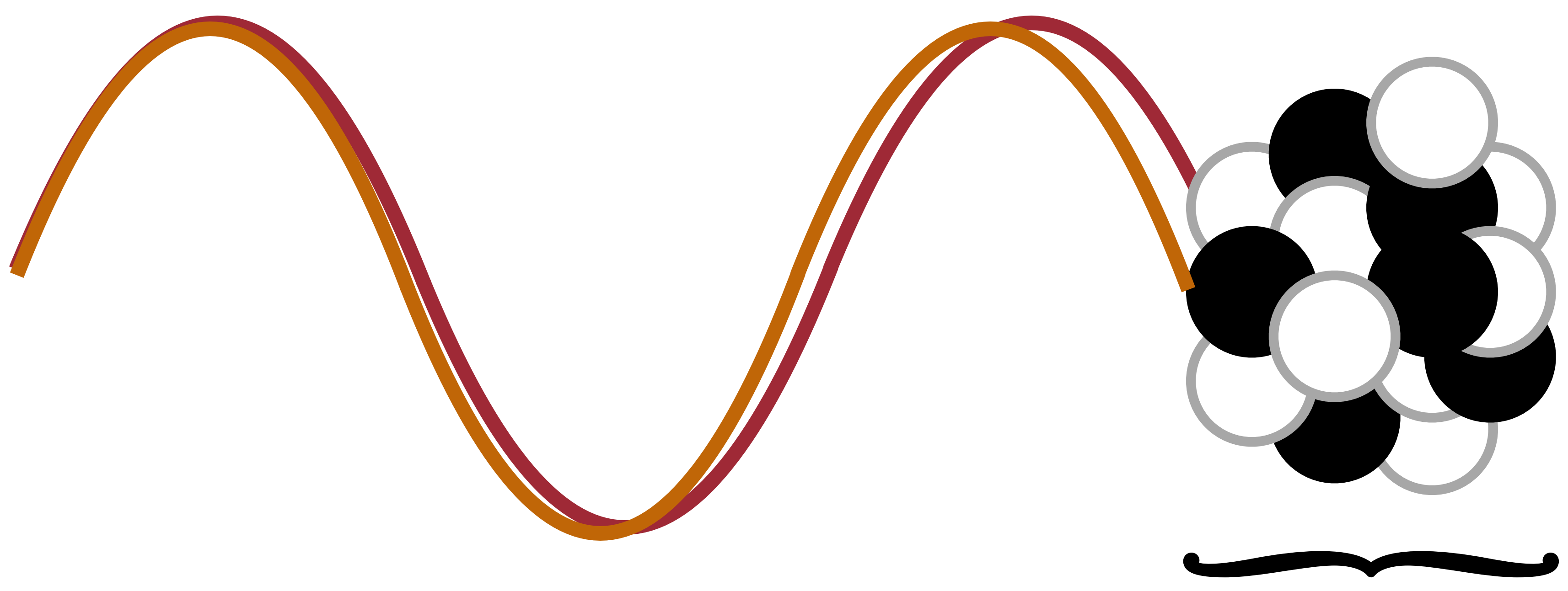

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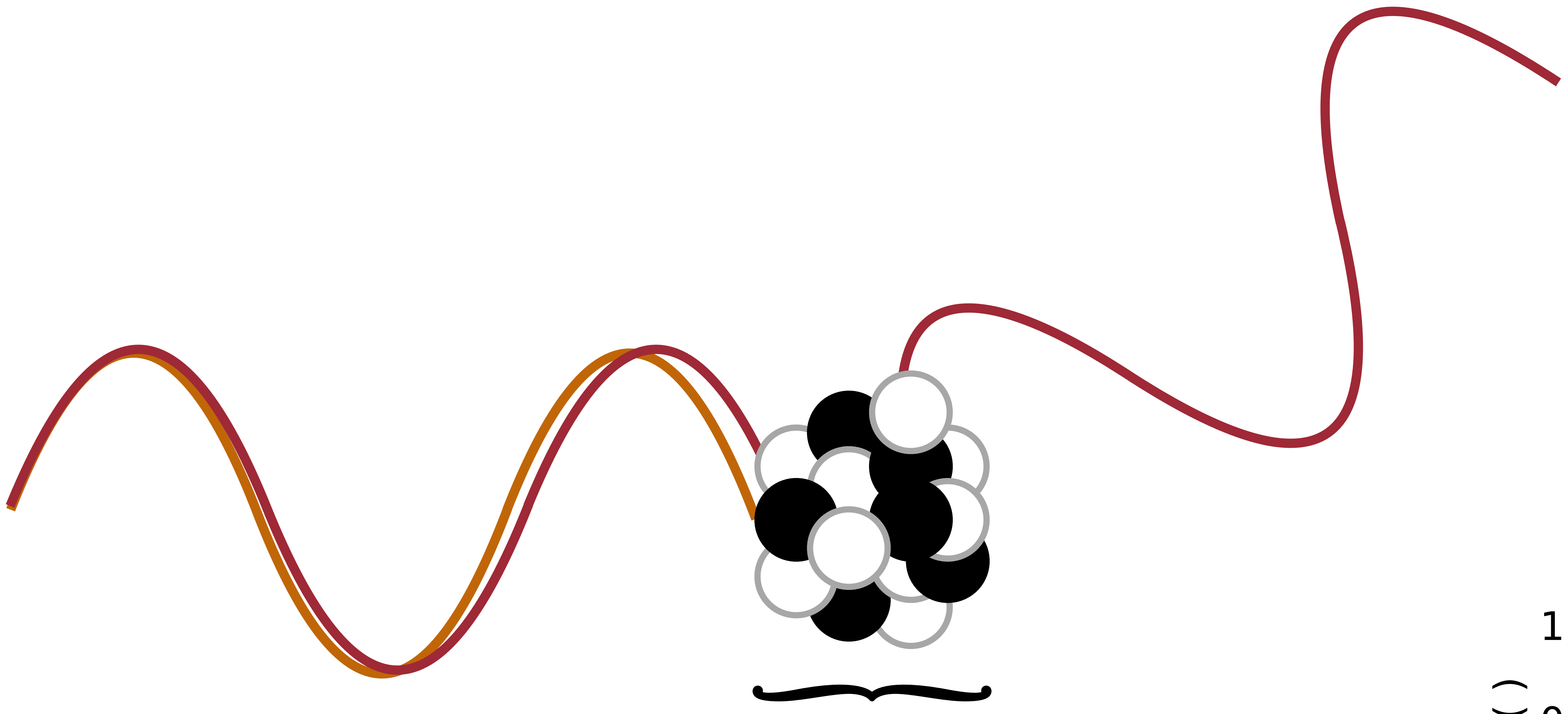
Resonance condition:

absorption and resonant emission

Interaction of photons with nuclei



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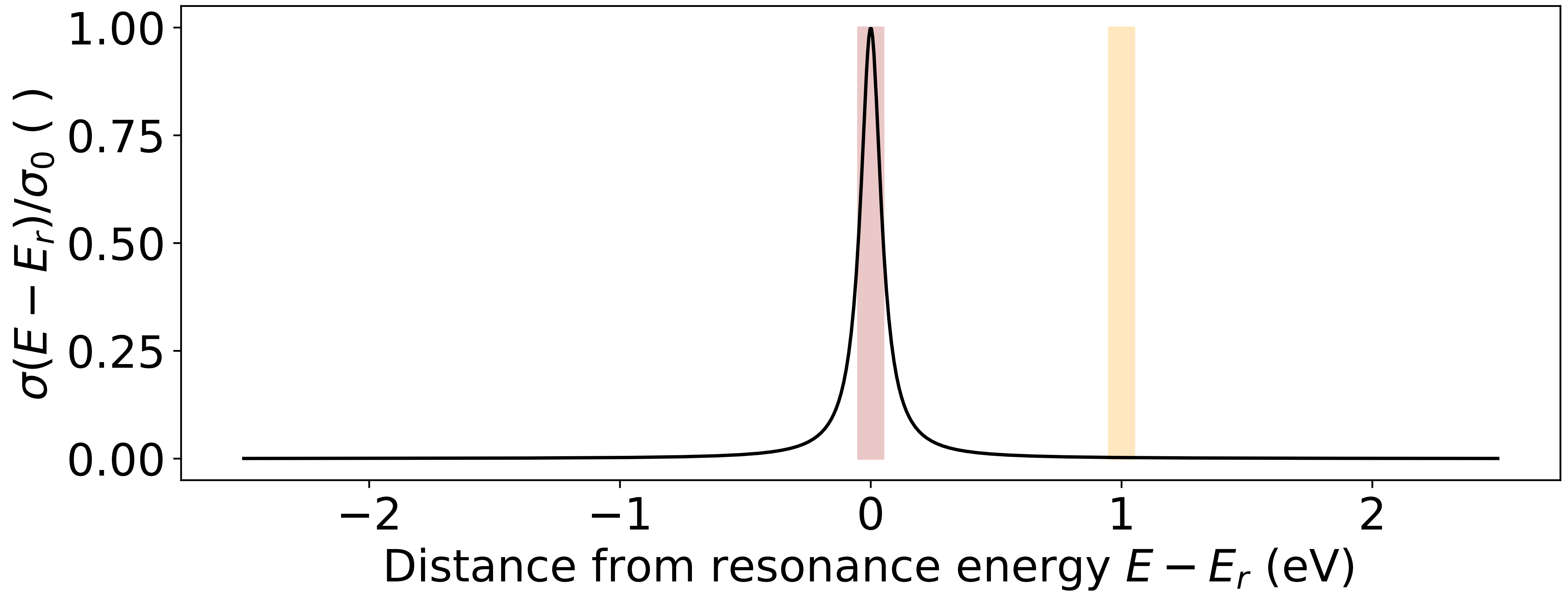
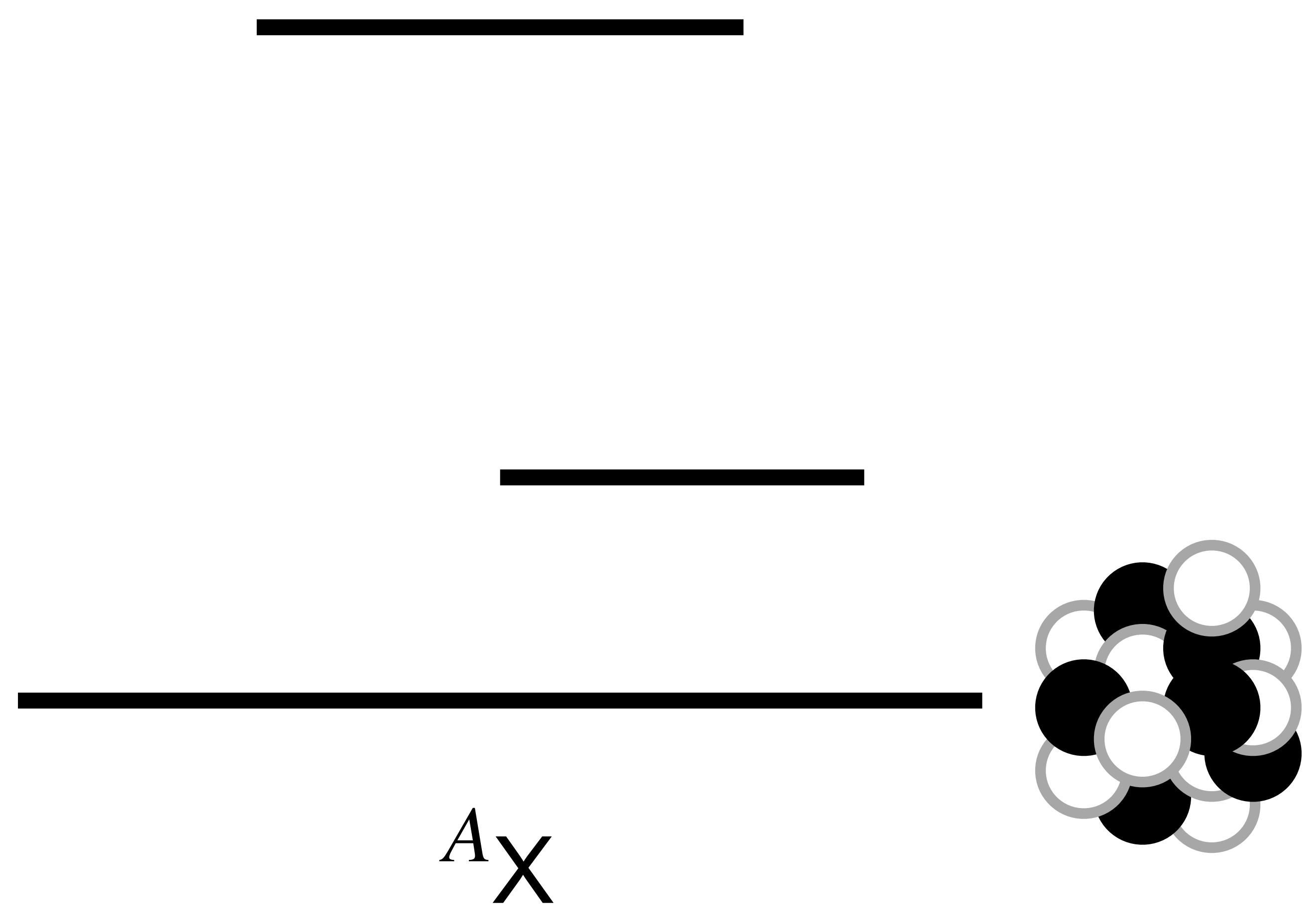


Photonuclear reactions



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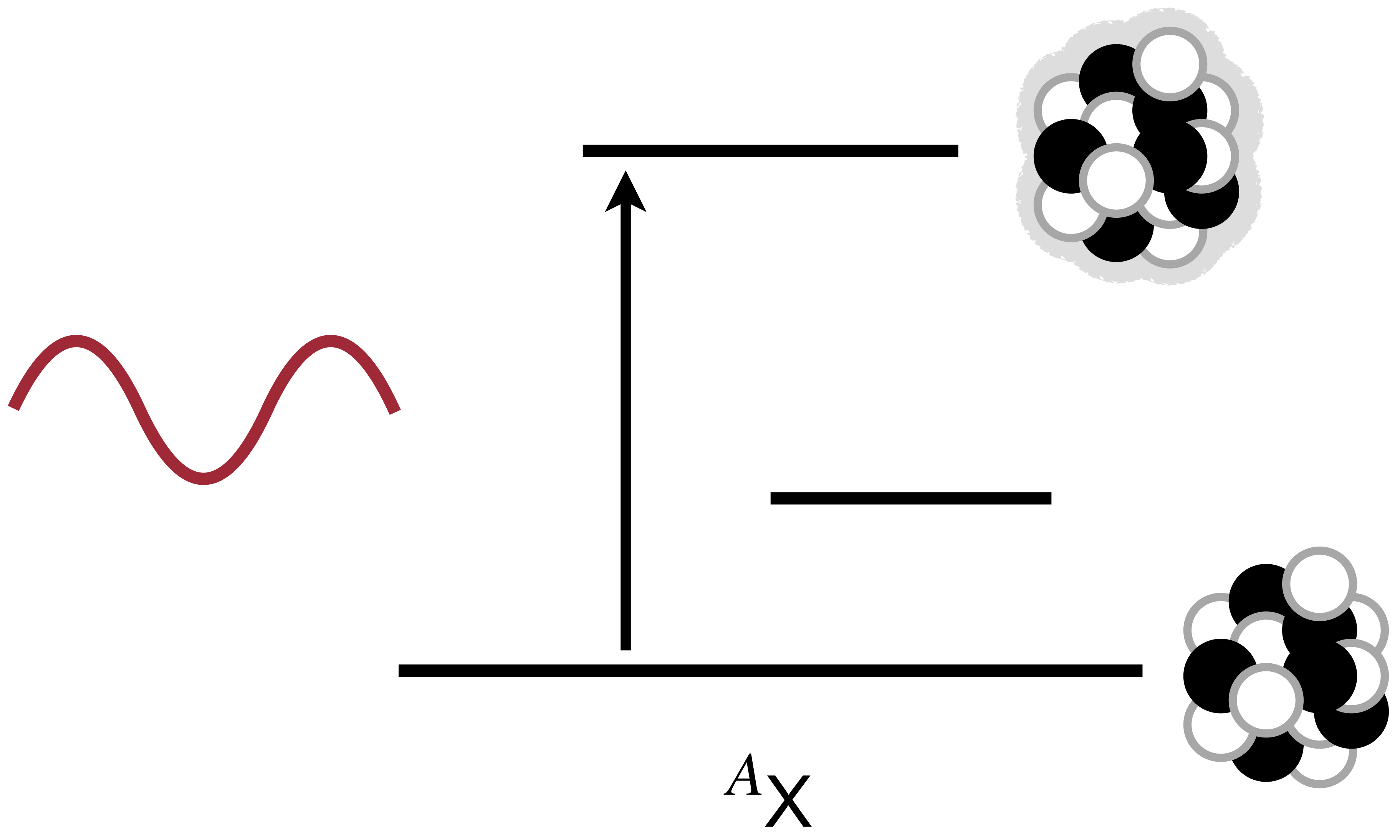

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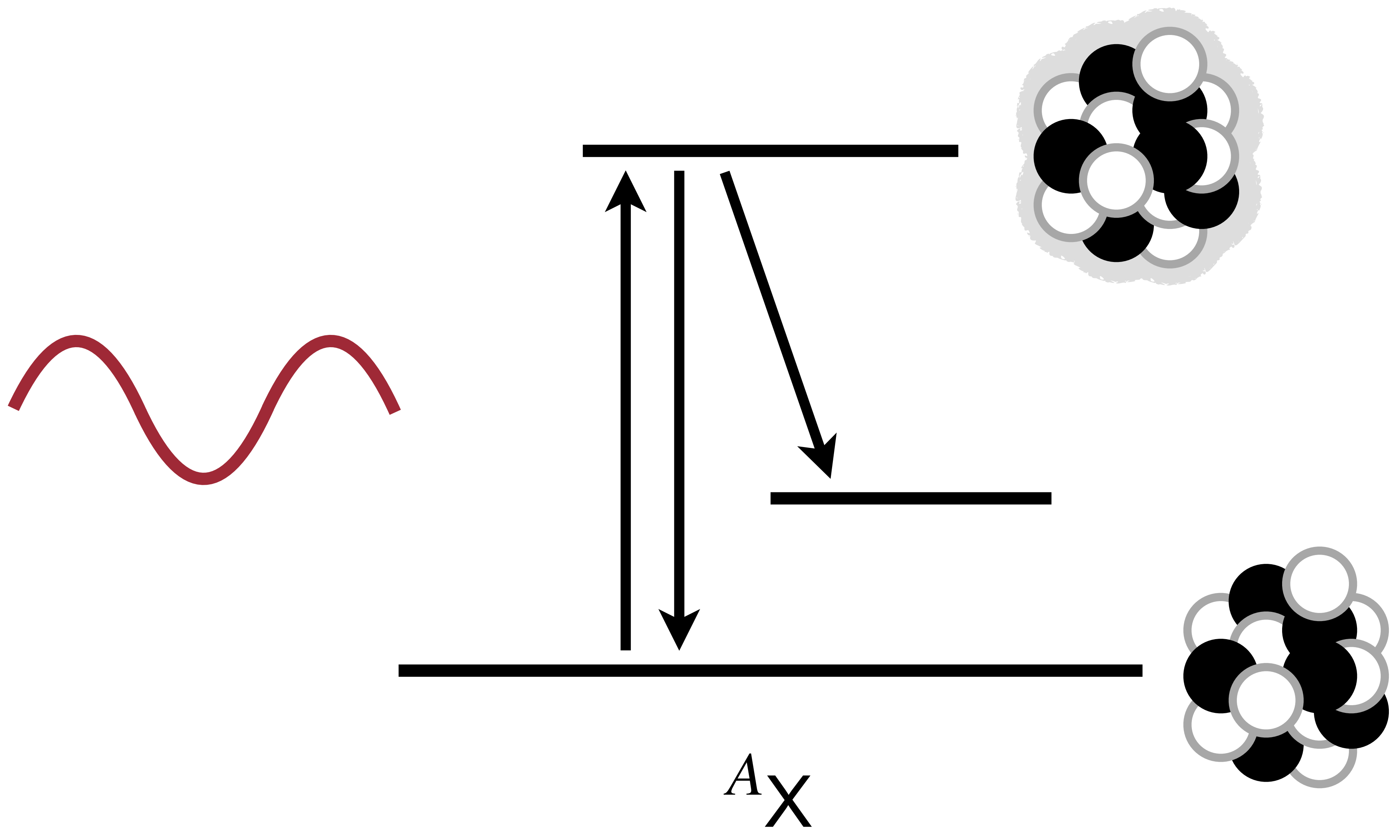

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  Schiff, Phys. Rev. 70, 761 (1946)

- photoactivation

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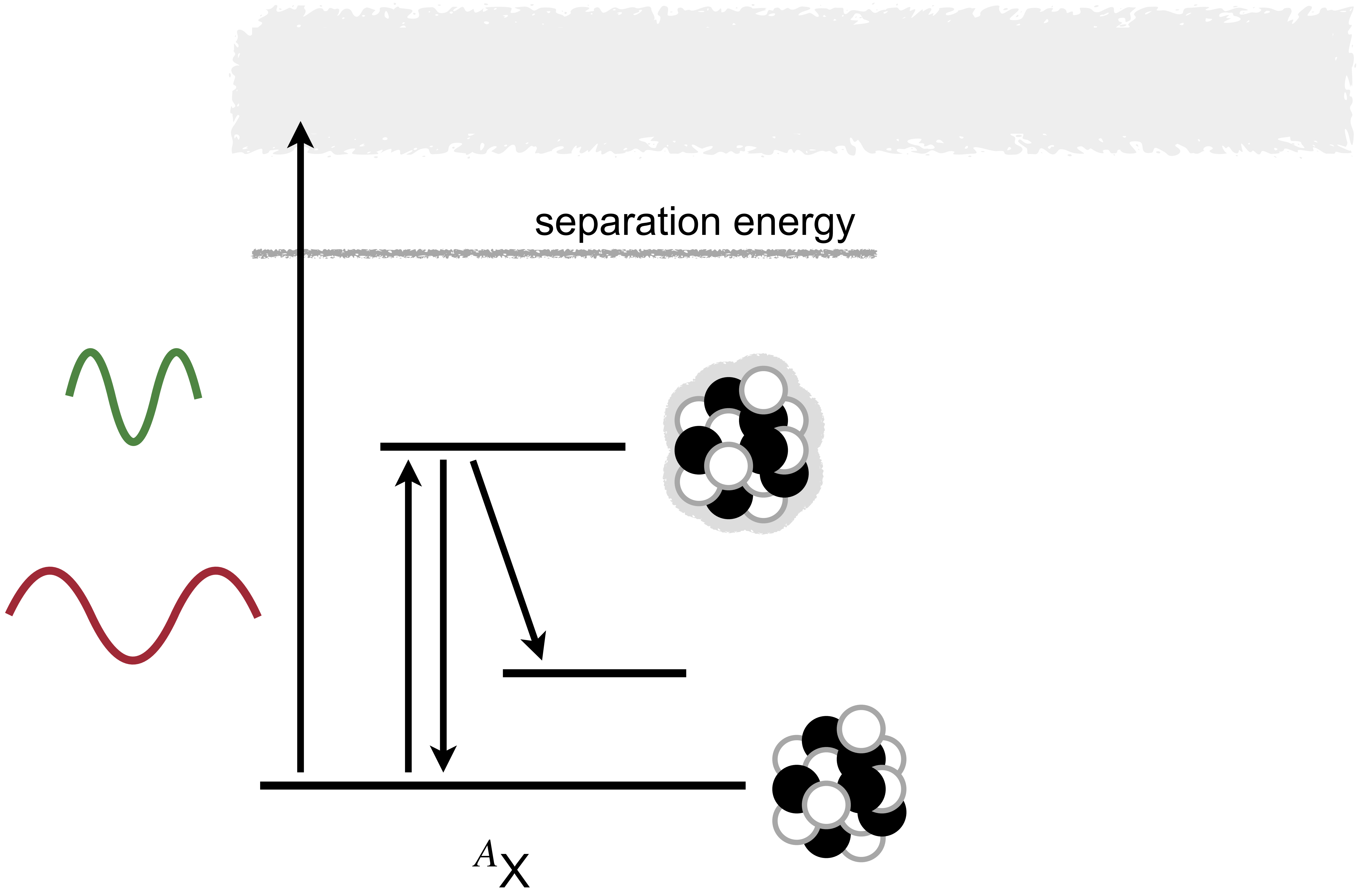

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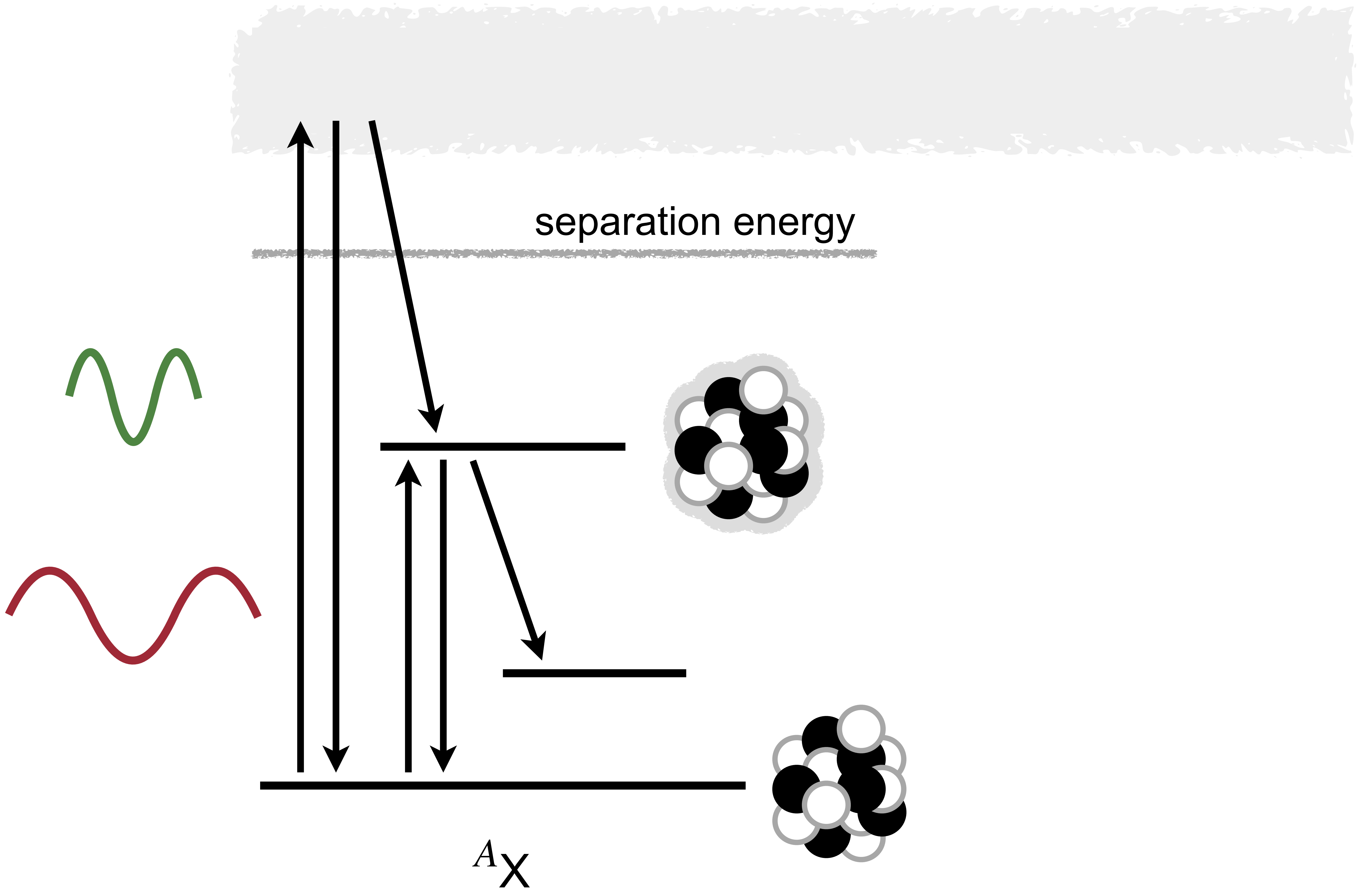

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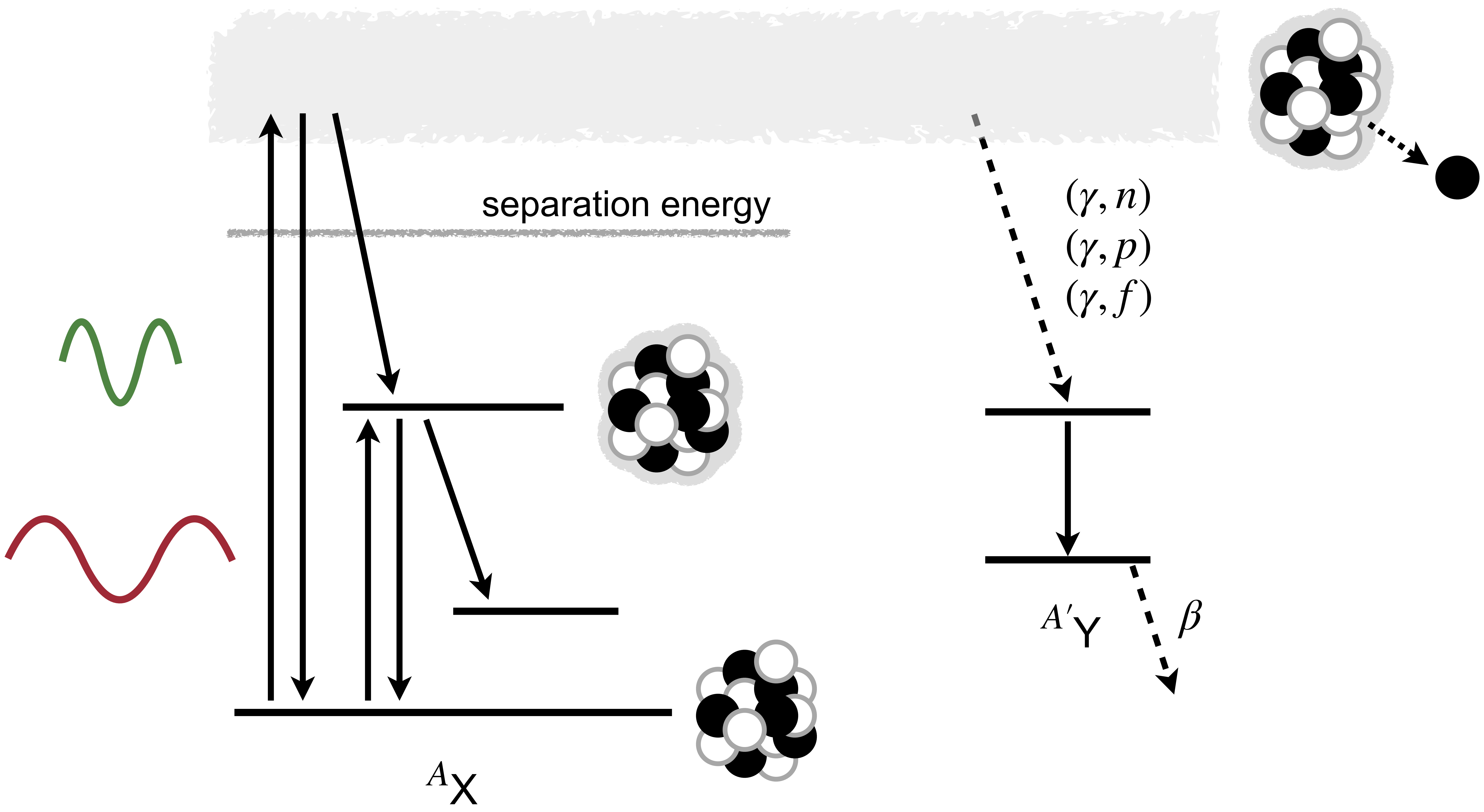

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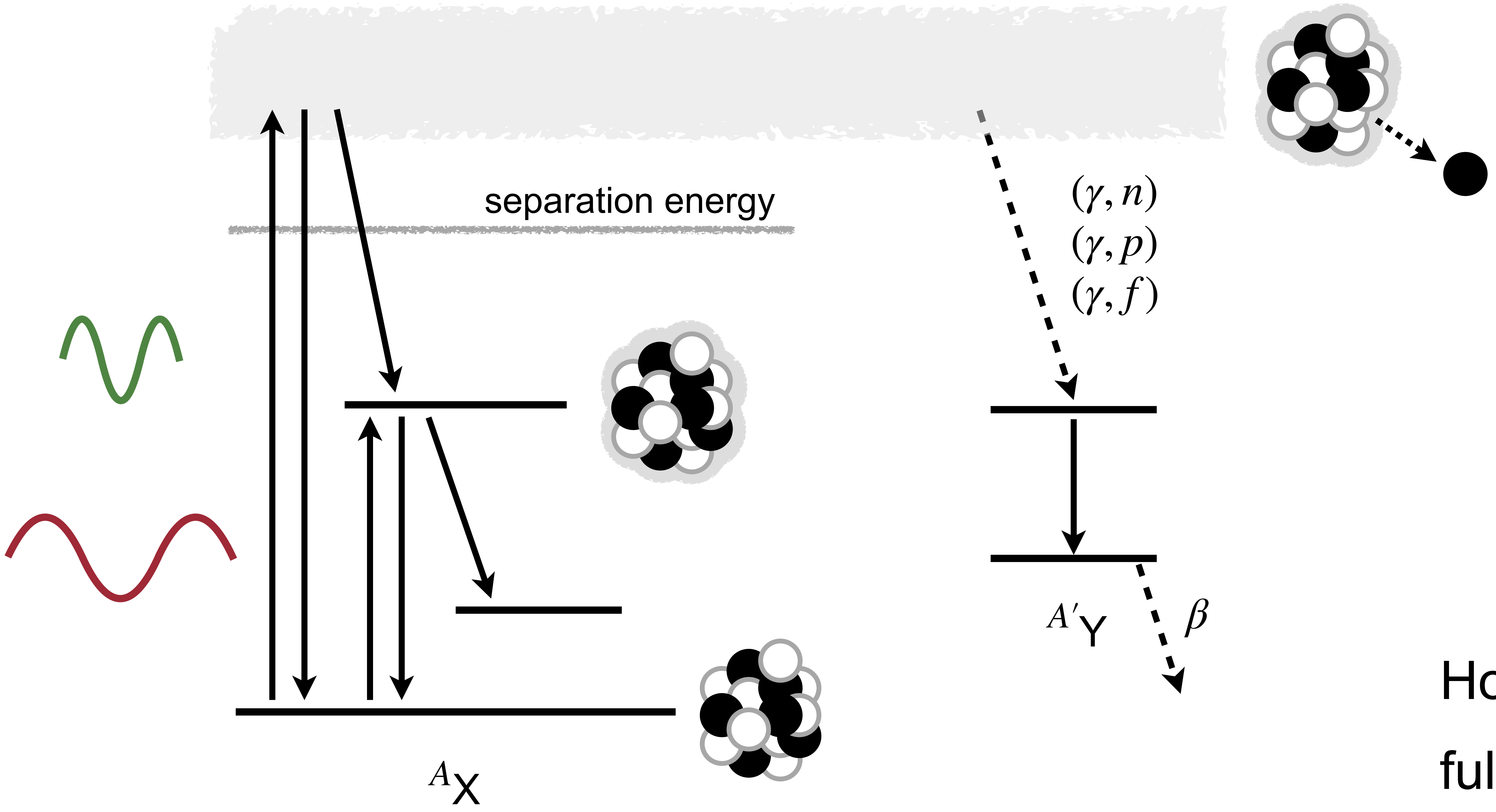

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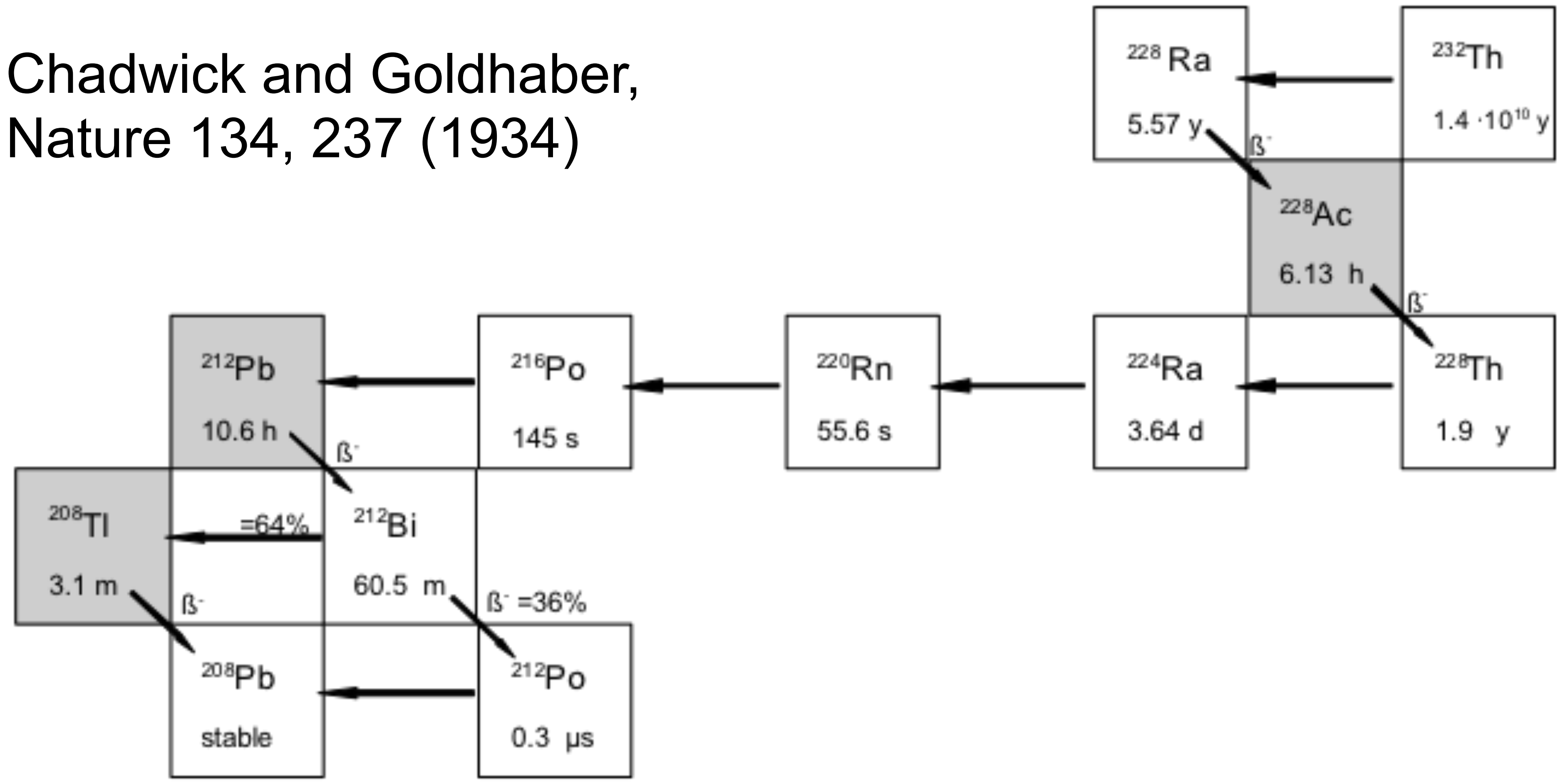
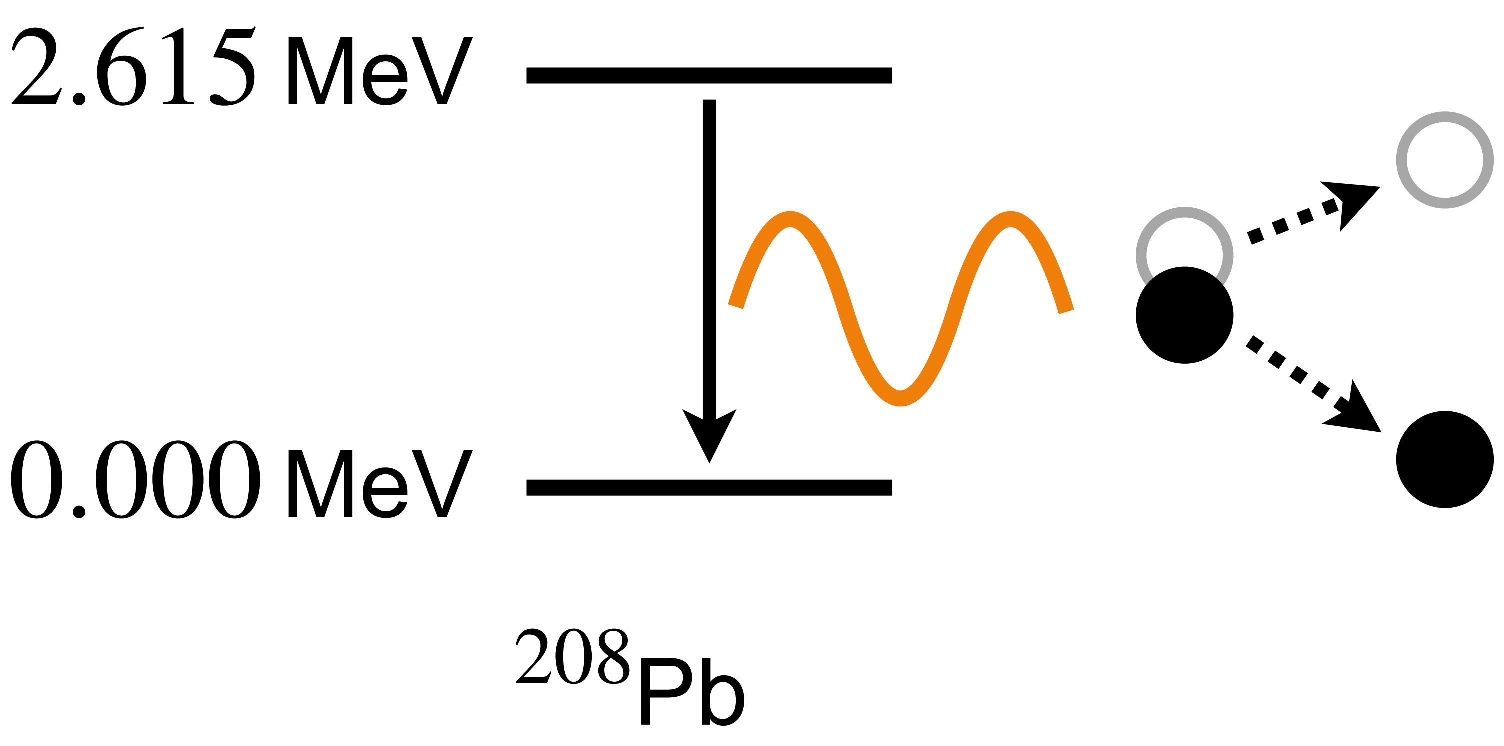
How to produce photon beams fulfilling a resonance condition?

Generation of photon “beams” — the early days

^{232}Th decay chain:

Chadwick and Goldhaber,
Nature 134, 237 (1934)





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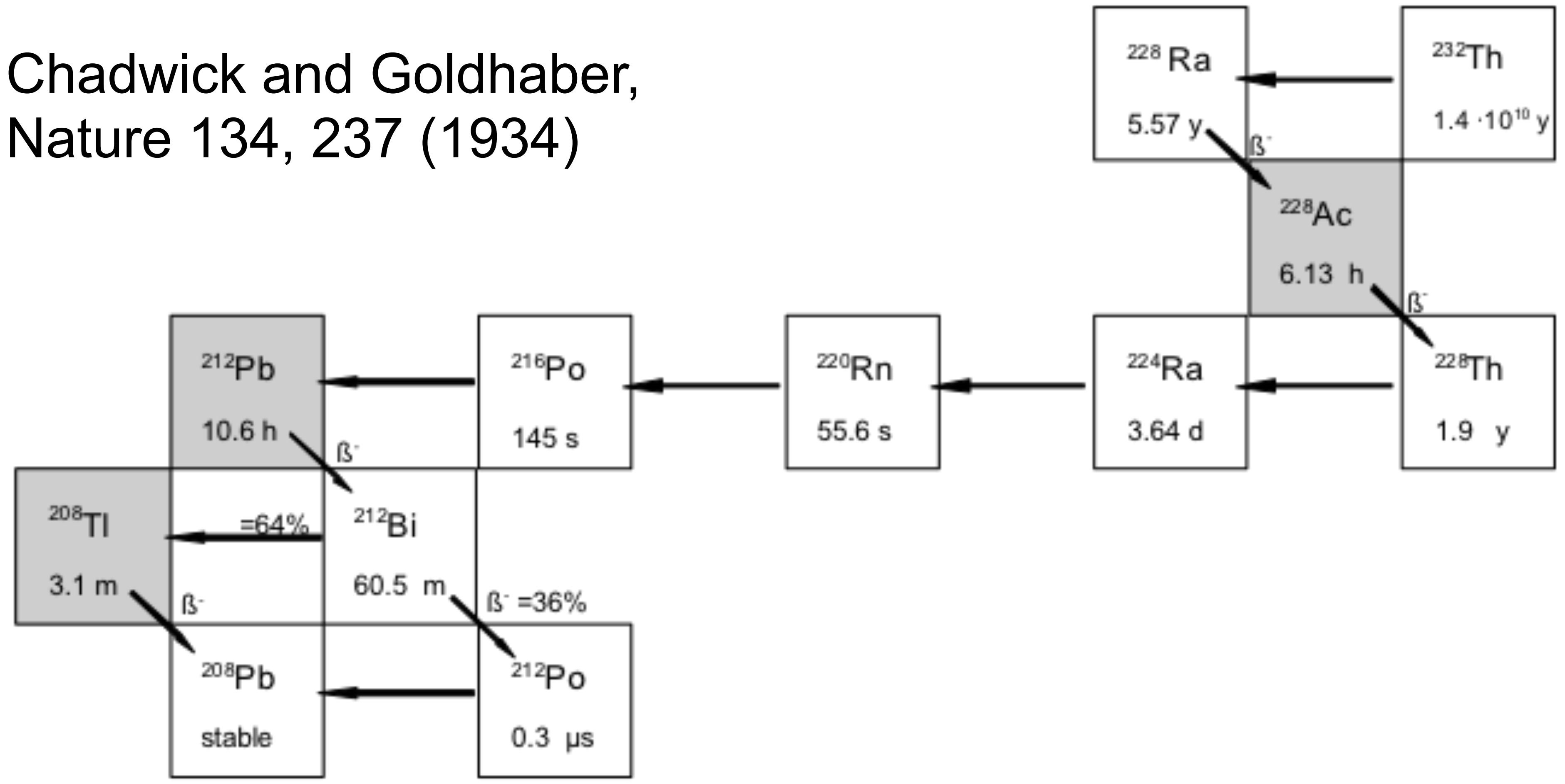
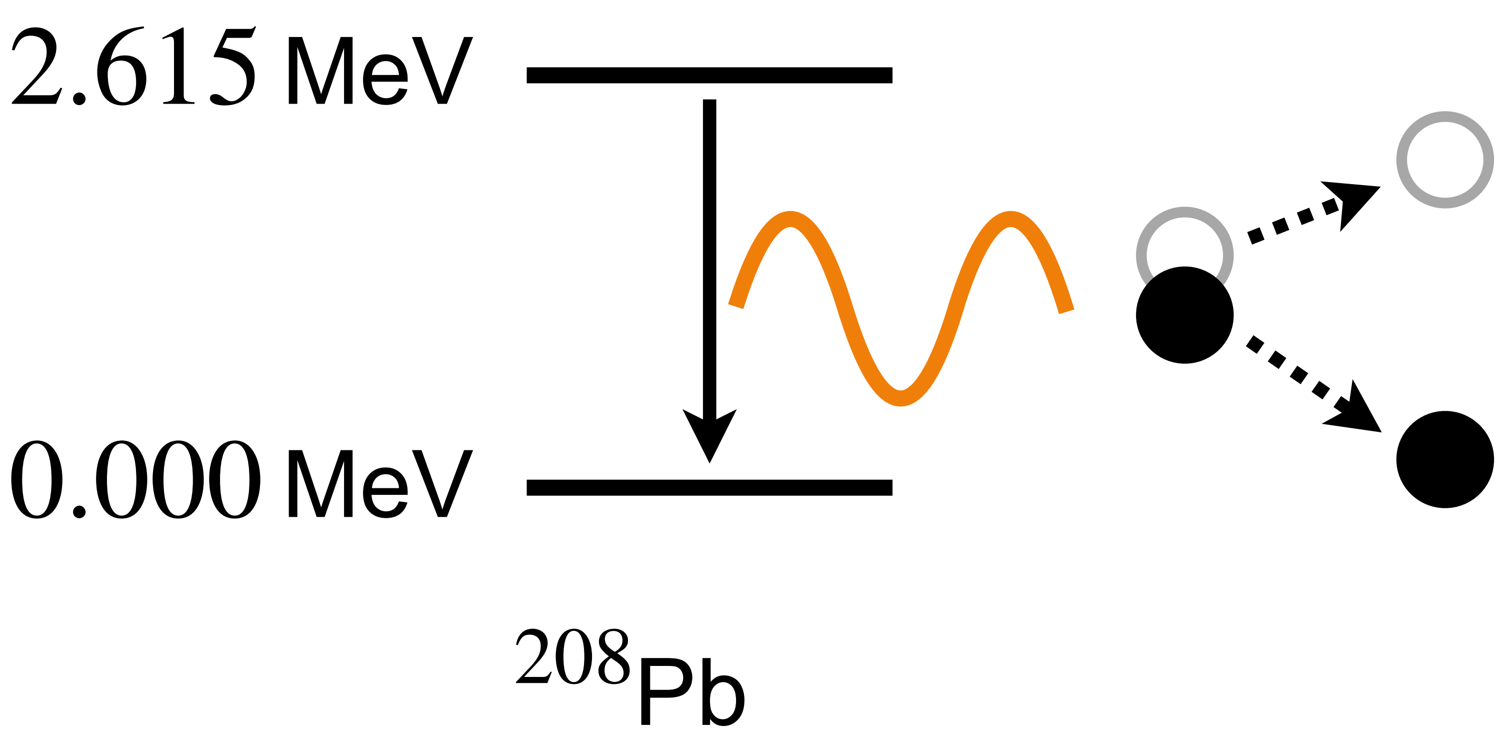
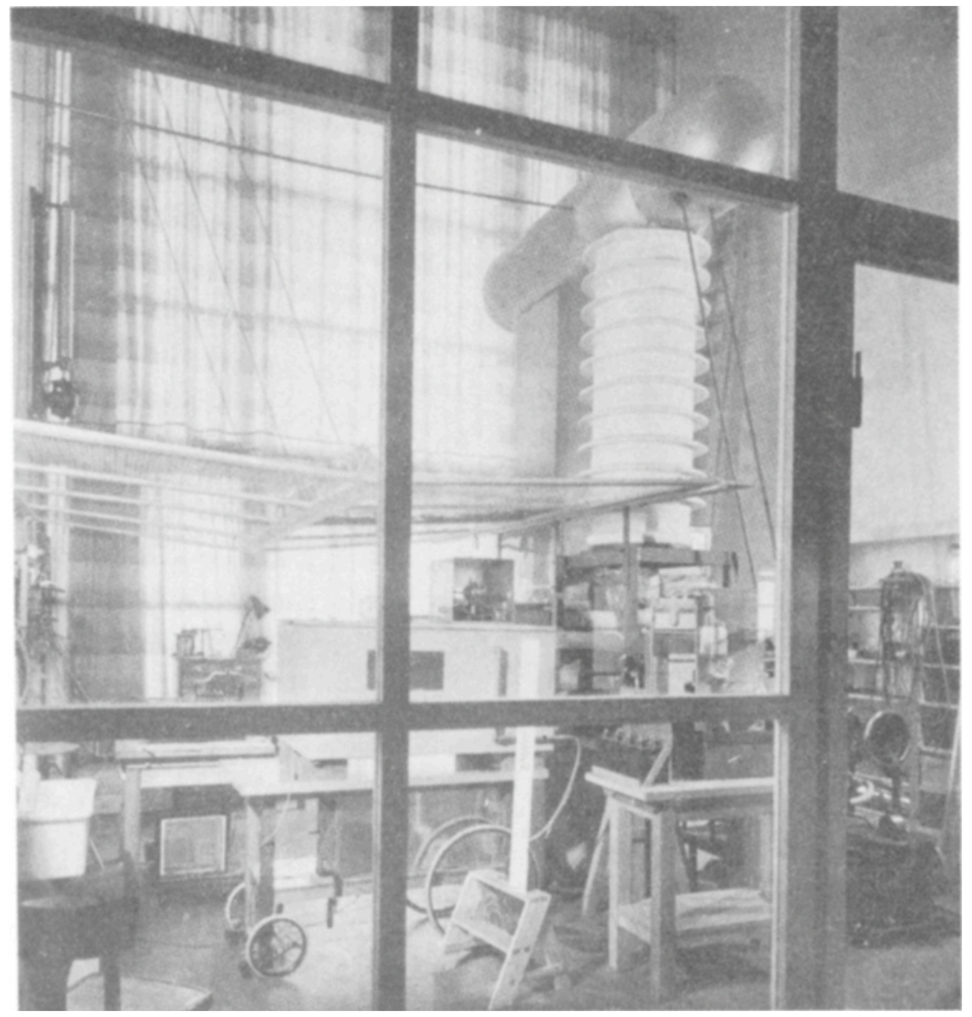




Potentially tunable γ-ray energies:

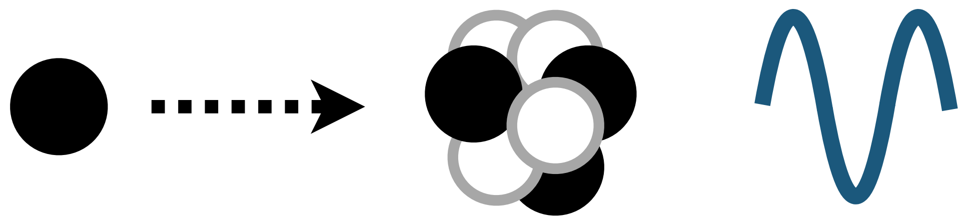
Bothe and Gentner, Z. Phys. 106, 236 (1937)



Bothe and Gentner,
Z. Phys. 104, 685 (1937)

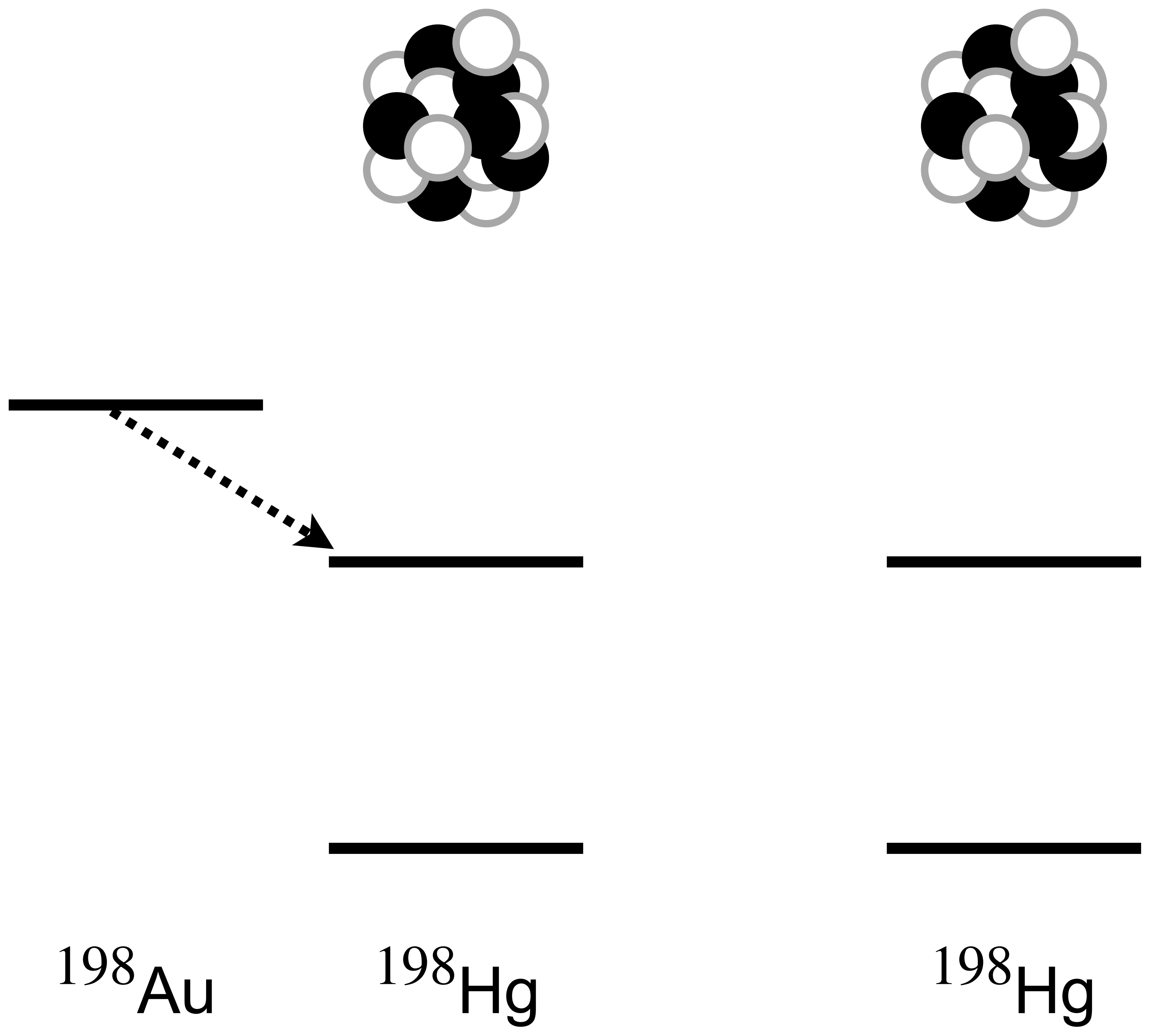
Reaction:

^{7}Li$(p,\gamma)^{8}$Be @ 440 keV



subsequent (γ,n) reactions

Nuclear resonance fluorescence



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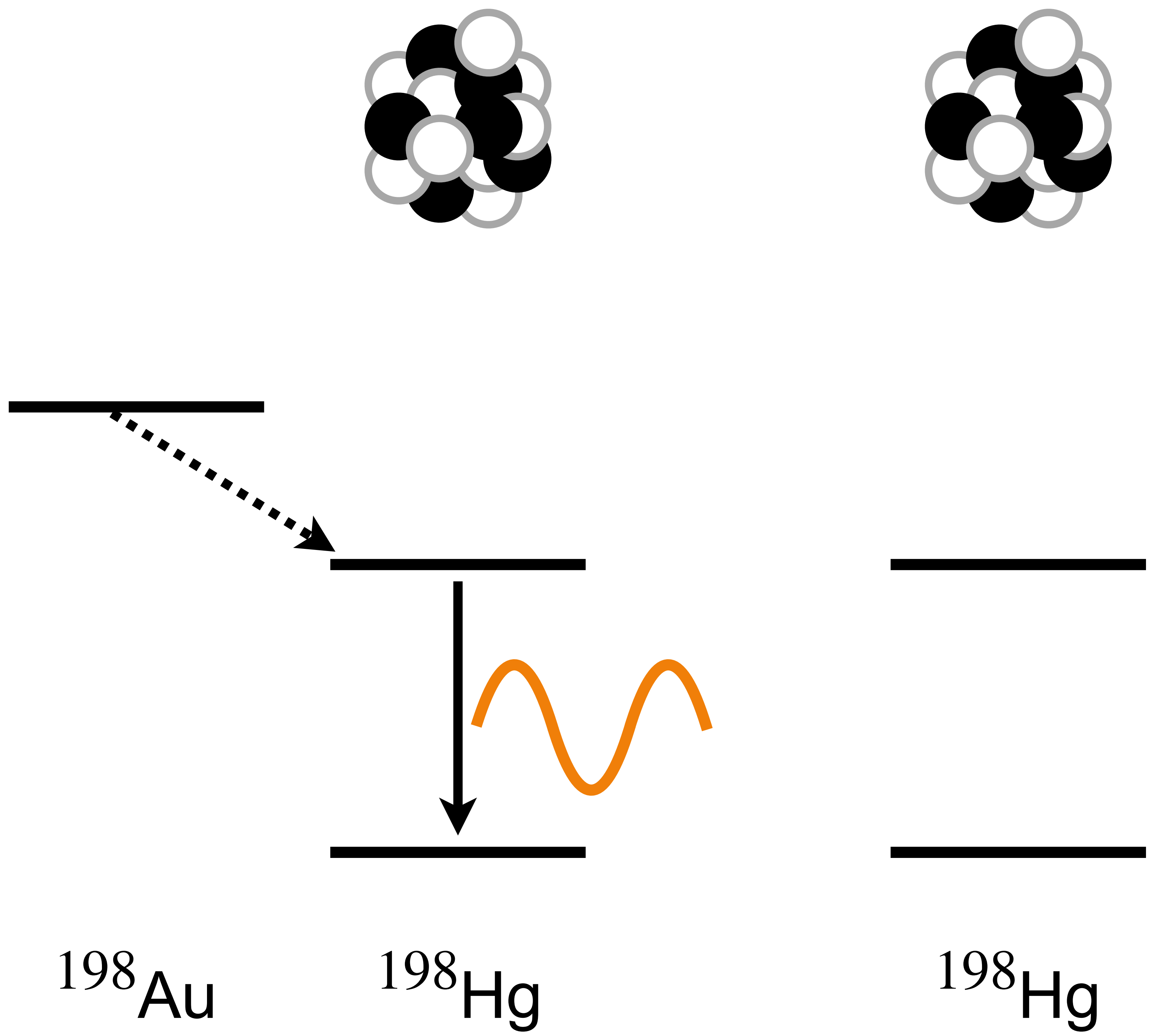

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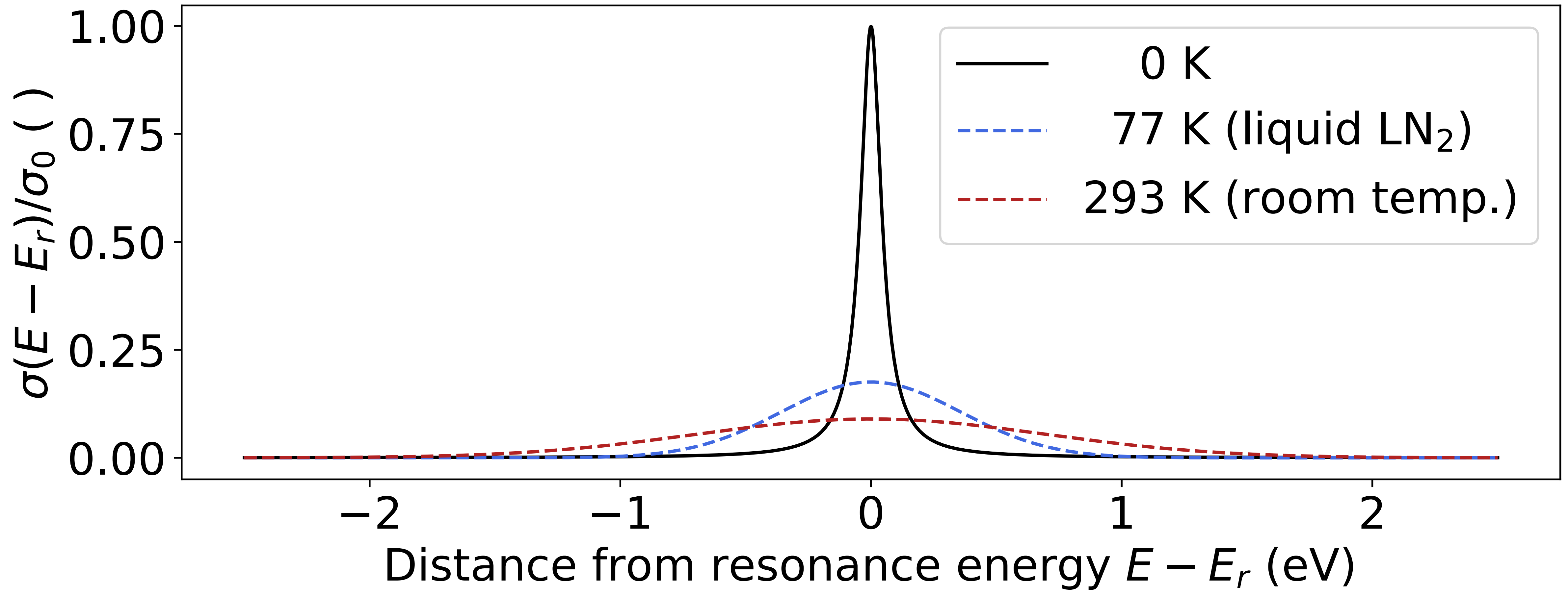
Doppler broadening:	10^0 eV
recoil energy:	10^2 eV



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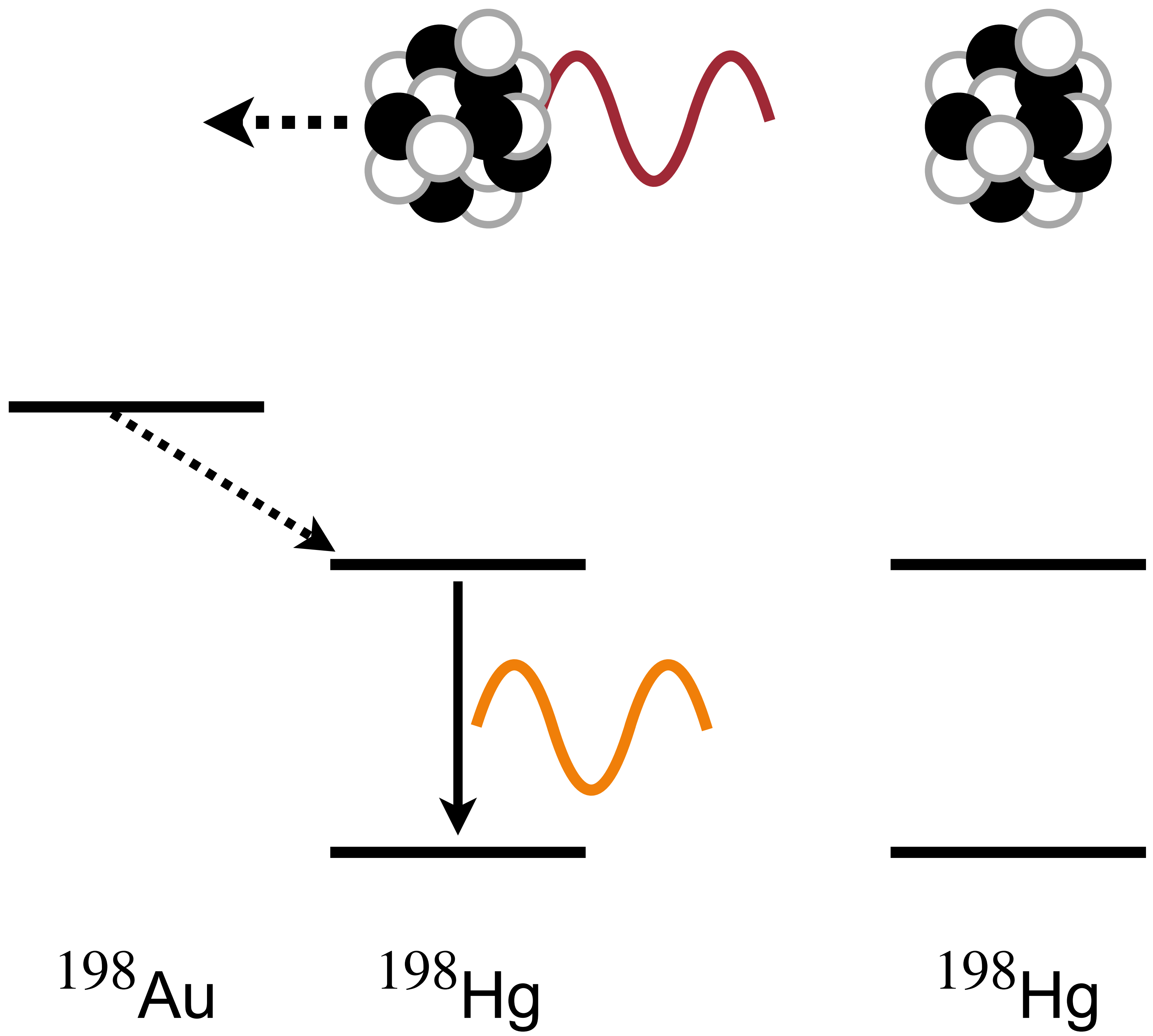

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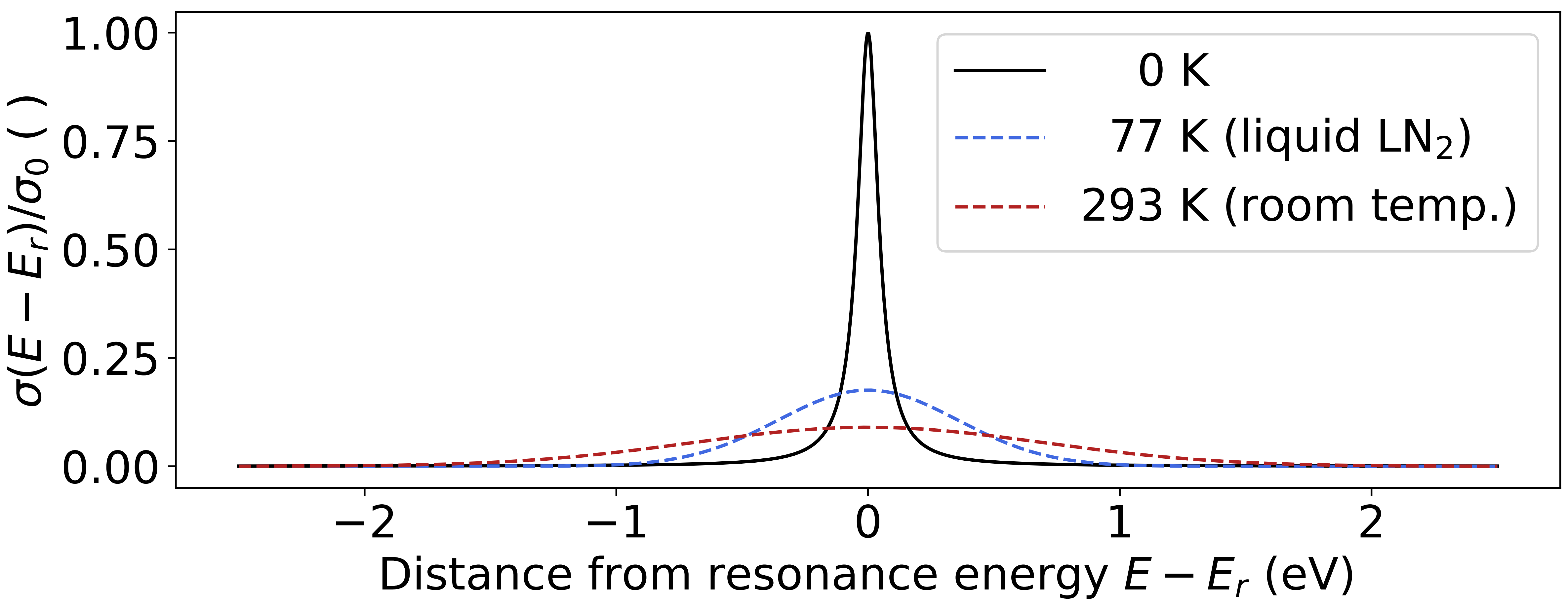

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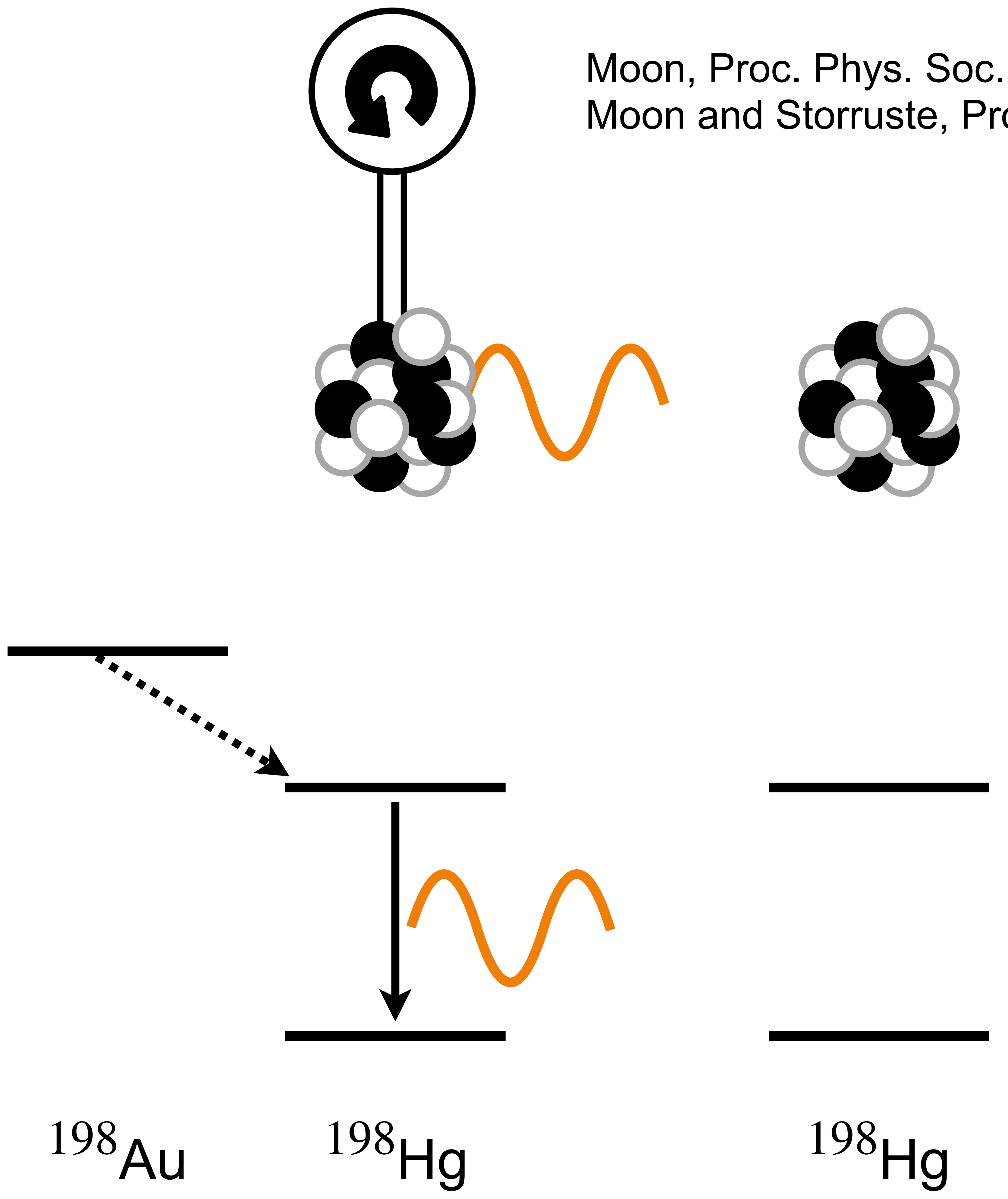

Moon, Proc. Phys. Soc. A 64, 76 (1951)
Moon and Storruste, Proc. Phys. Soc. A 66, 585 (1953)

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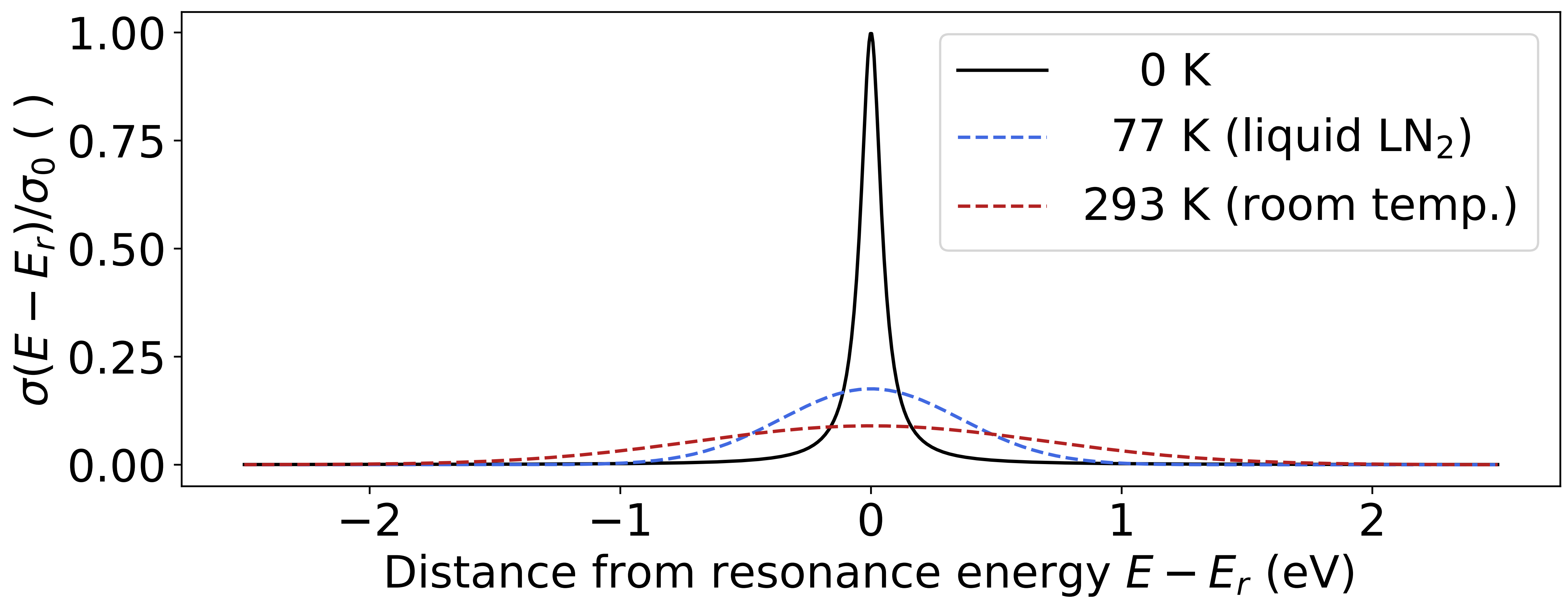

Nuclear resonance fluorescence with bremsstrahlung

Alternative: continuous photon spectrum — electron-generated bremsstrahlung.

Baldwin and Klaiber, Phys. Rev. 71, 3 (1947)

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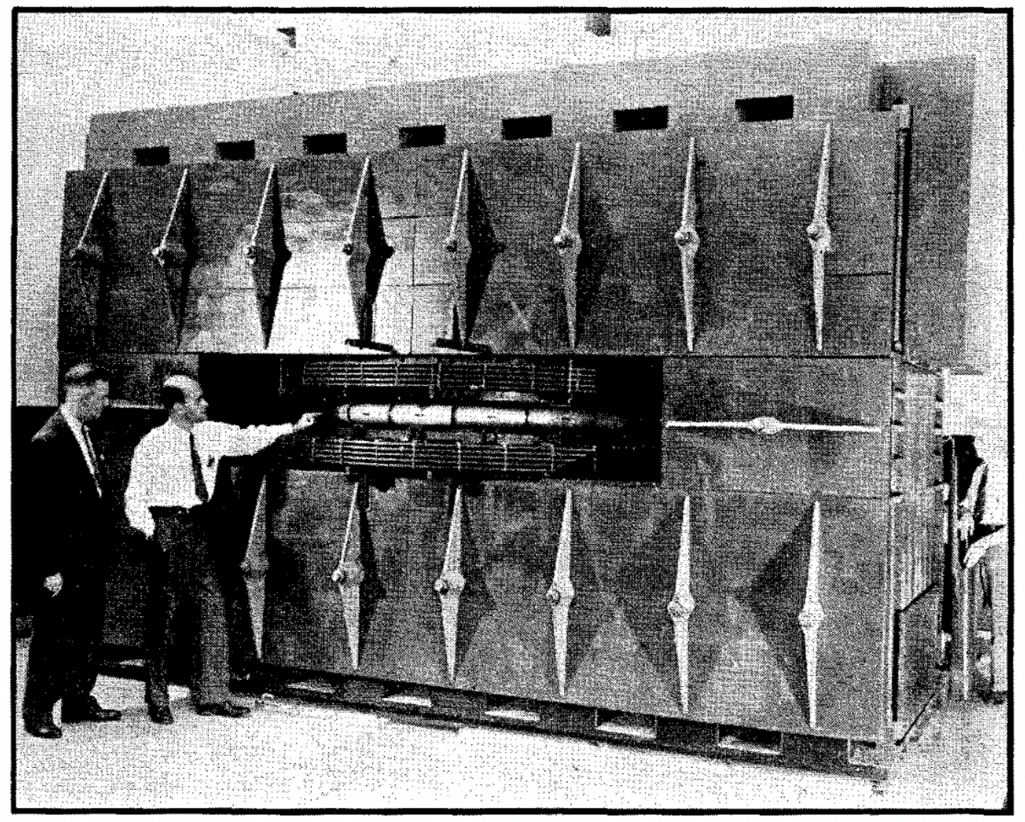

Westendorp and Charlton,
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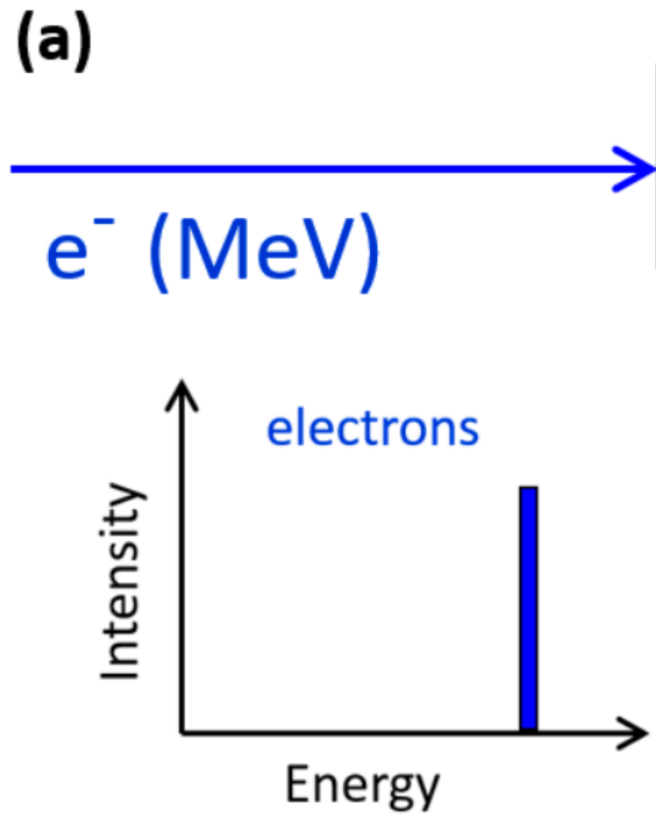

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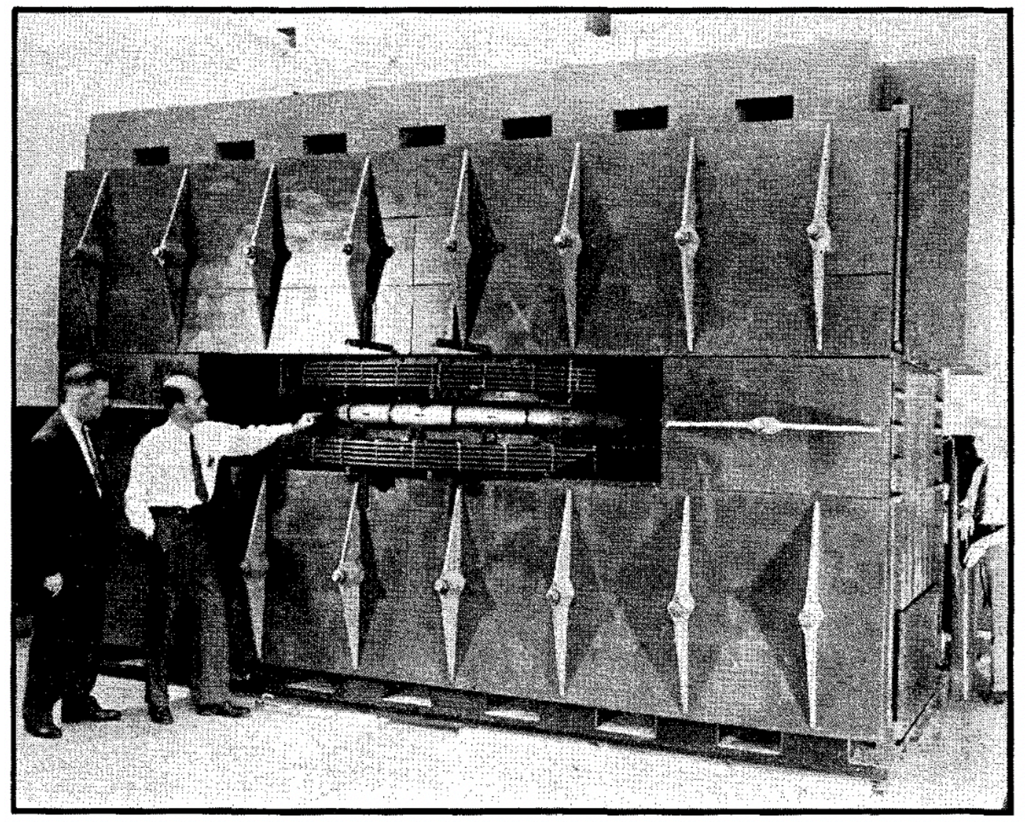

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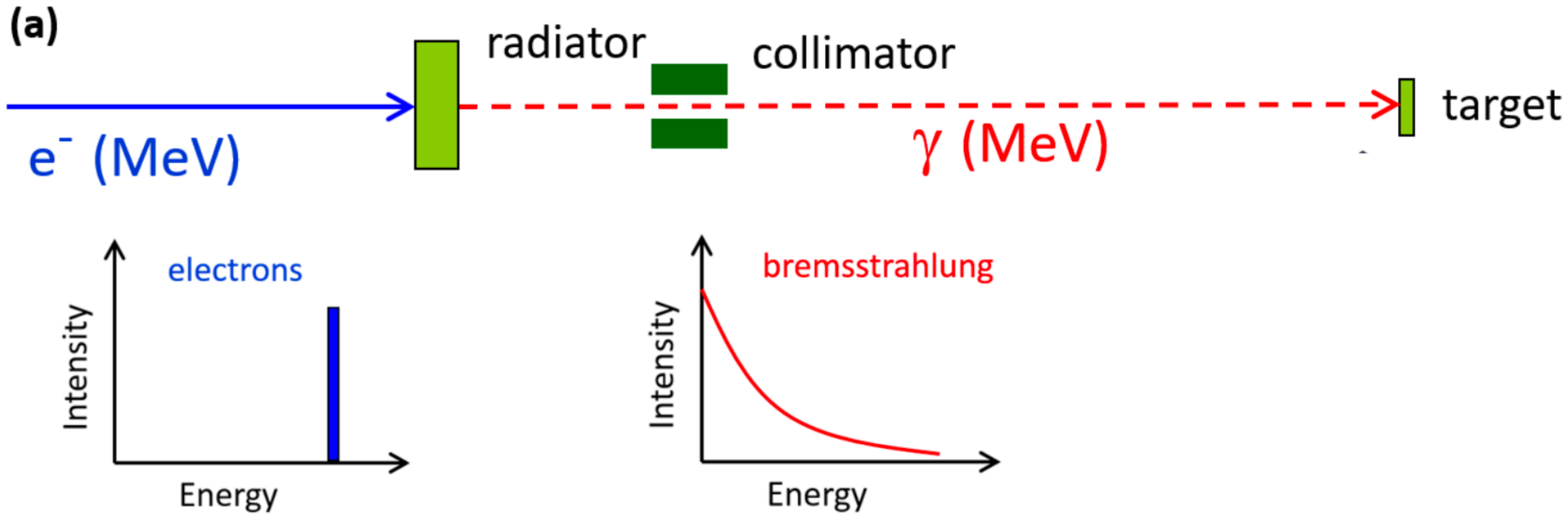

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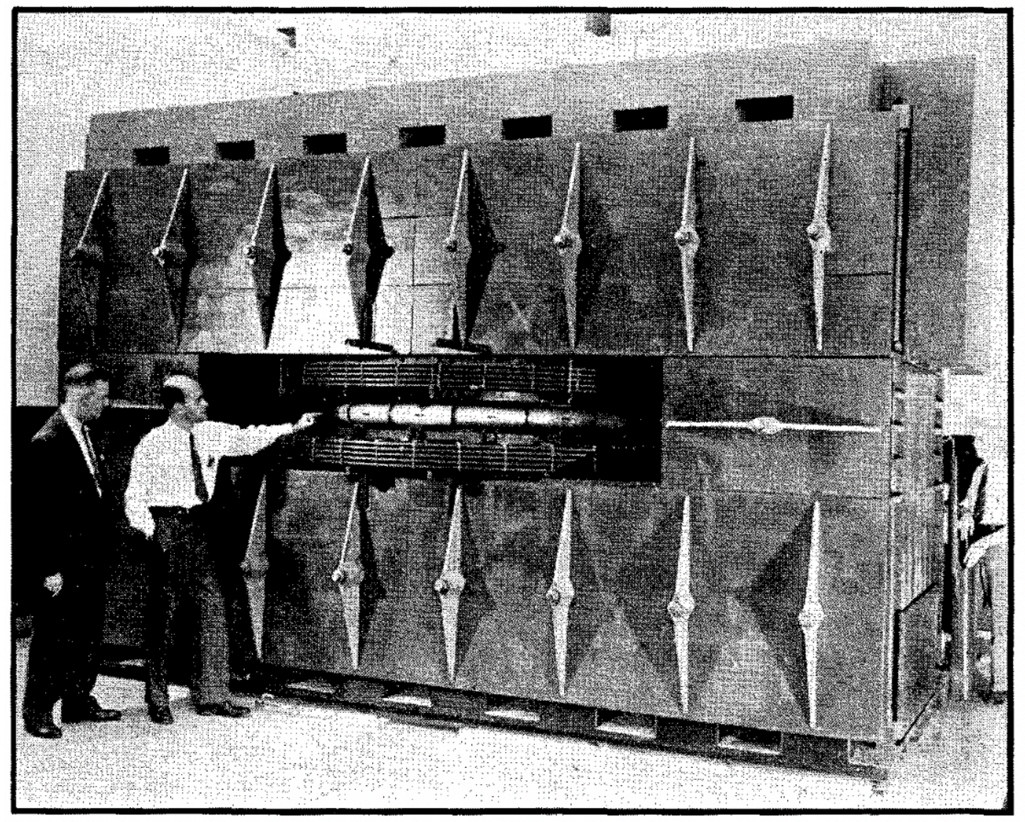

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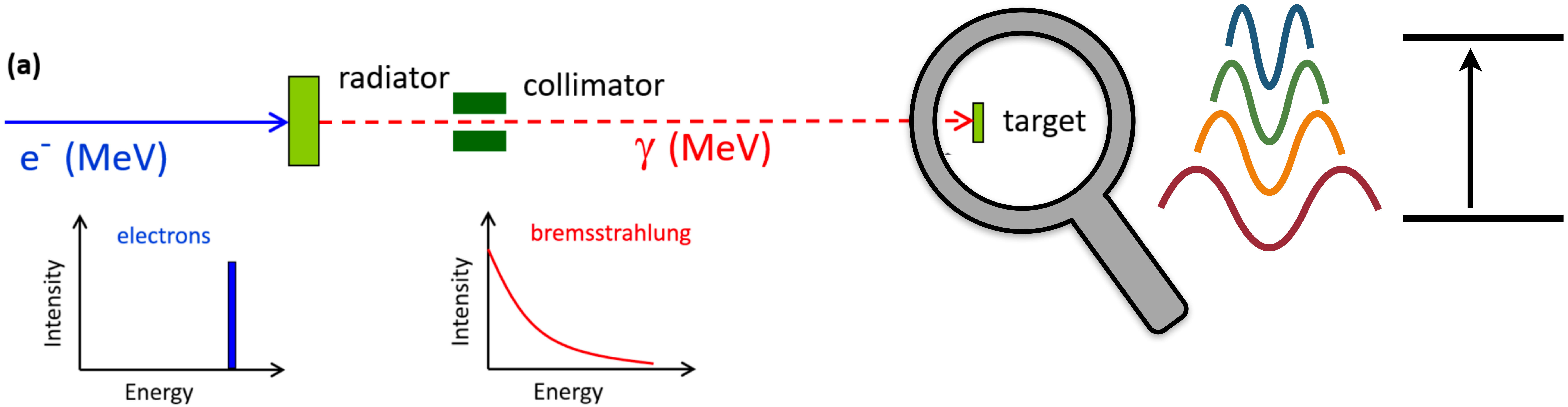

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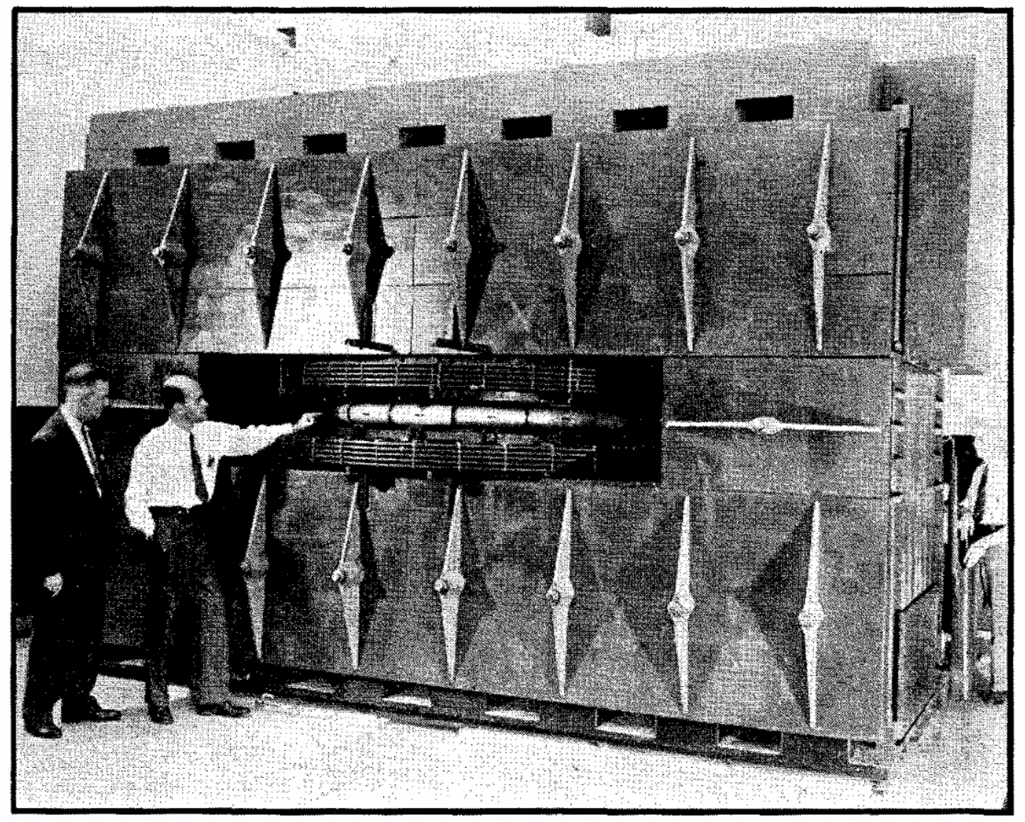

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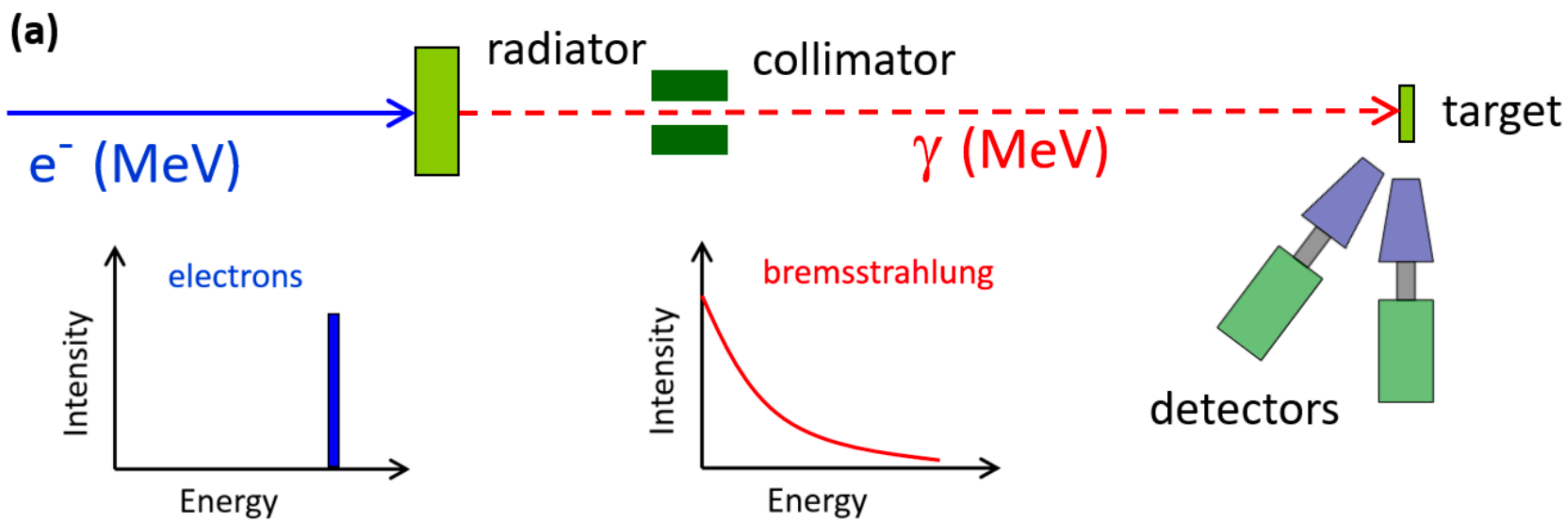

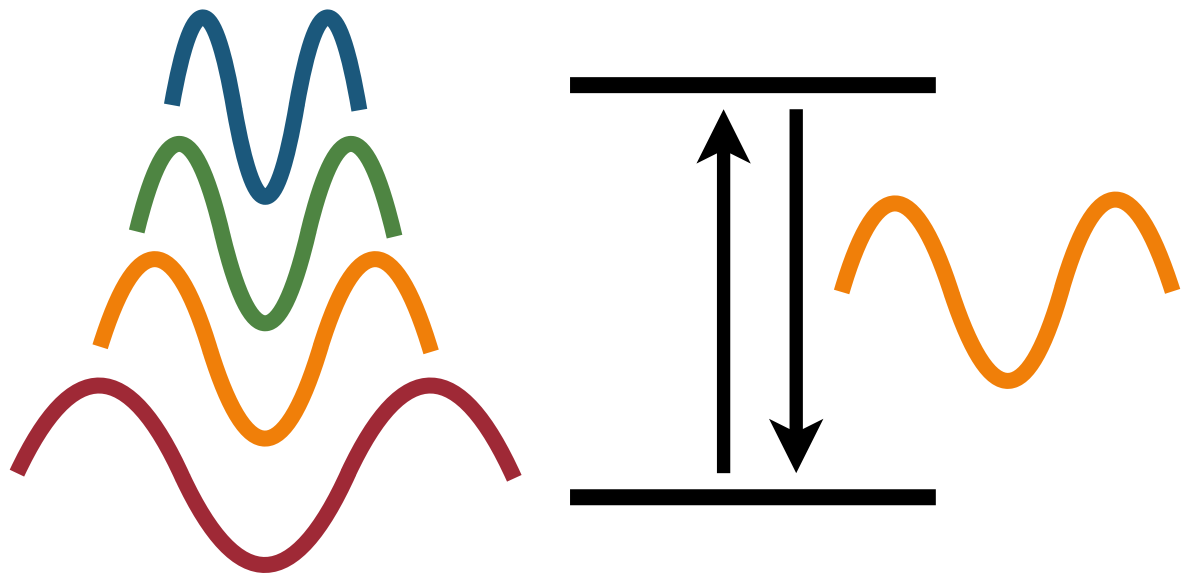

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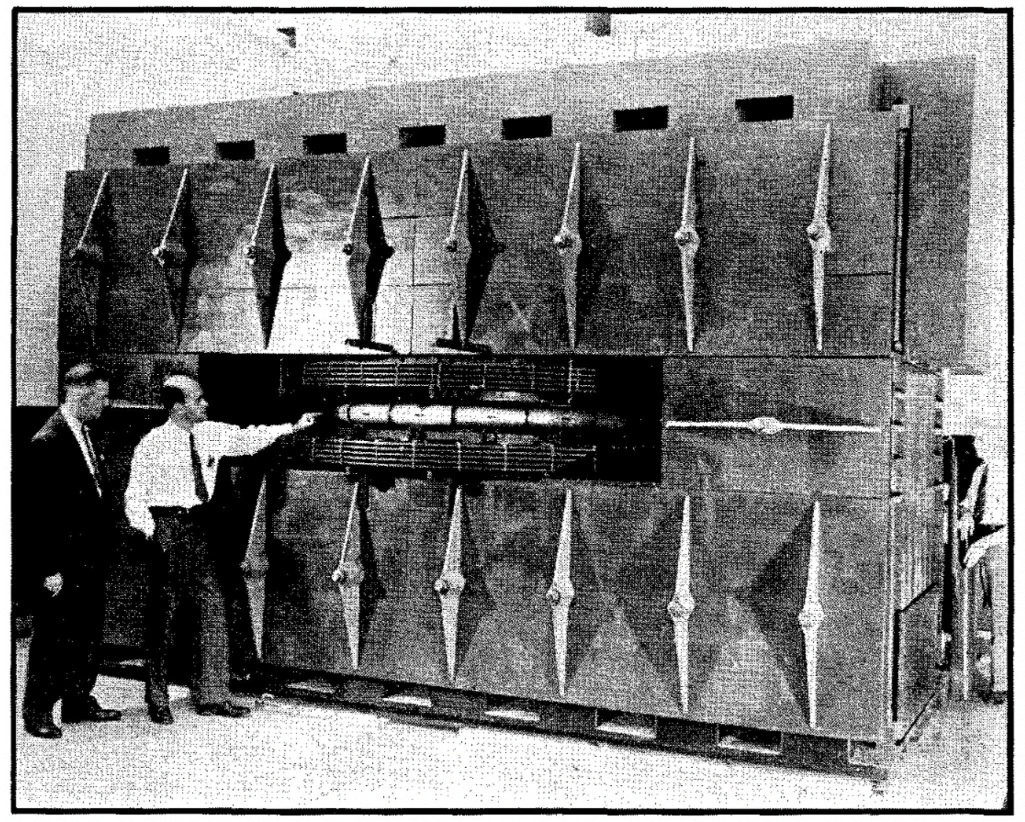

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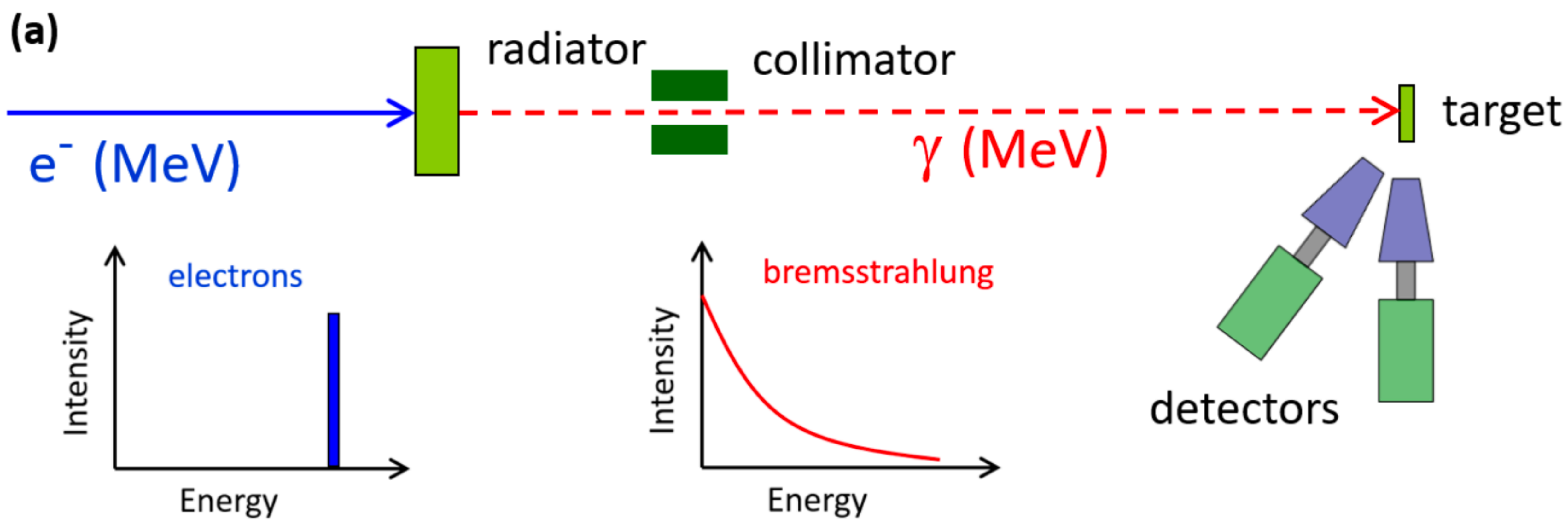
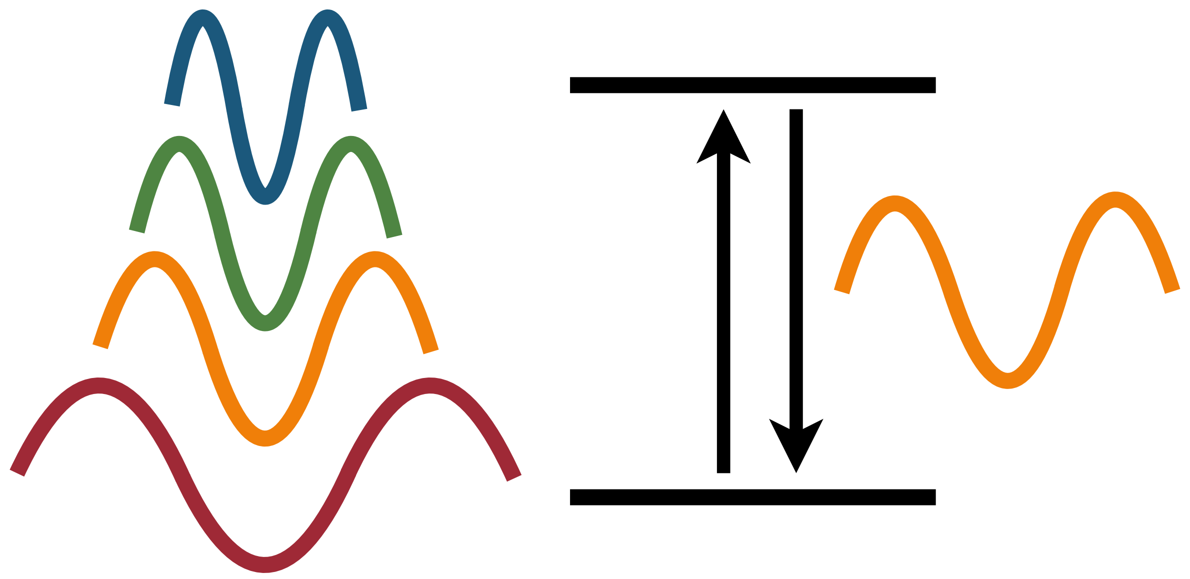


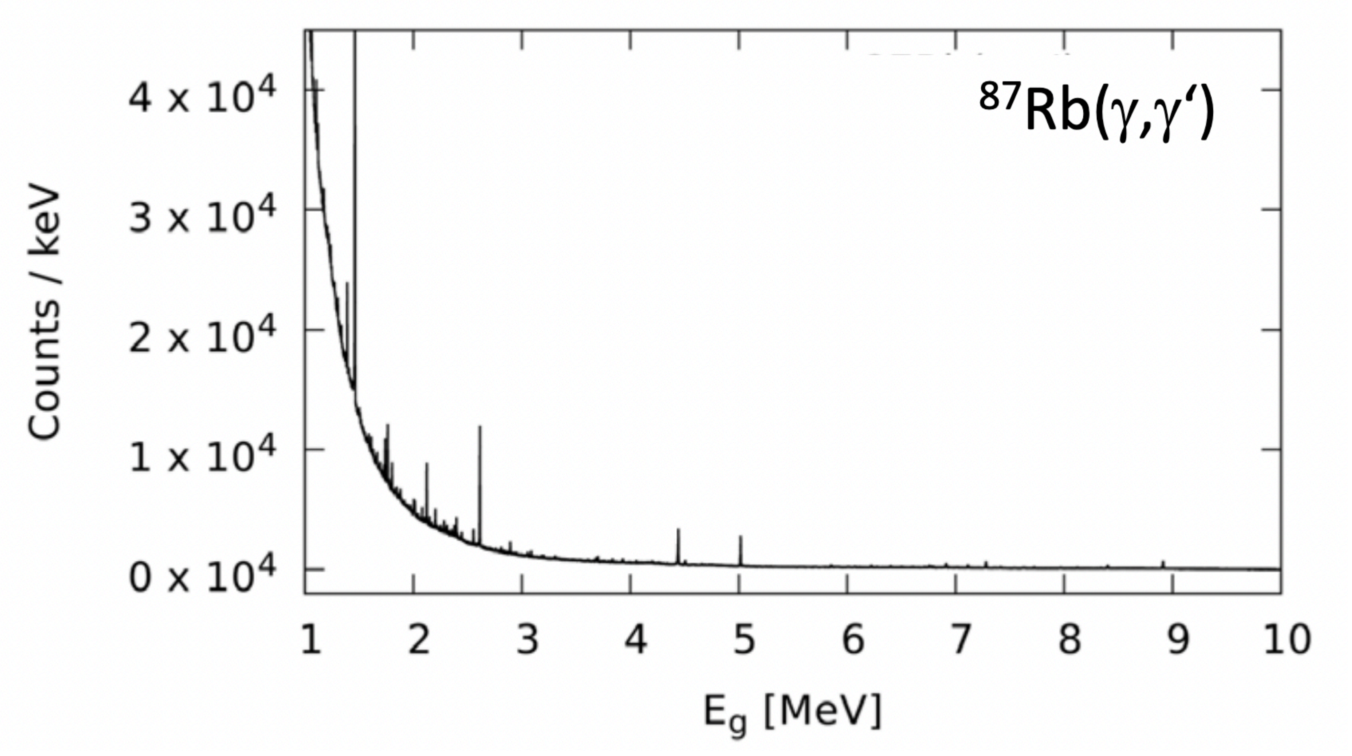


Normal- and superconducting linear electron accelerators were the "workhorses" for photo-nuclear research from the 1980s to the early 2000s.

Kneissl, Prog. Part. Nucl. Phys. 37, 349 (1996)
Kneissl, J. Phys. G 32, R217 (2006)

Nuclear resonance fluorescence with bremsstrahlung

Experiments using photons from bremsstrahlung enable an "all-in-one-go" approach. However, this comes at a cost.



Contributions to spectrum:

- nuclear γ-rays
- detector response
- nonresonant background
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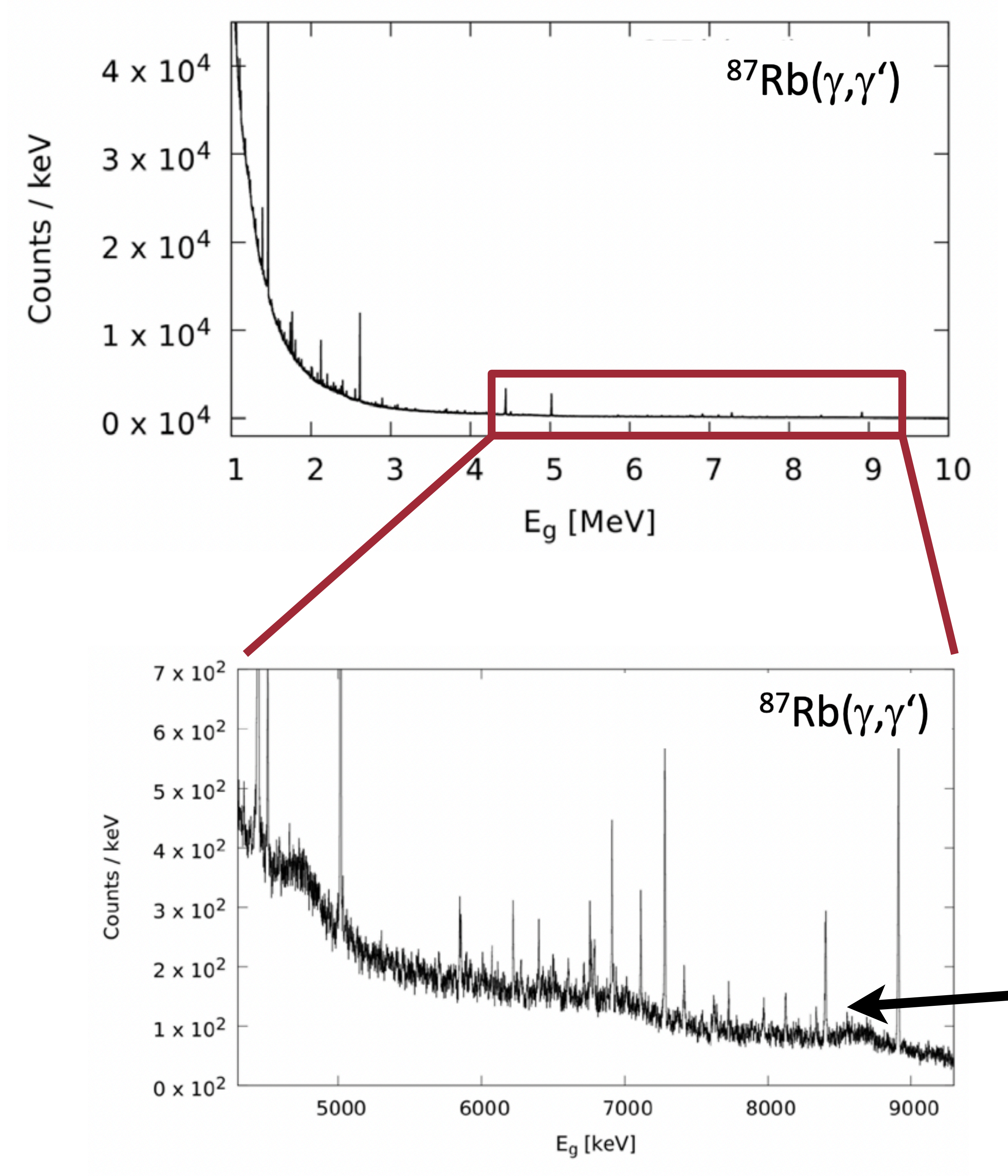

Courtesy of Wilhelmy and Zilges

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uniqueness?

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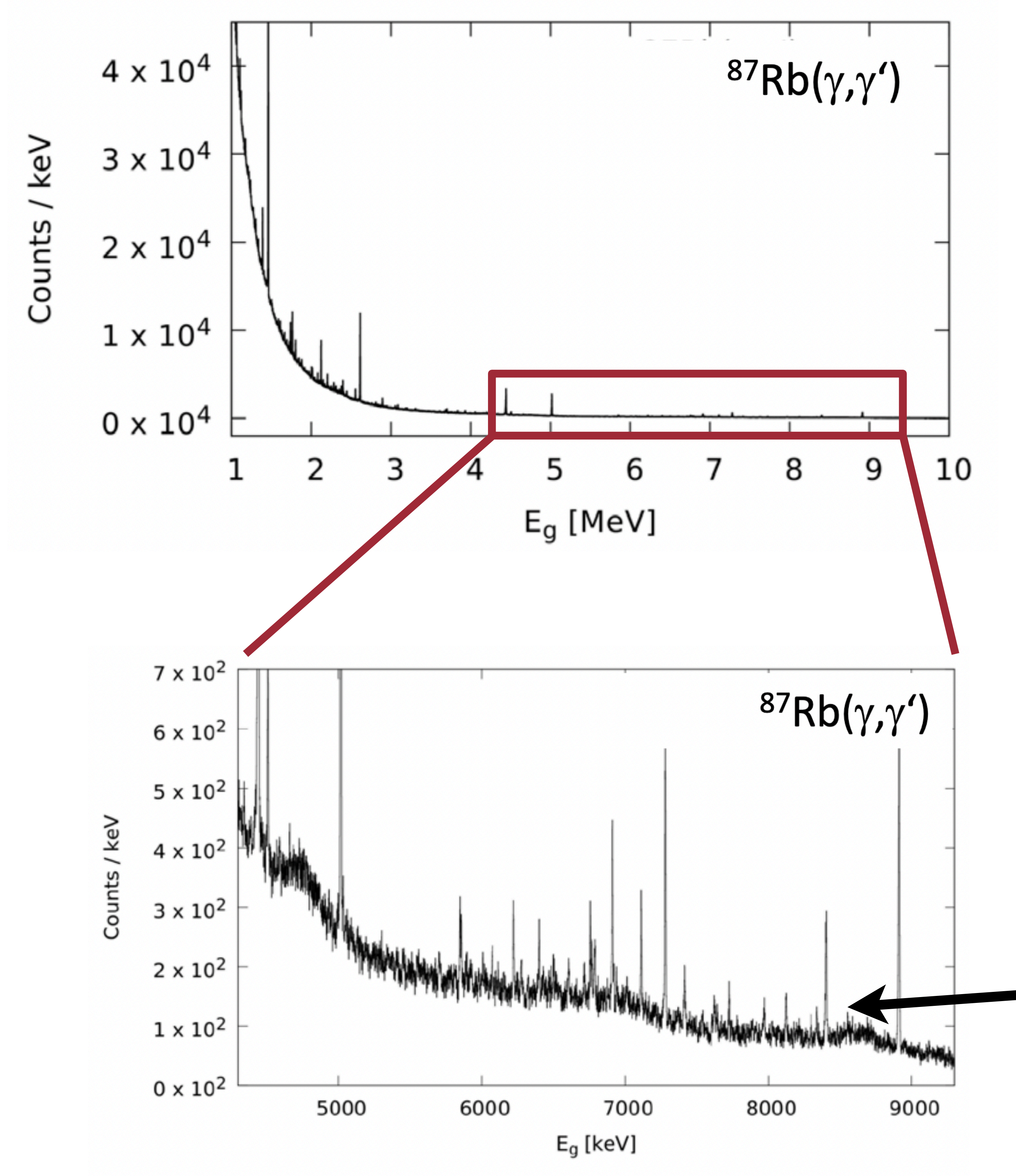

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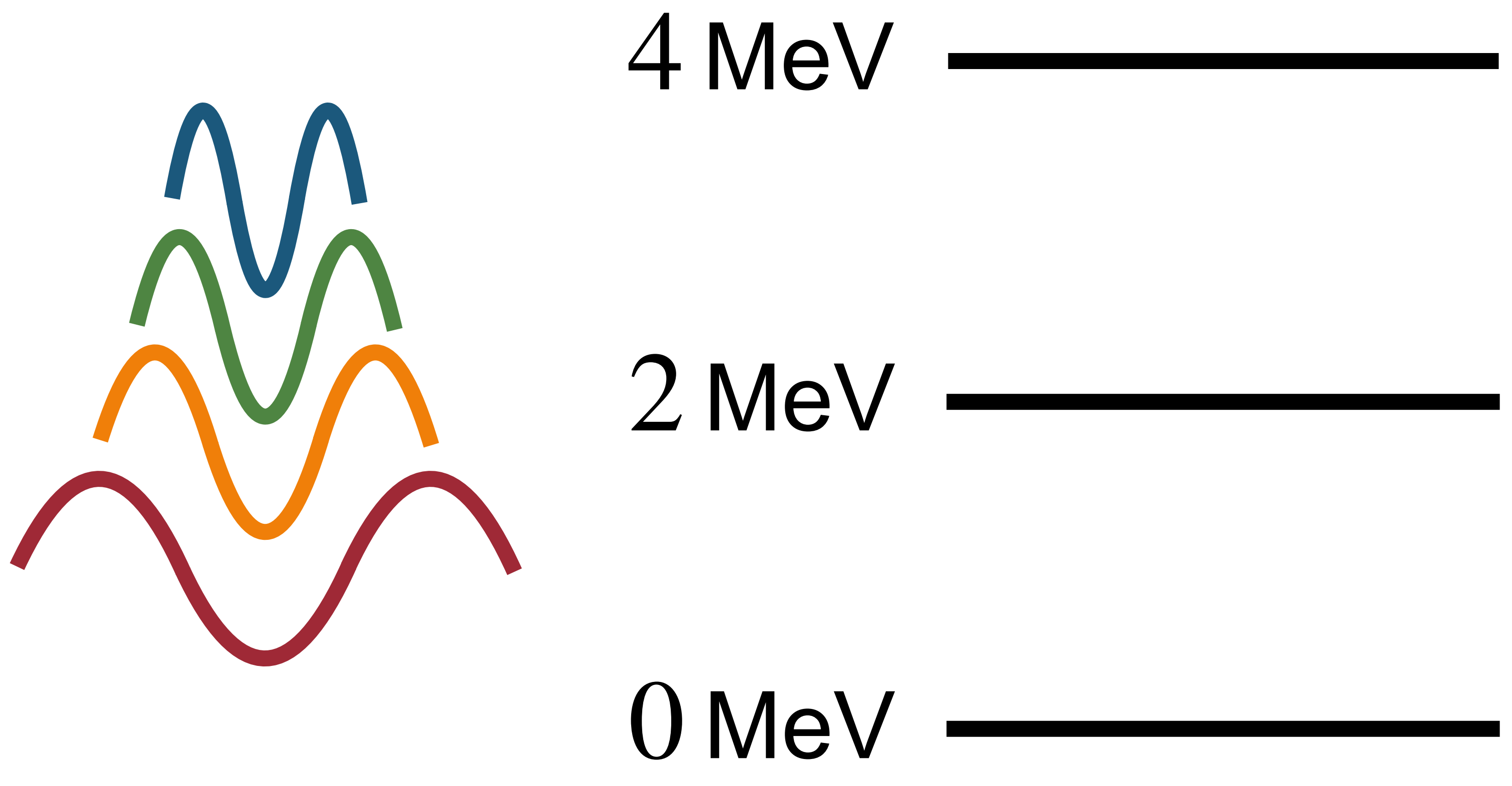

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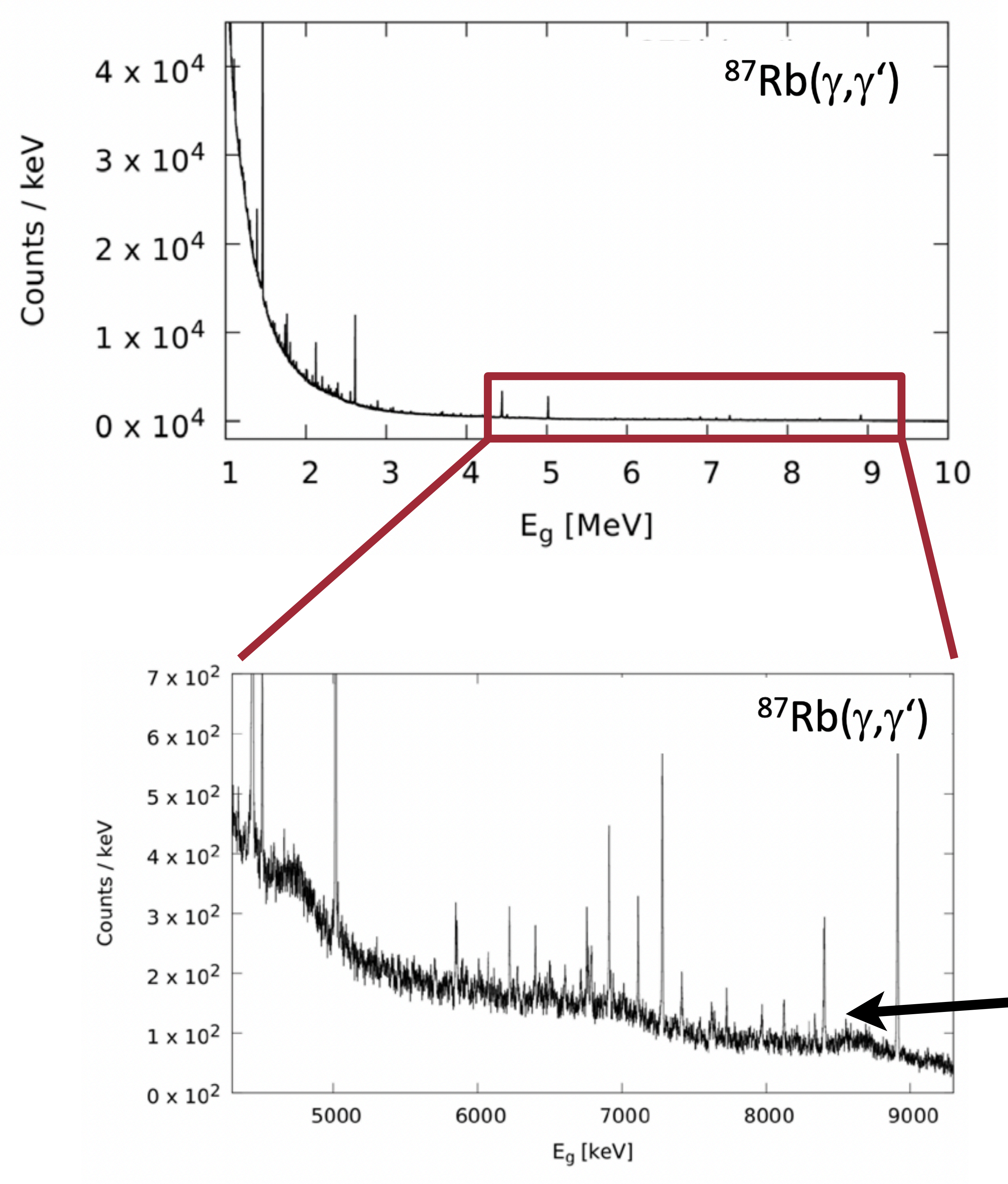

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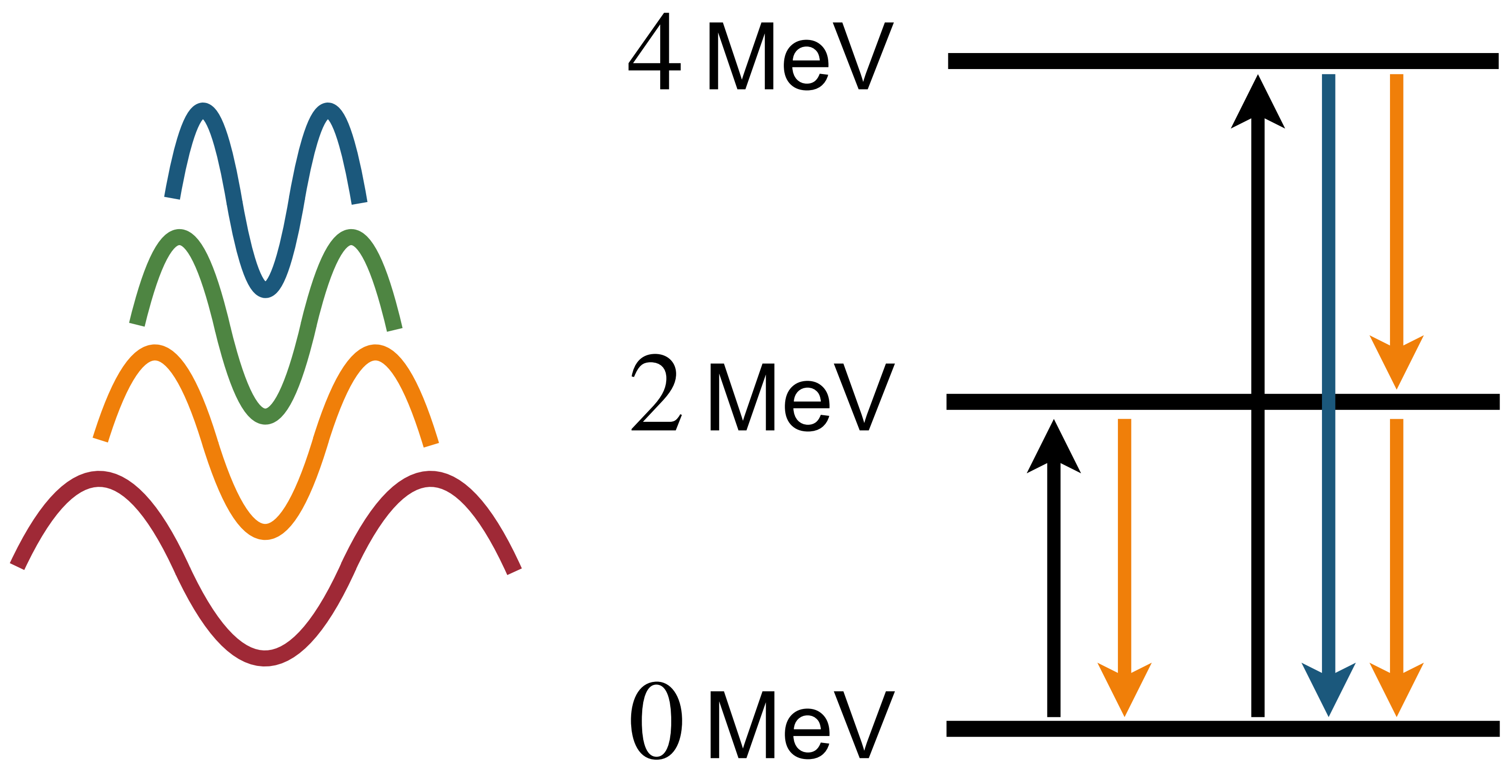

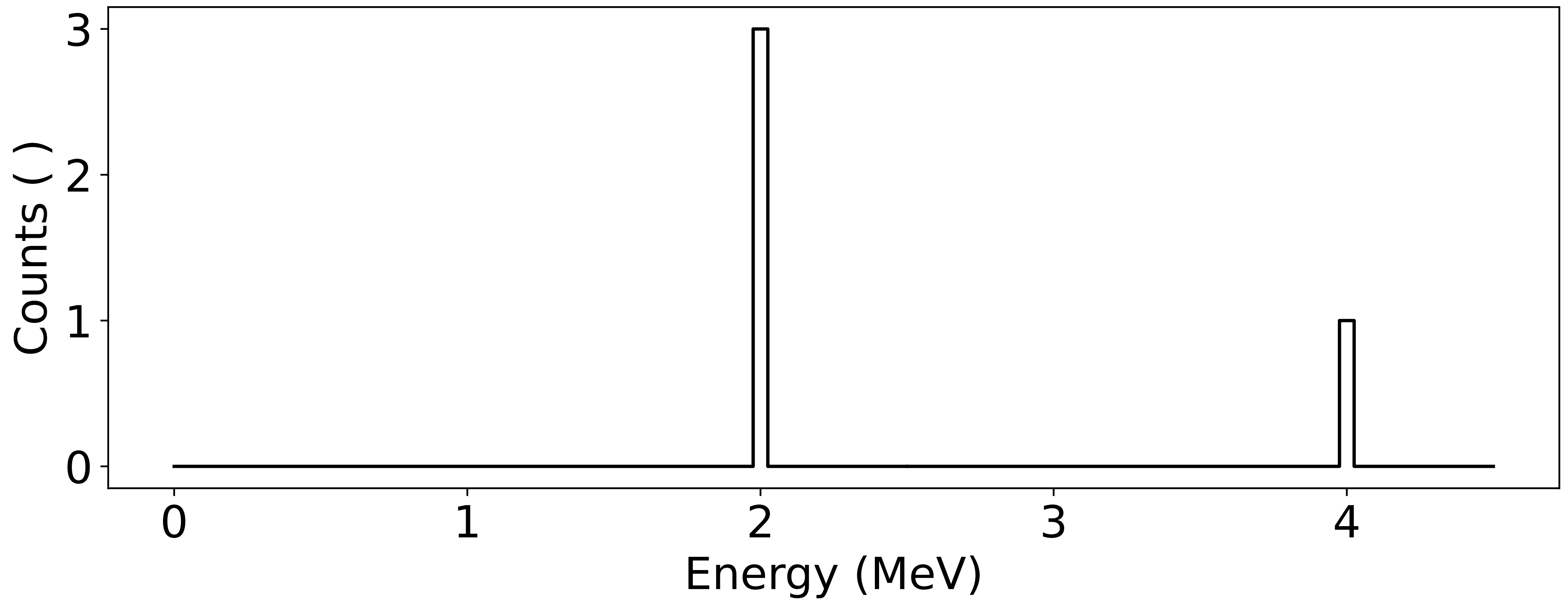

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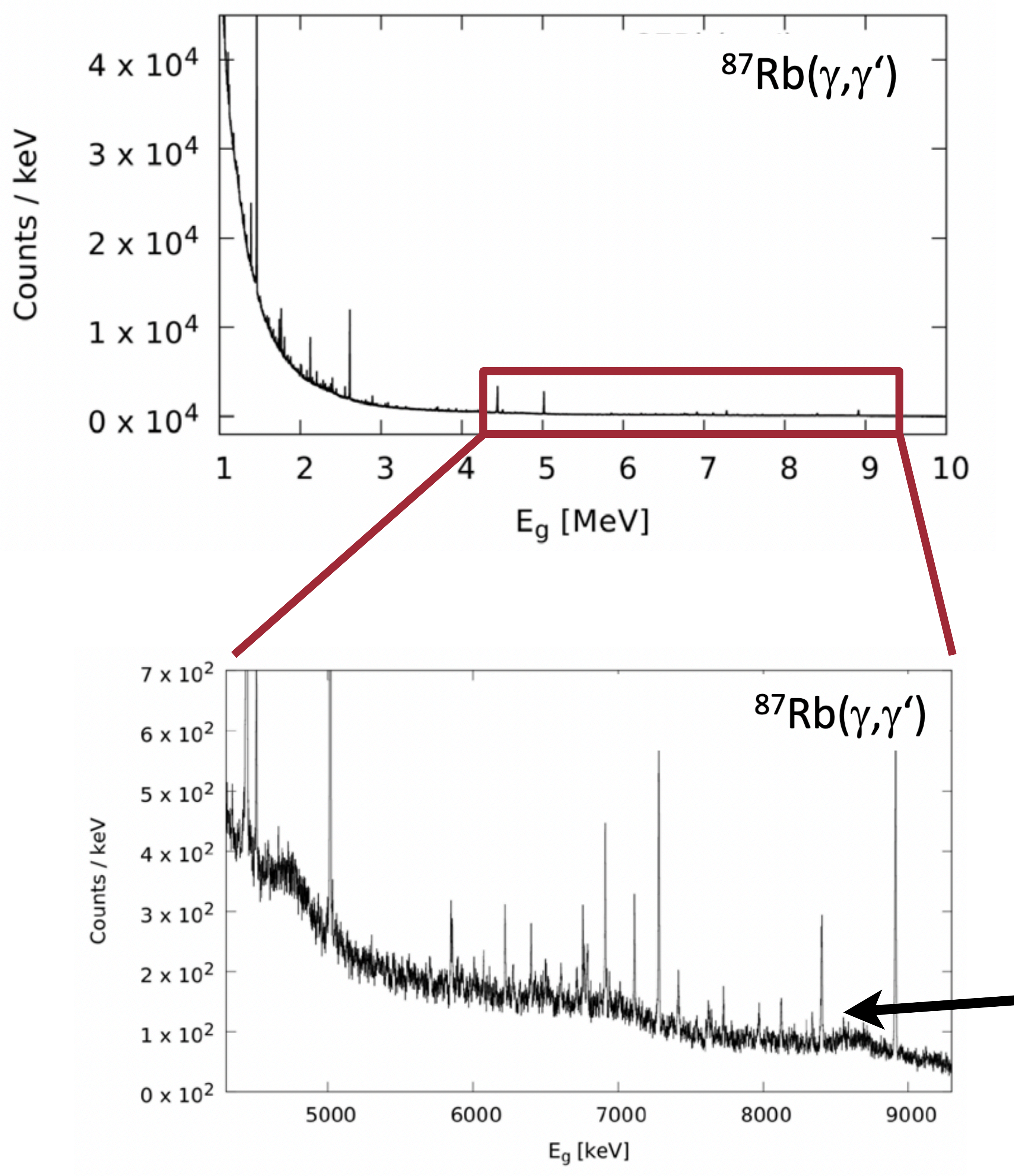

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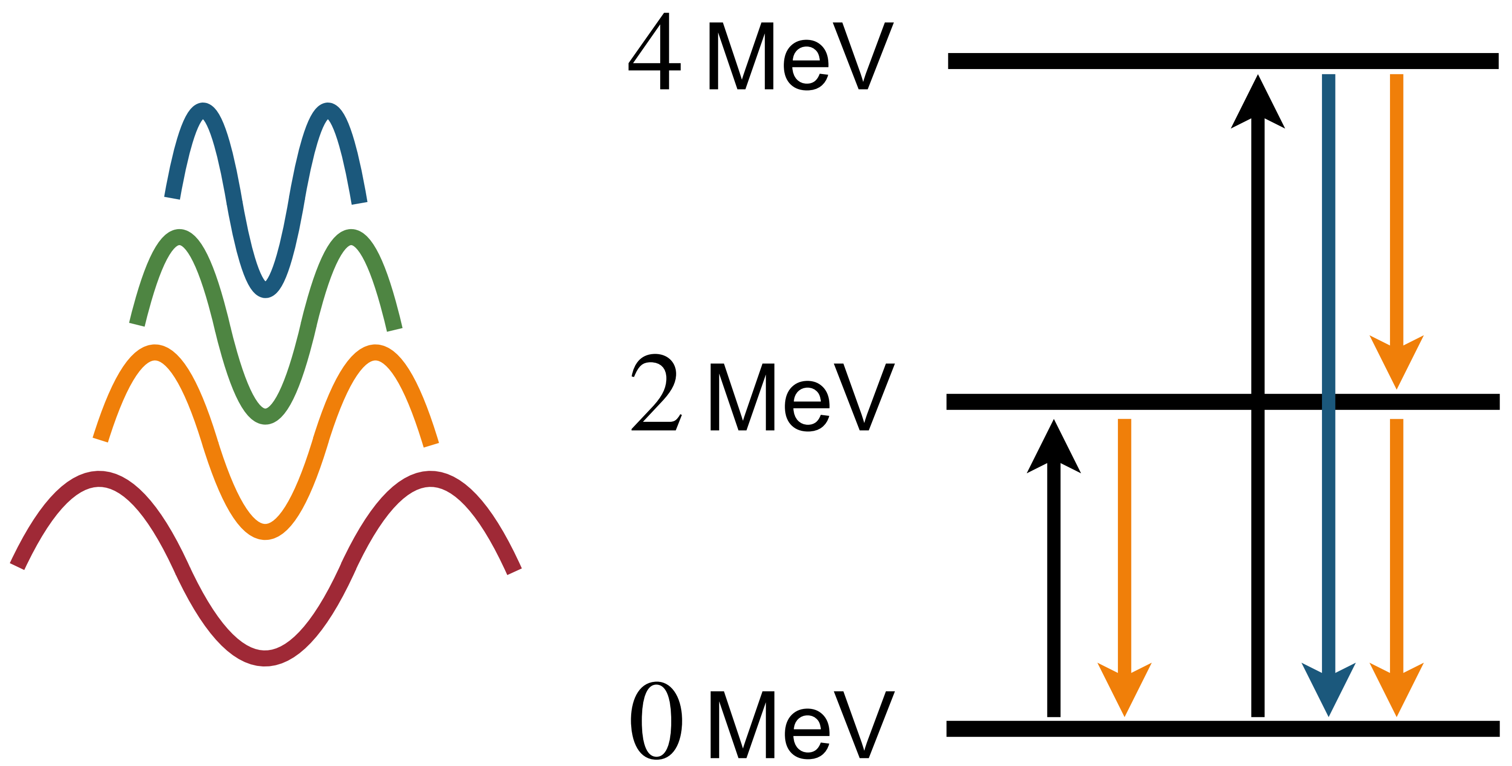

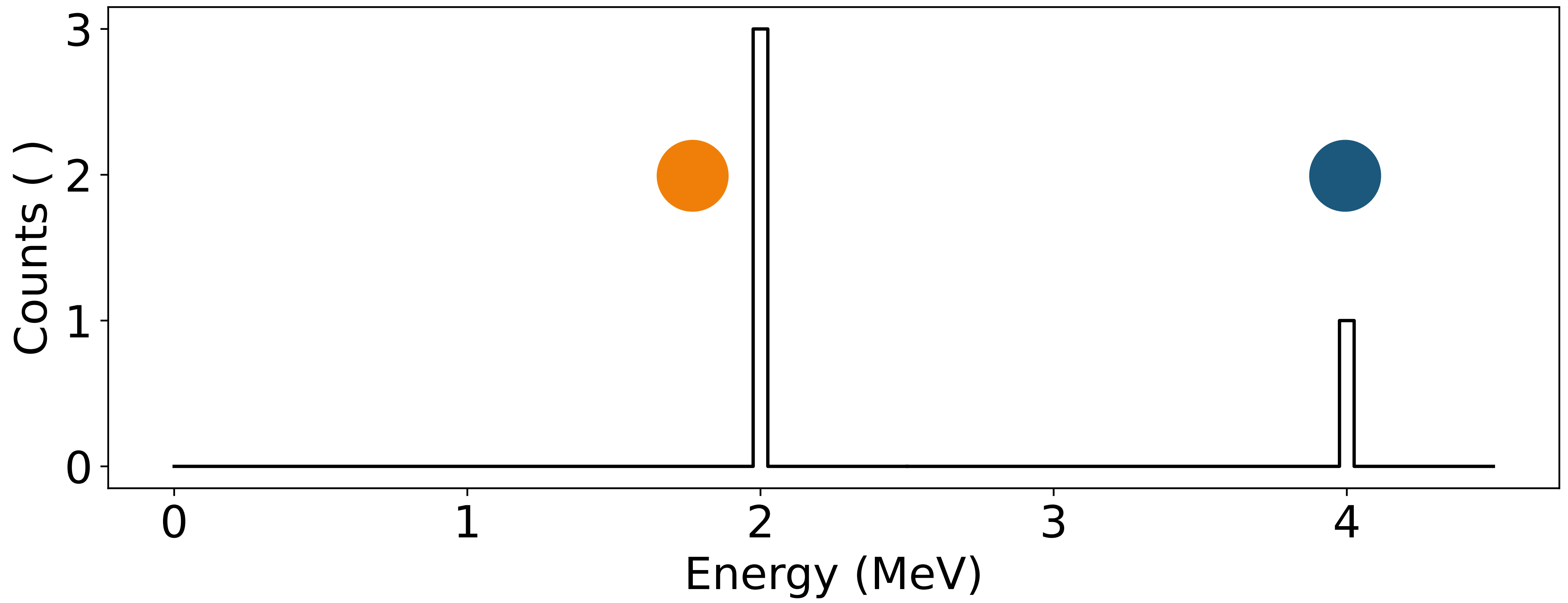

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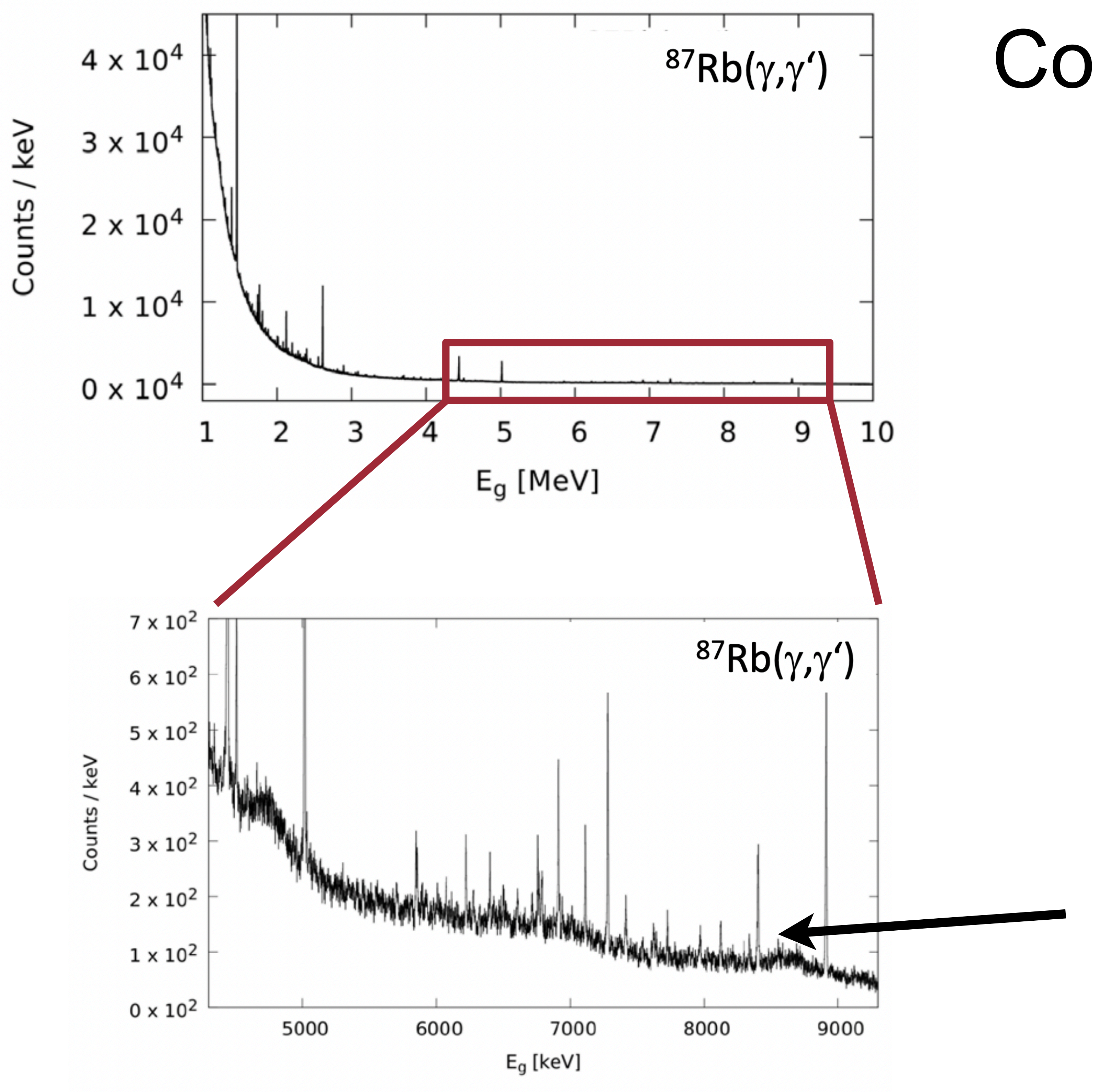

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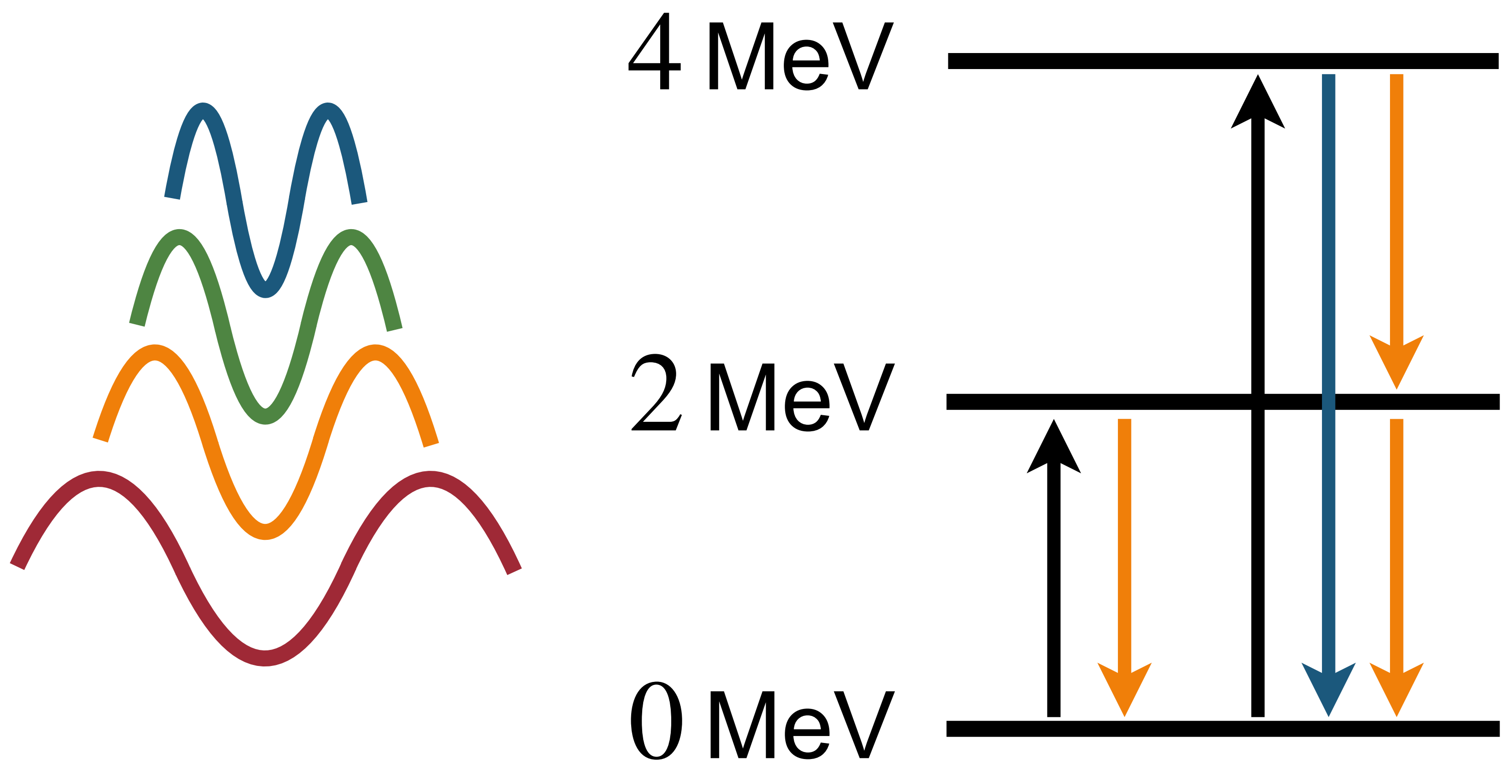

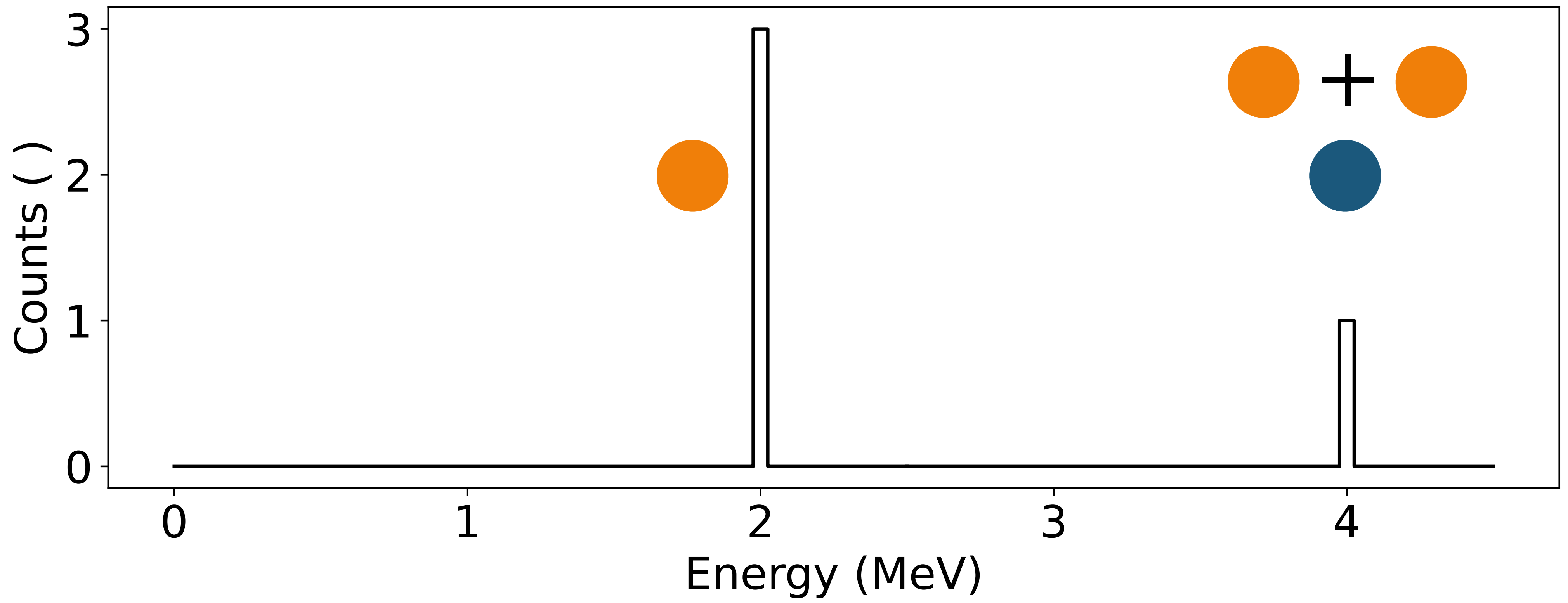

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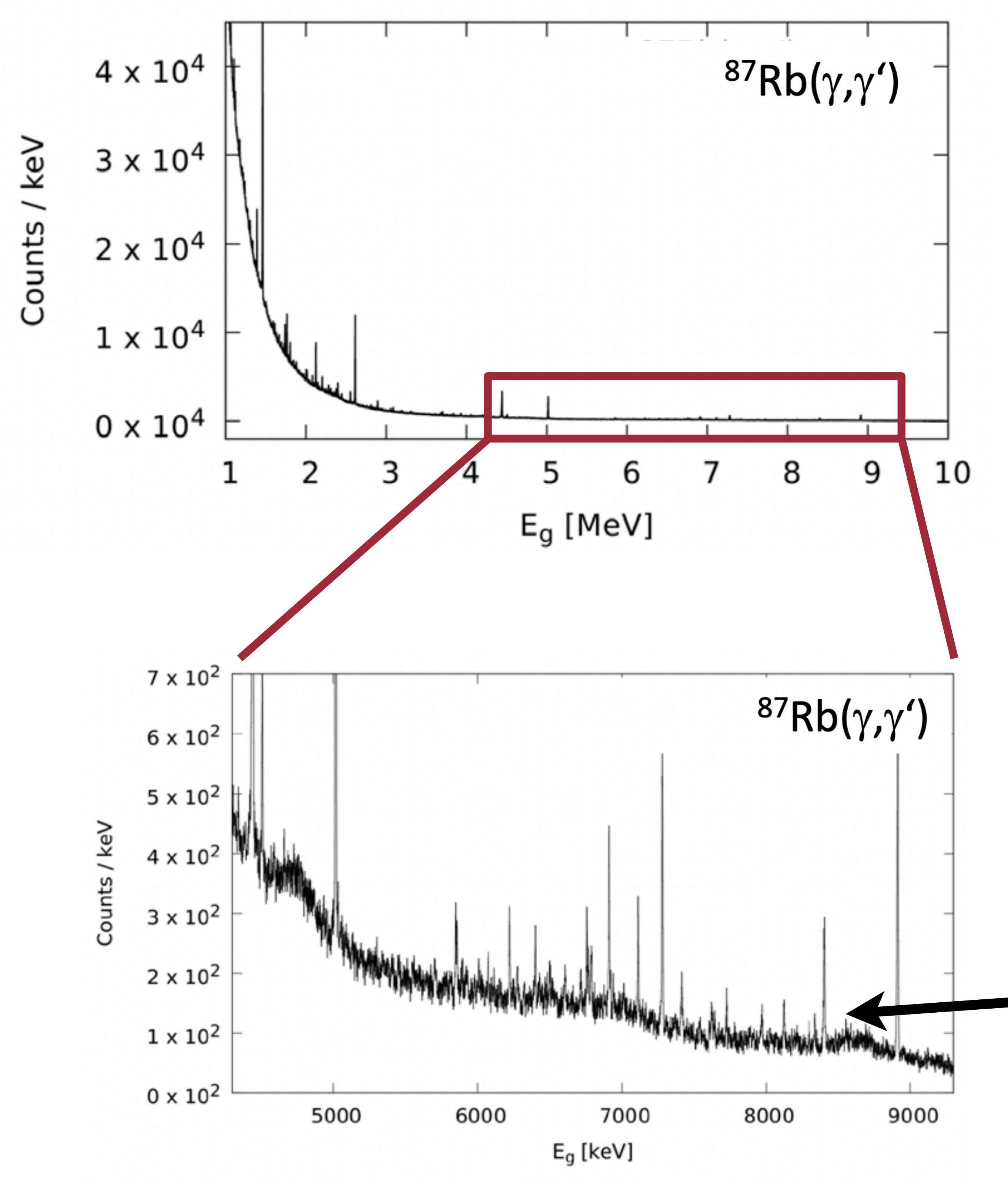

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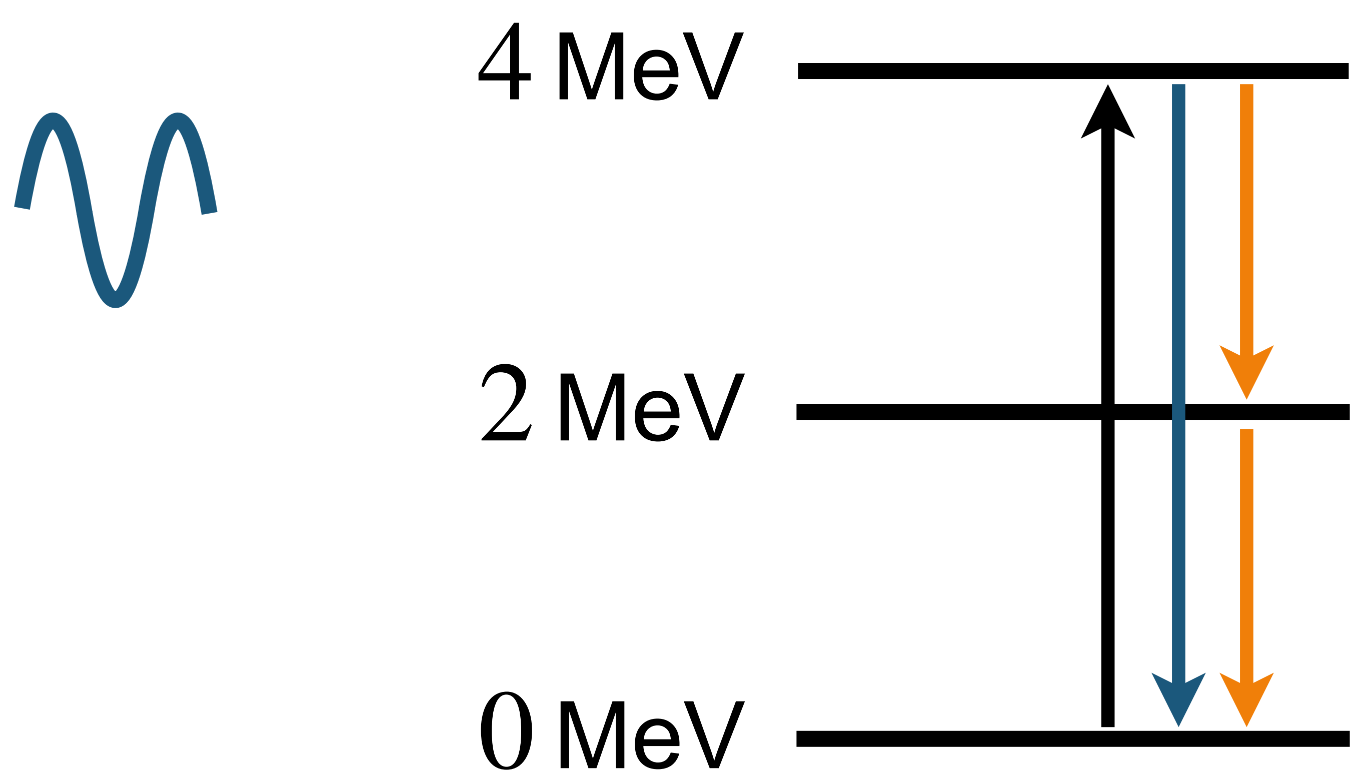

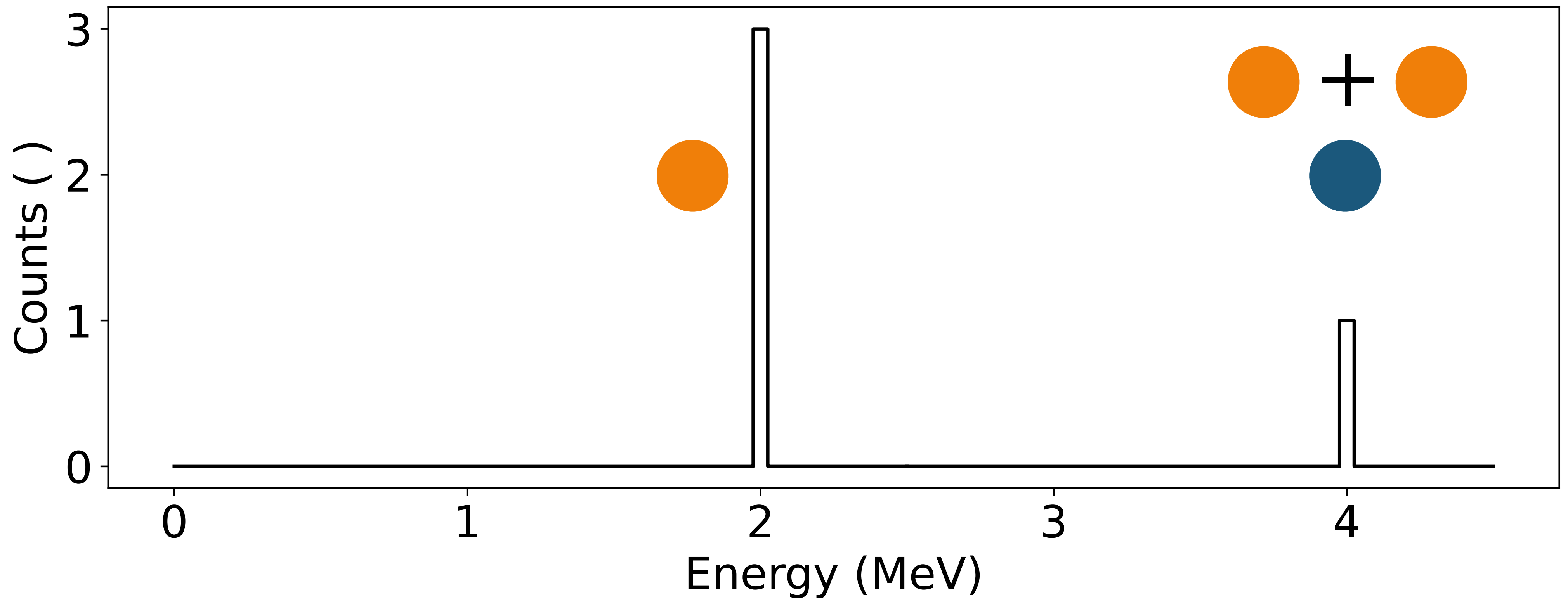

Quasimonochromatic and polarized photon beams

Polarized photon beams with narrow bandwidth are produced by Laser-Compton Backscattering.

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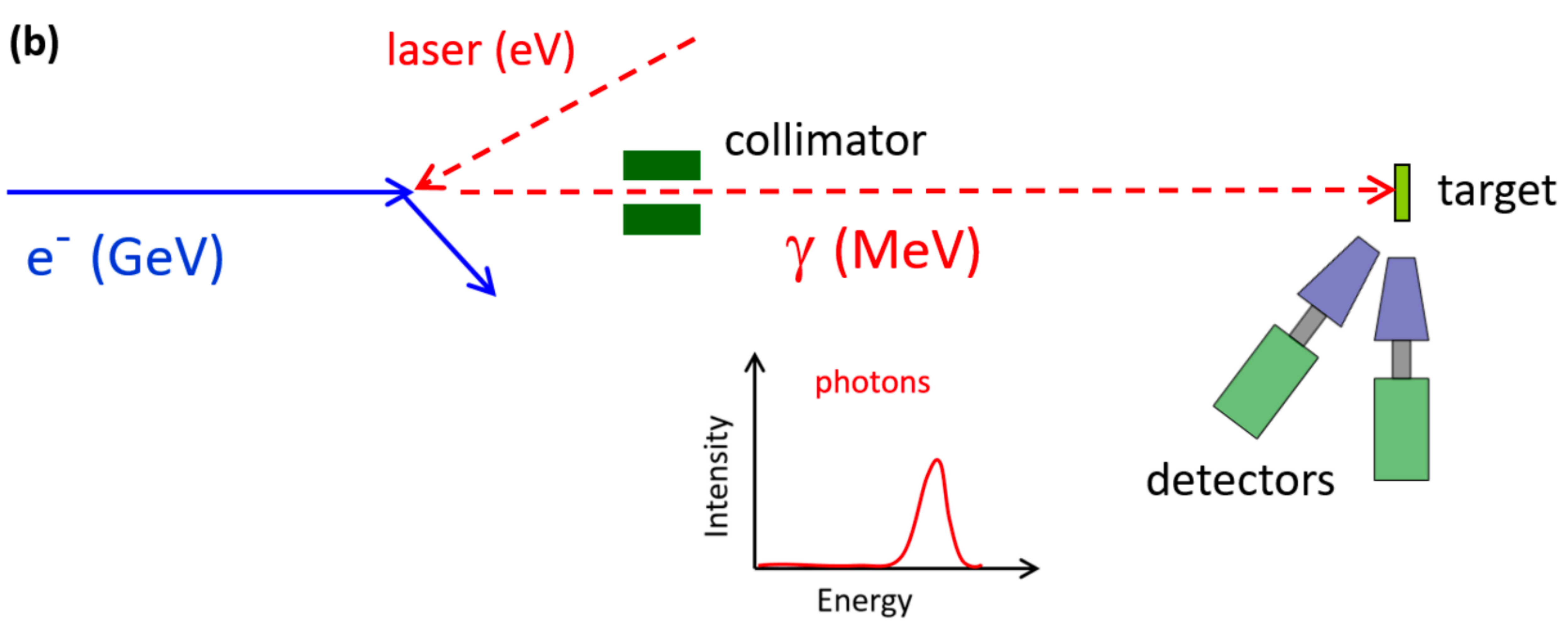

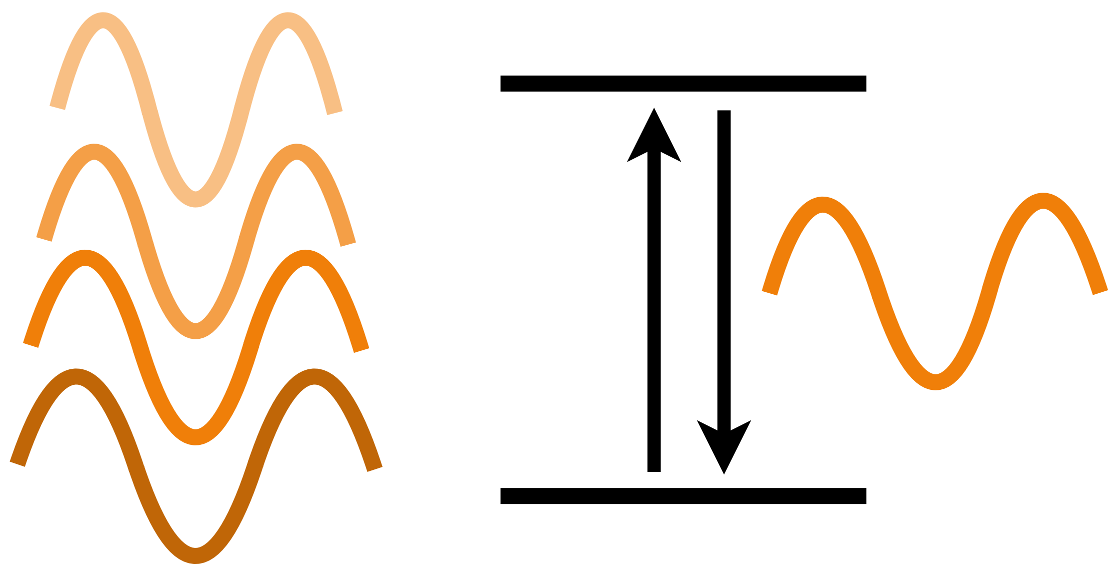

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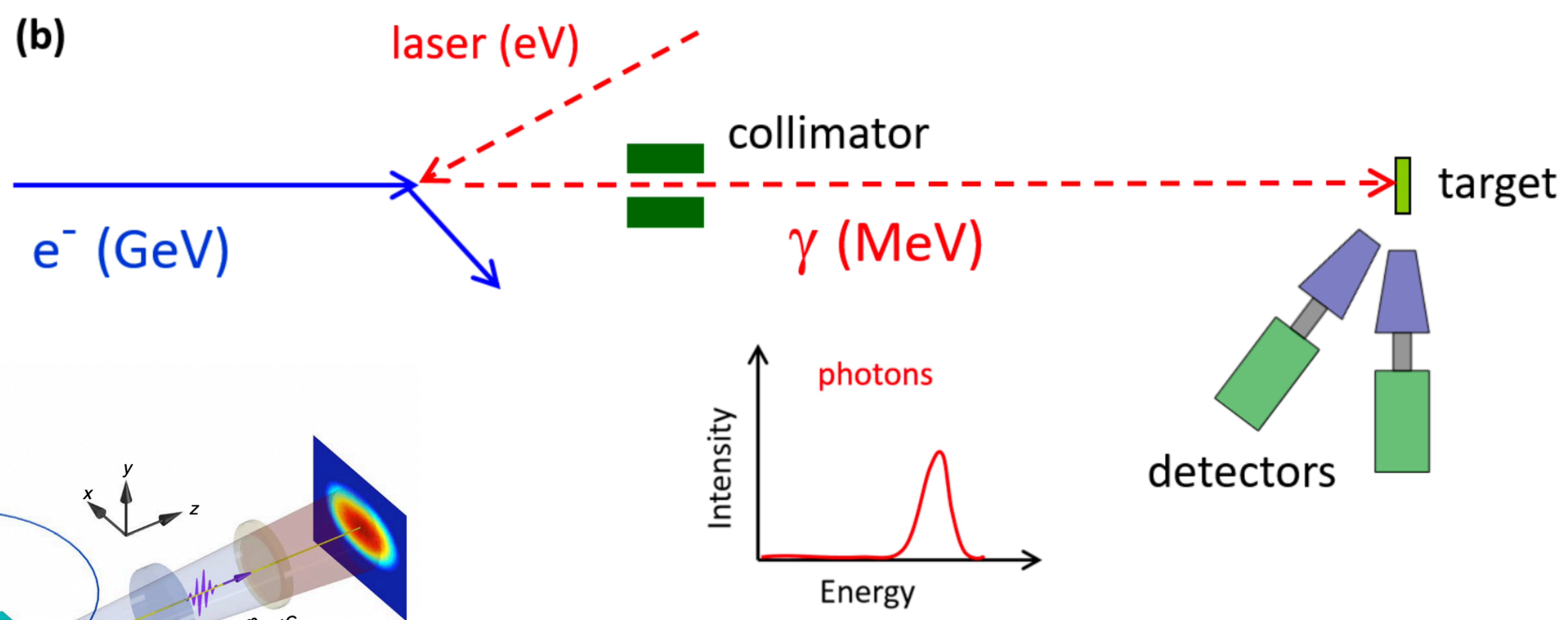
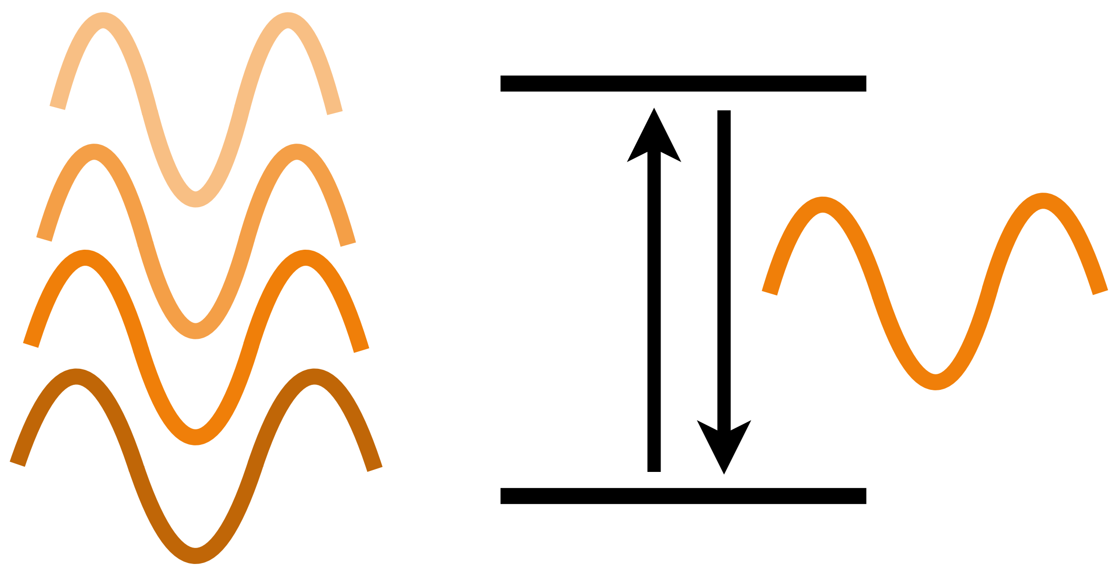
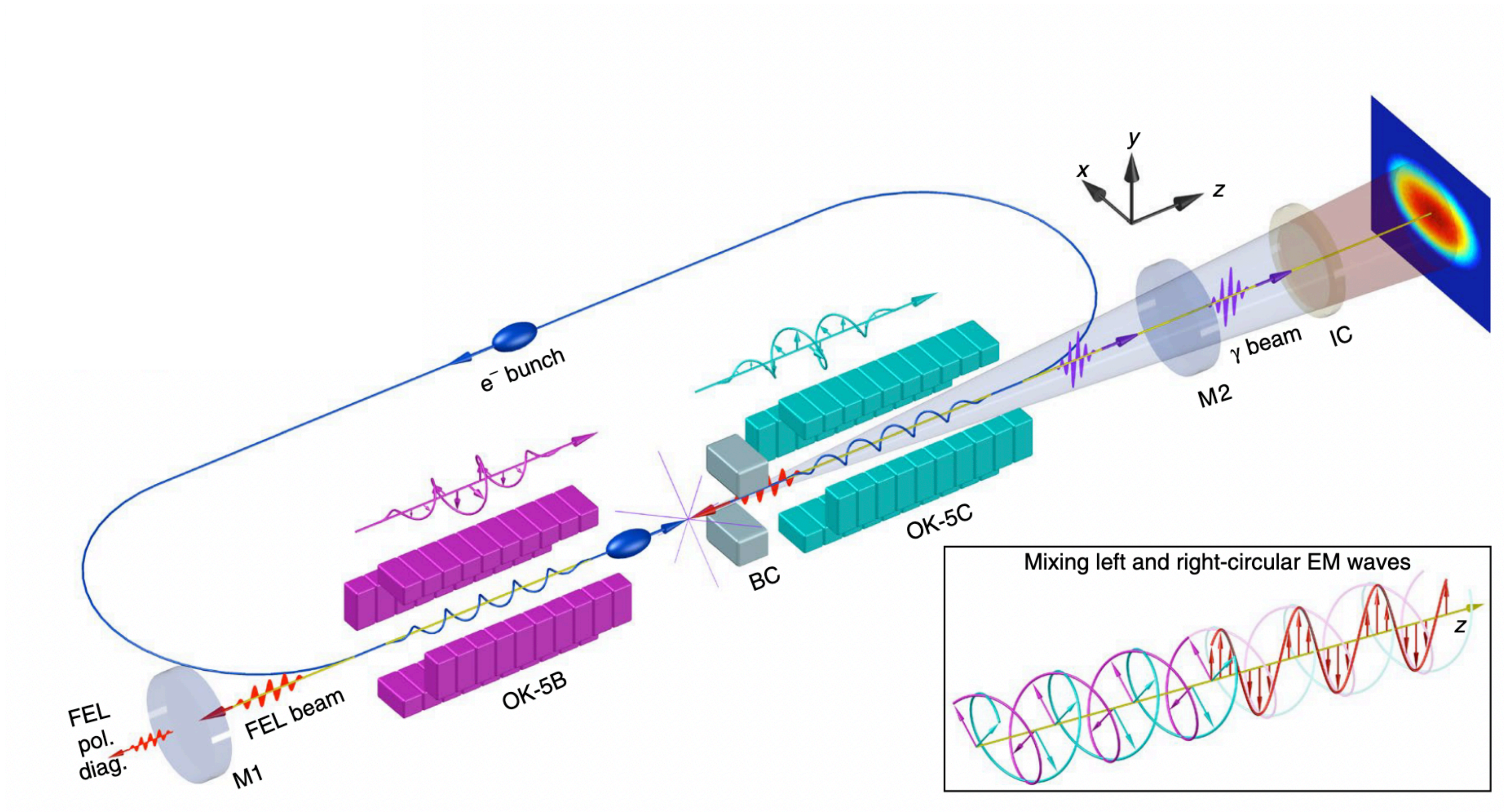






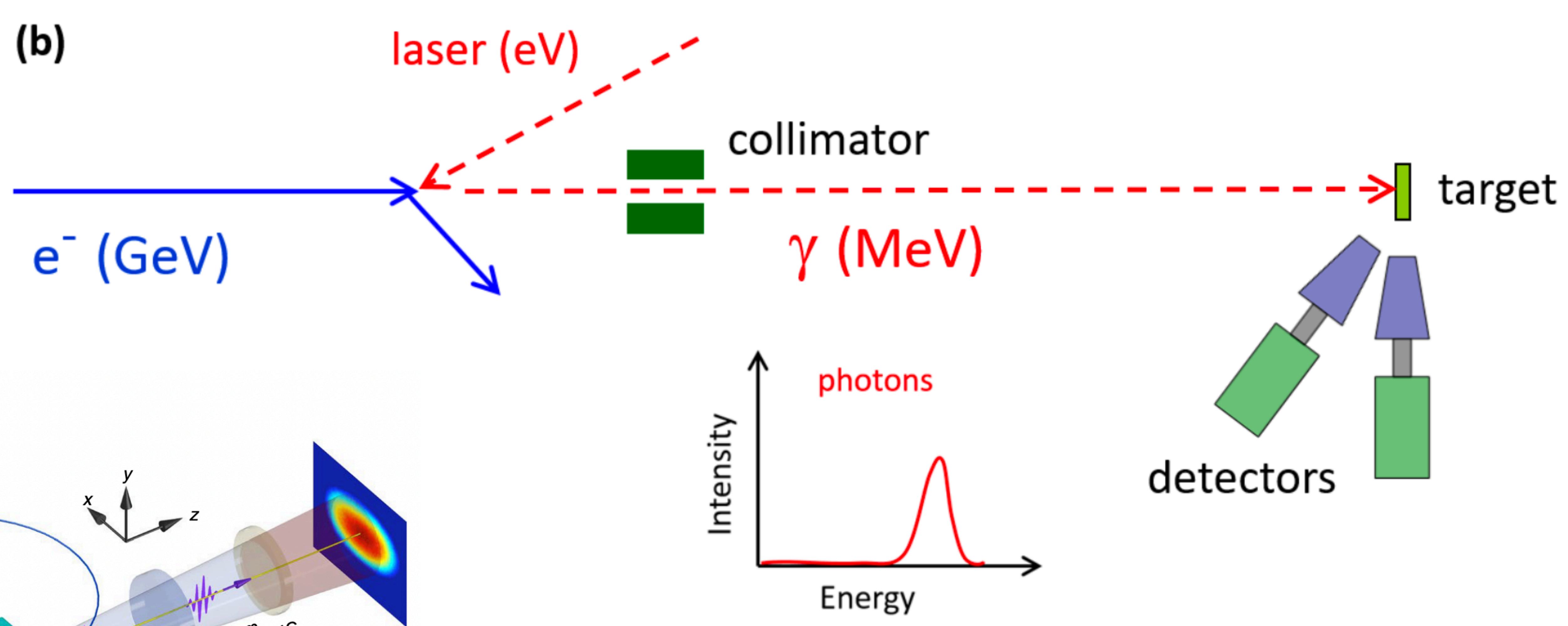
Yan, Nat. Photonics 13, 629 (2019)

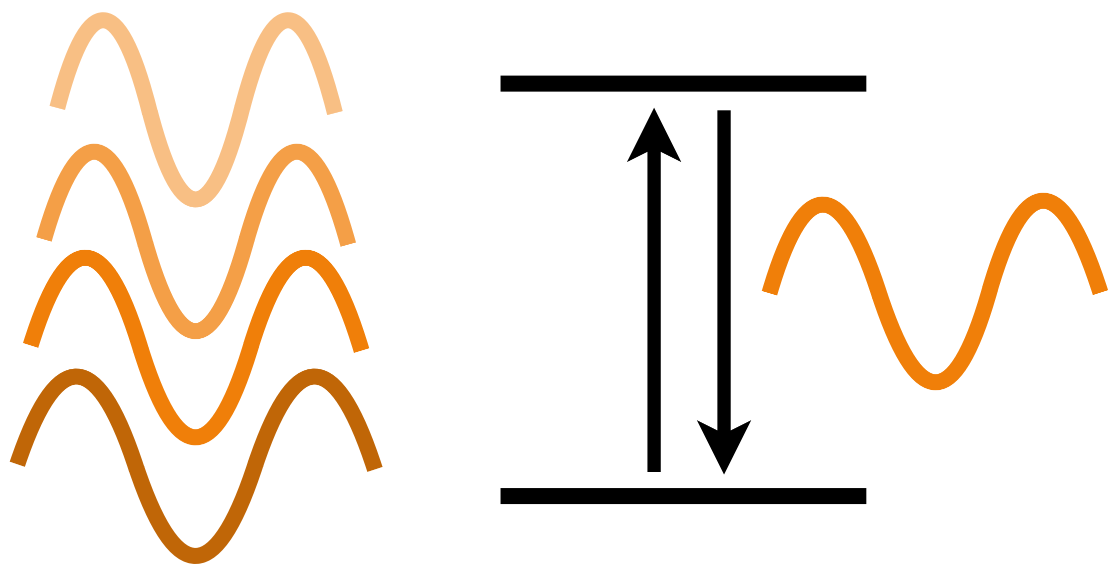
Quasimonochromatic and polarized photon beams

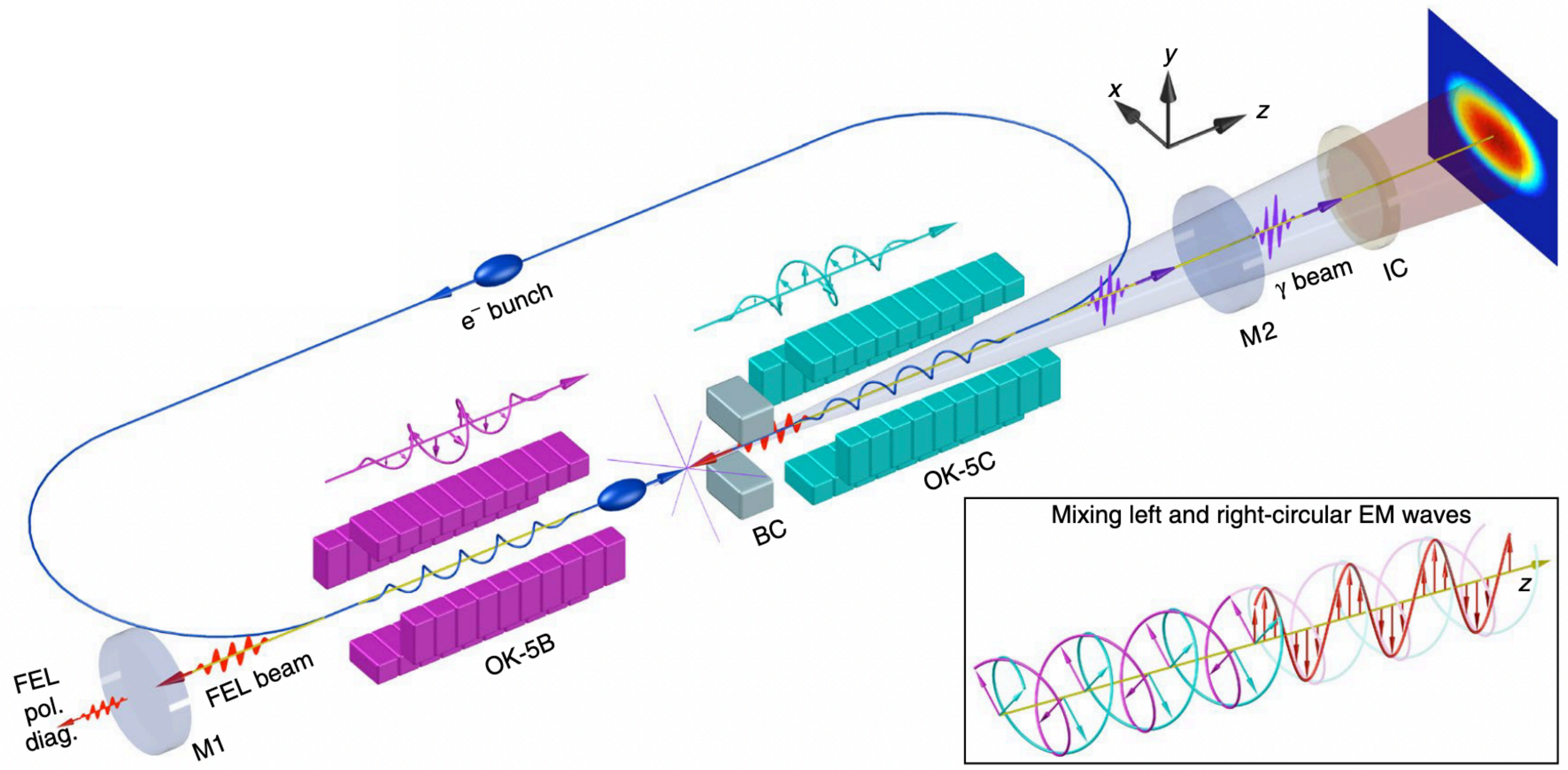
Polarized photon beams with narrow bandwidth are produced by Laser-Compton Backscattering.

Milburn, Phys. Rev. Lett. 10, 75 (1963)

Litvinenko, Phys. Rev. Lett. 78, 4569 (1997)







Yan, Nat. Photonics 13, 629 (2019)

Properties:

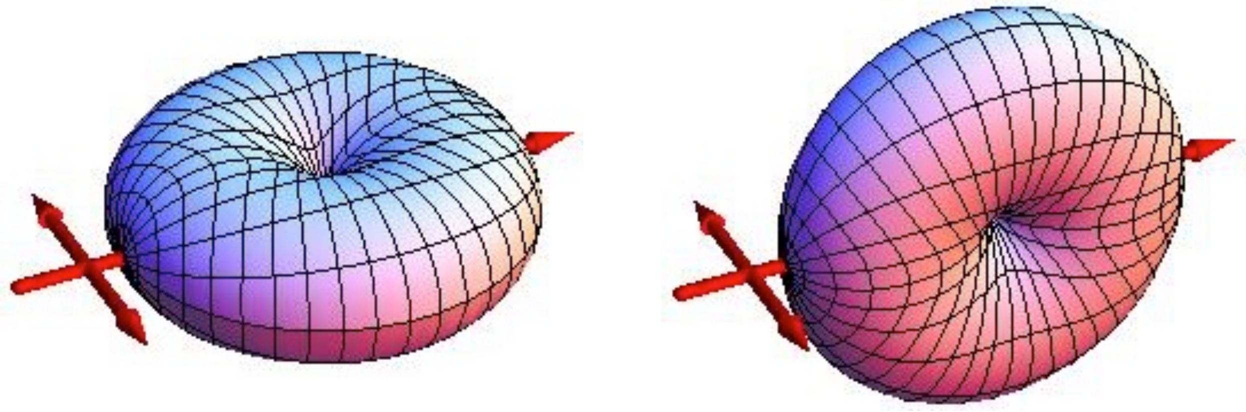
- $E_\gamma = 2 - 130$ MeV
- $\Delta E_\gamma / E_\gamma = 1 - 3\,\%$
- photon flux $\leq 10^9\, \gamma s^{-1}$
- linear pol. $> 99\,\%$

Quasimonochromatic and polarized photon beams

Polarized photons in the entrance channel enable the determination of…

Angular distribution for
$0^+ \rightarrow 1^{\pi} \rightarrow 0^+$ cascade:

$$W(\vartheta, \varphi) = 1 + \frac{1}{2}\Big[P_2(\cos\vartheta) + \frac{1}{2}\pi\cos(2\varphi)P_2^{(2)}(\cos\vartheta)\Big]$$



$\pi = +1$ $\qquad$ $\pi = -1$

Quasimonochromatic and polarized photon beams

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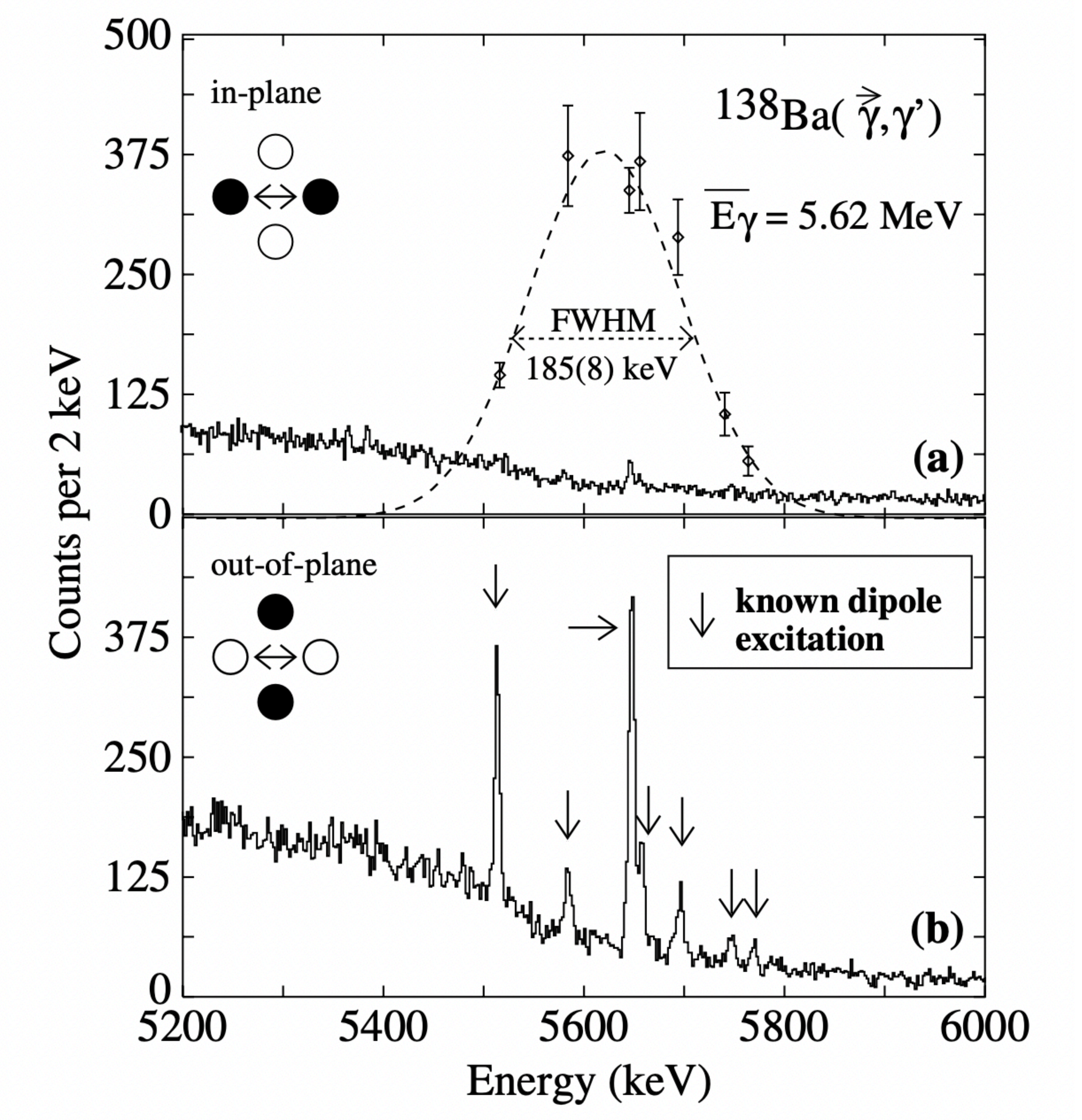

Pietralla, Phys. Rev. Lett. 88, 012502 (2002)

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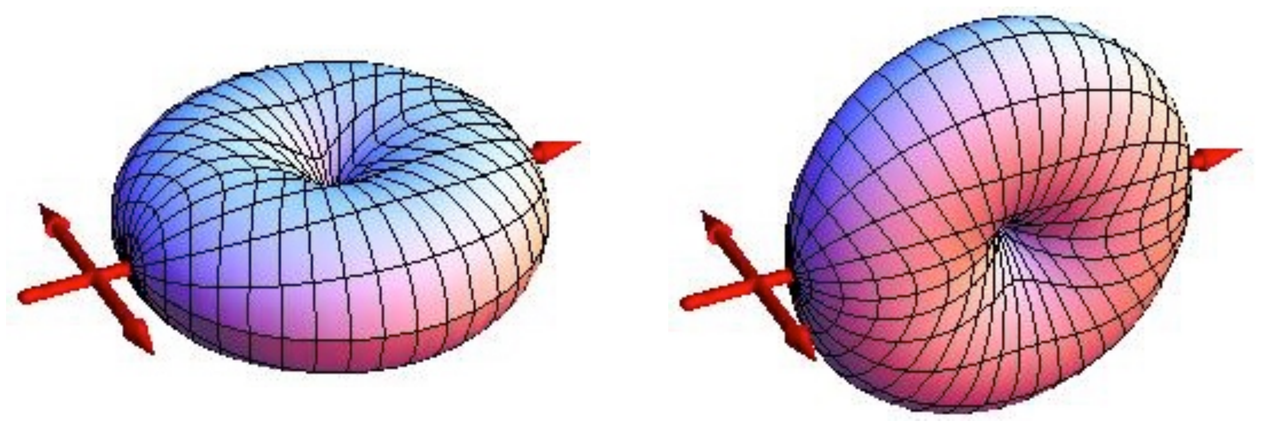

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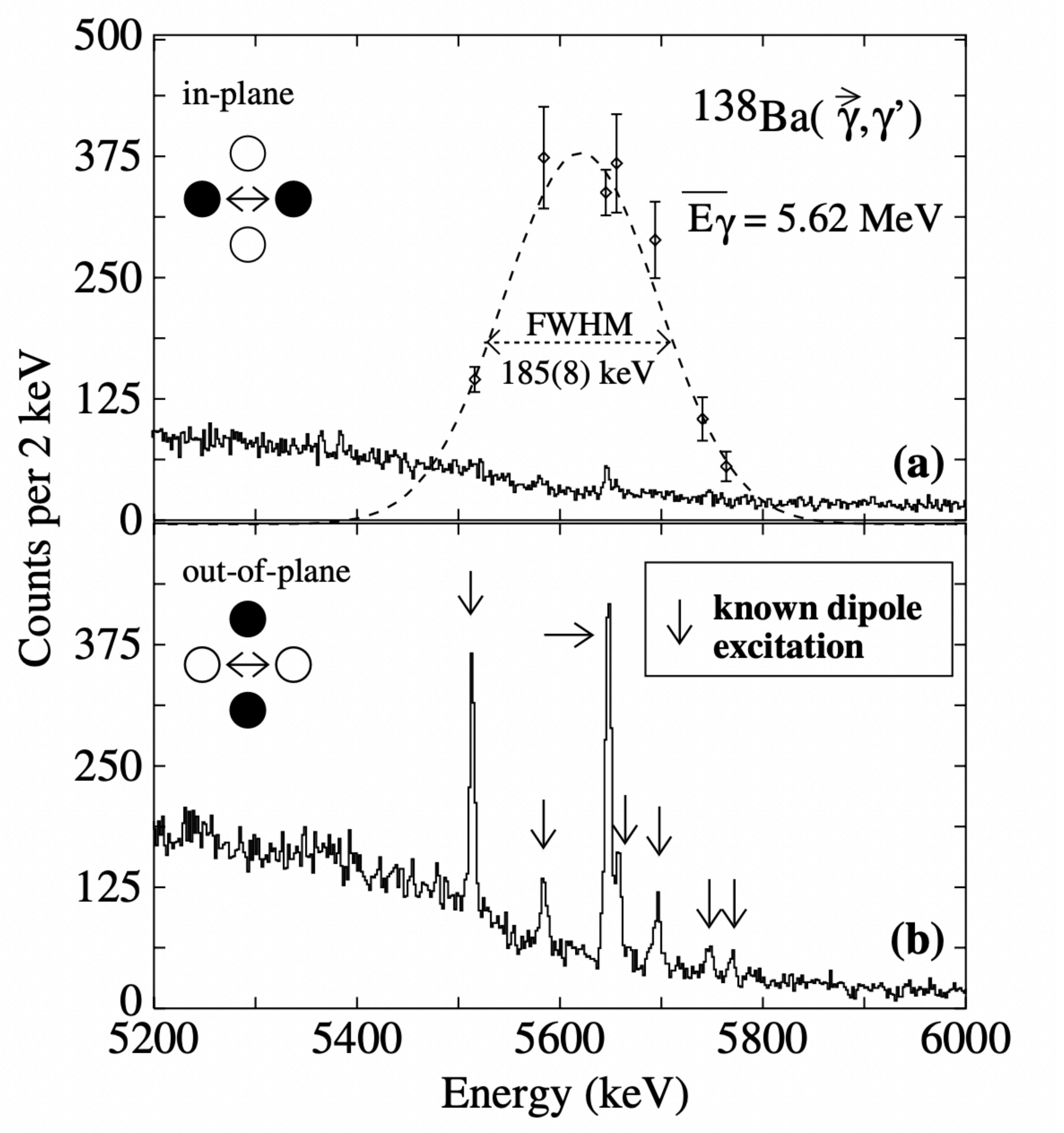

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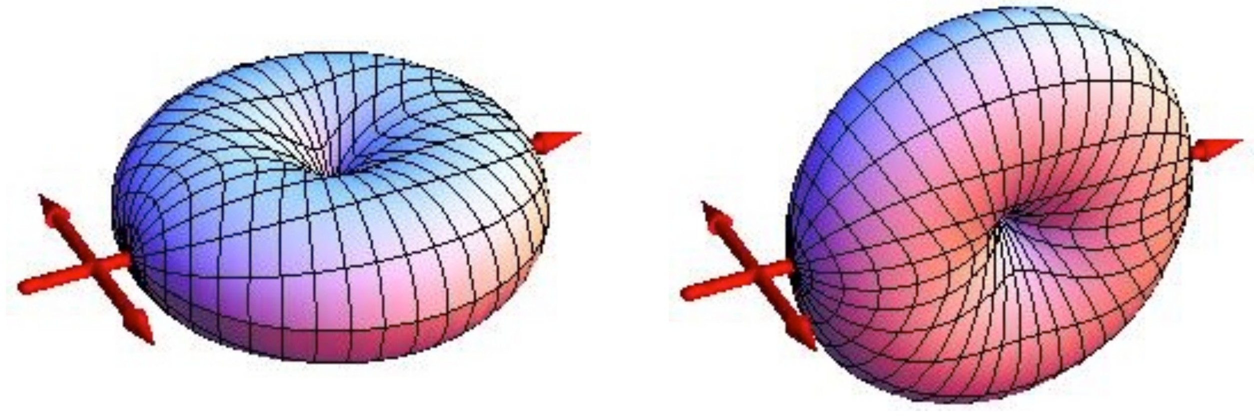
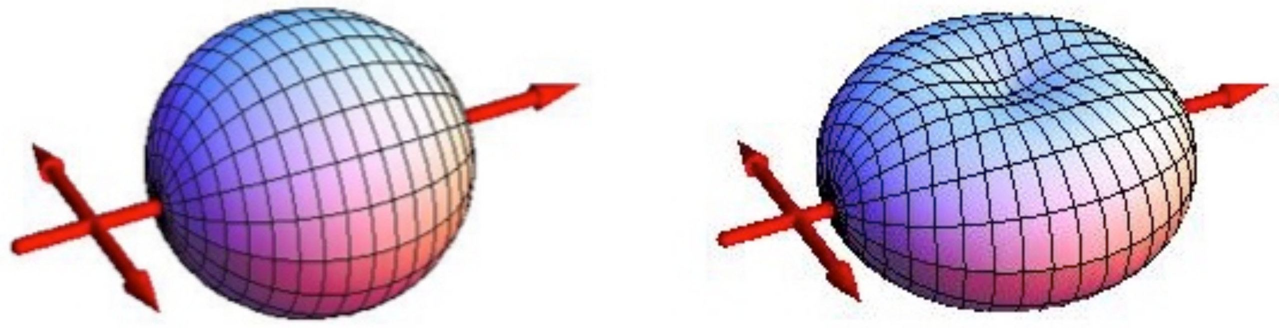
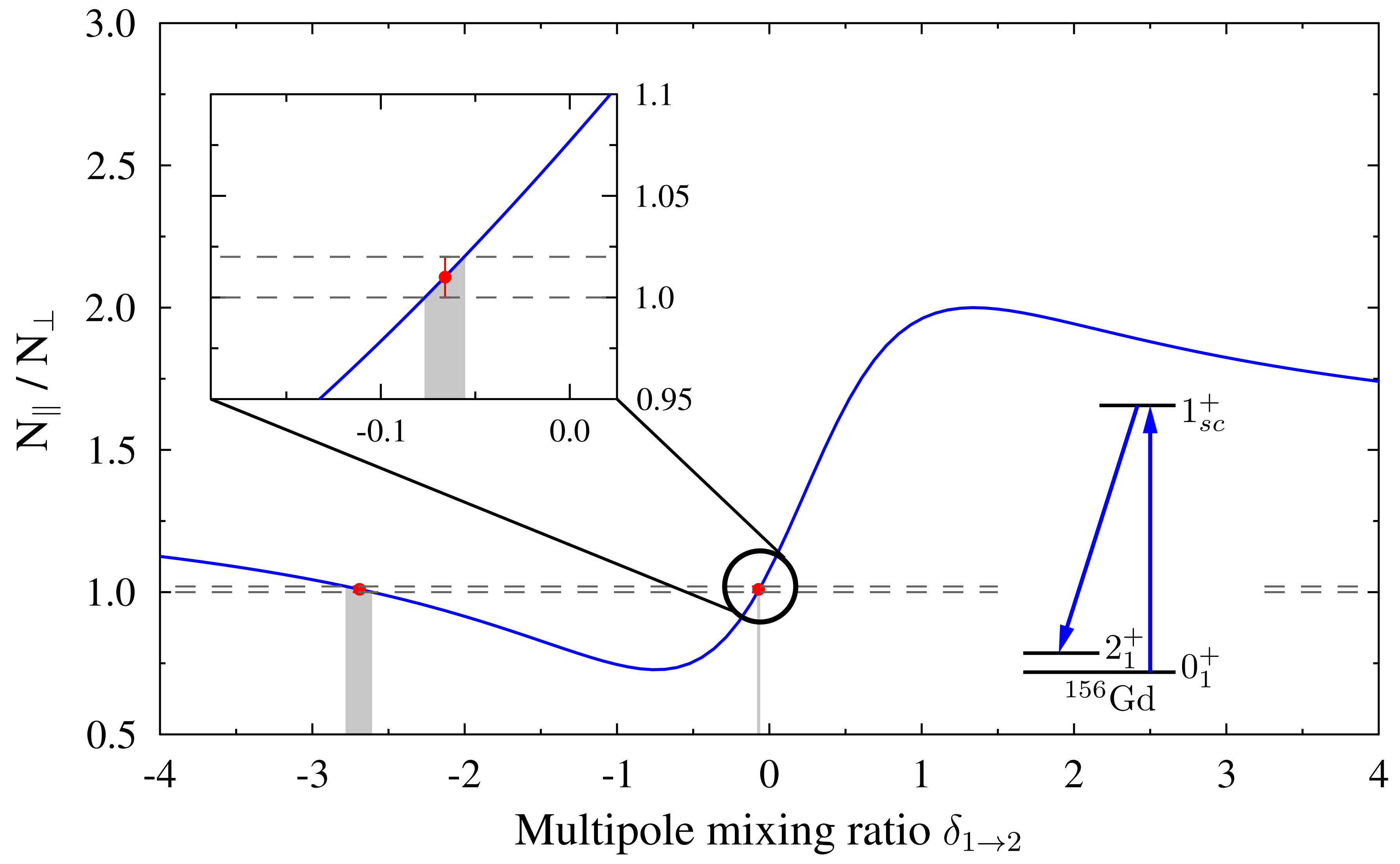


$\pi = +1$ $\pi = -1$

multipole mixing ratios.





Beck, Phys. Rev. Lett. 118, 212502 (2017)

Nuclear physics with photon beams

Observables:

- excitation energies
- angular momenta
- branching ratios
- level lifetimes

With additional polarization information:

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Disadvantages:

- ⊖ low cross-section (target size, duration)
- ⊖ nonresonant background
- ⊖ inefficient detection

“Wishlist” for next-generation photon sources

Photon-beam side:

- narrower bandwidth $\Delta E/E$

  selective manipulation of single excited states

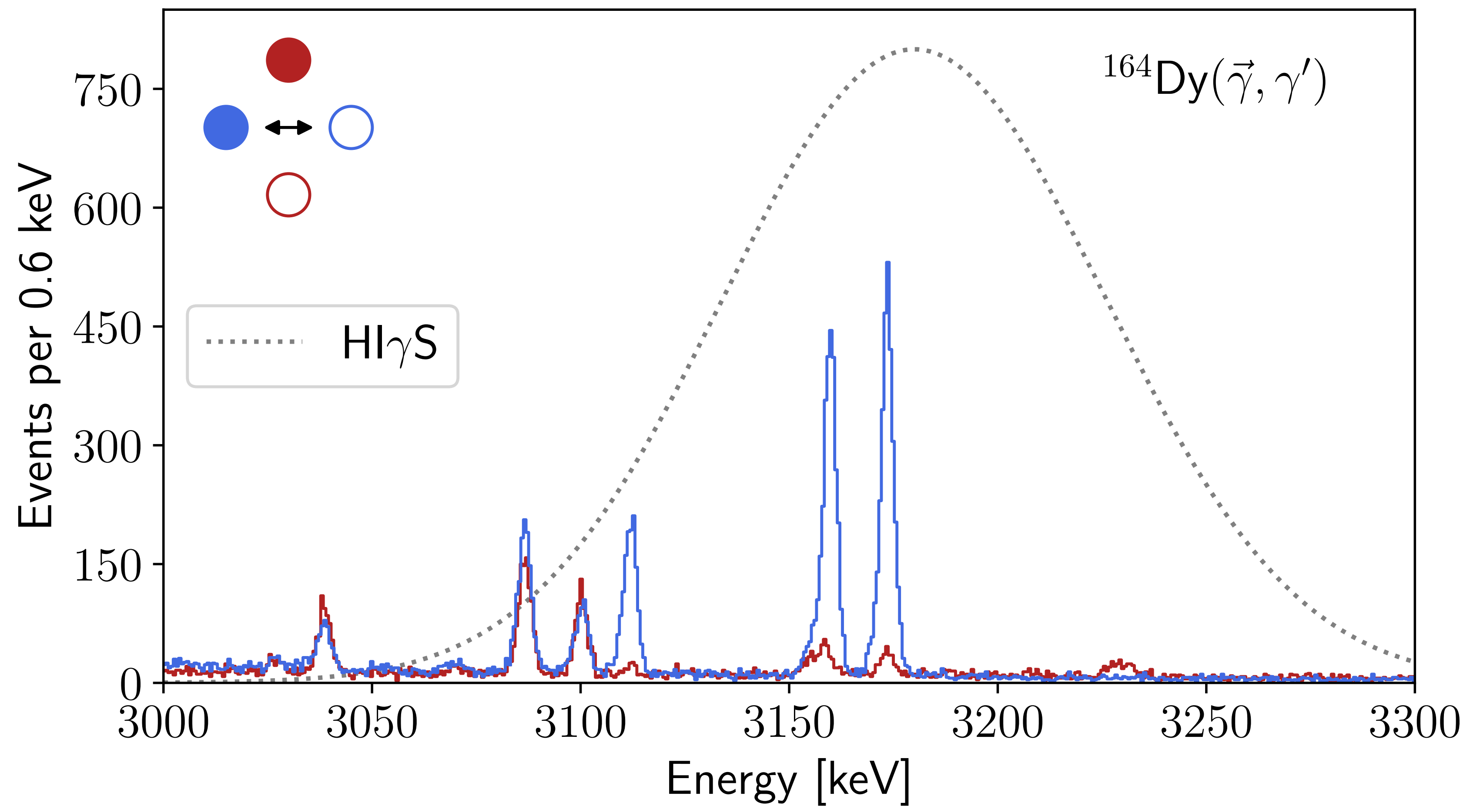
- reduced beam-spot size

  improved spatial resolution

- increased luminosity

  competition with low cross-section

- improved diagnostics



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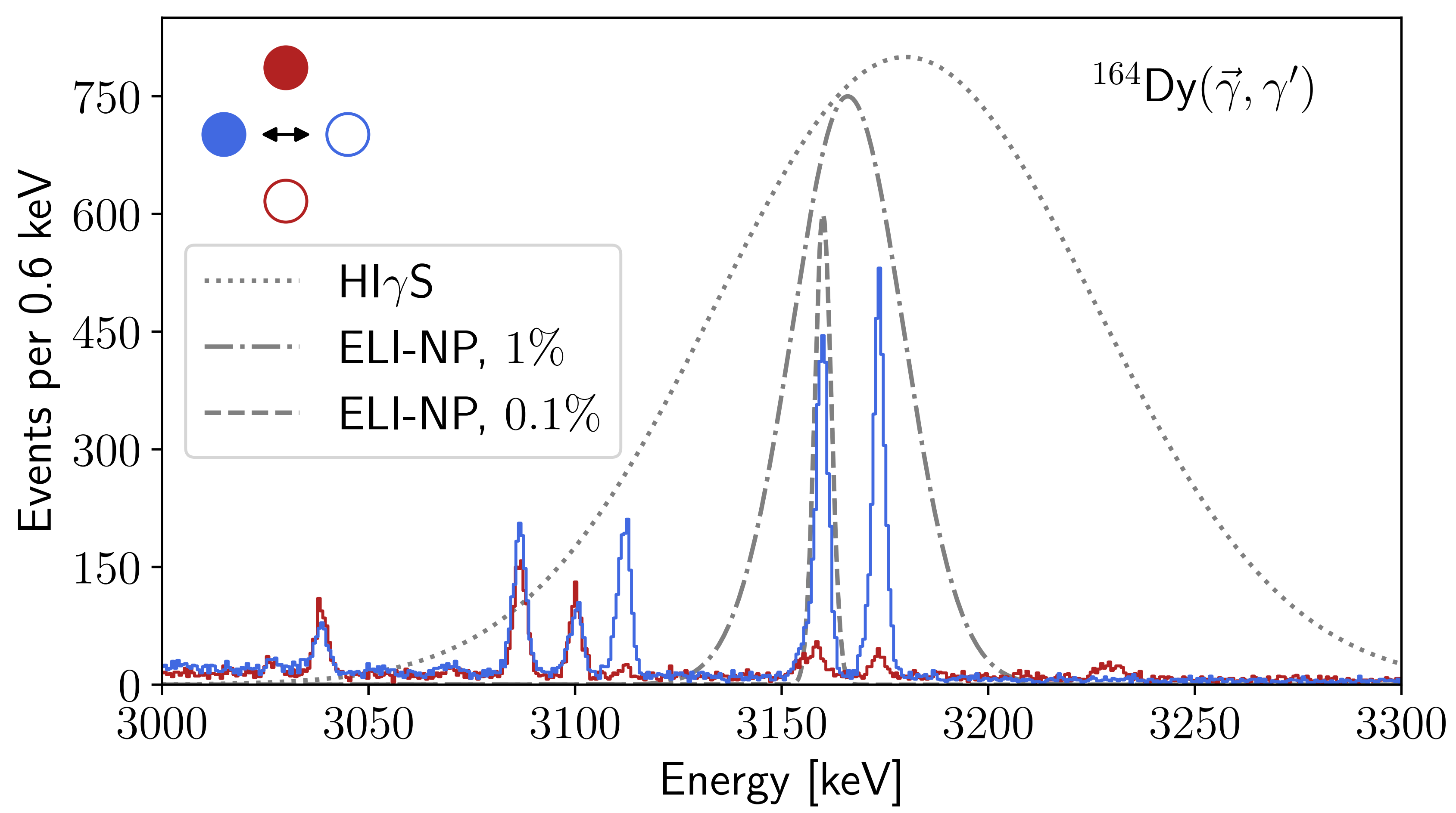

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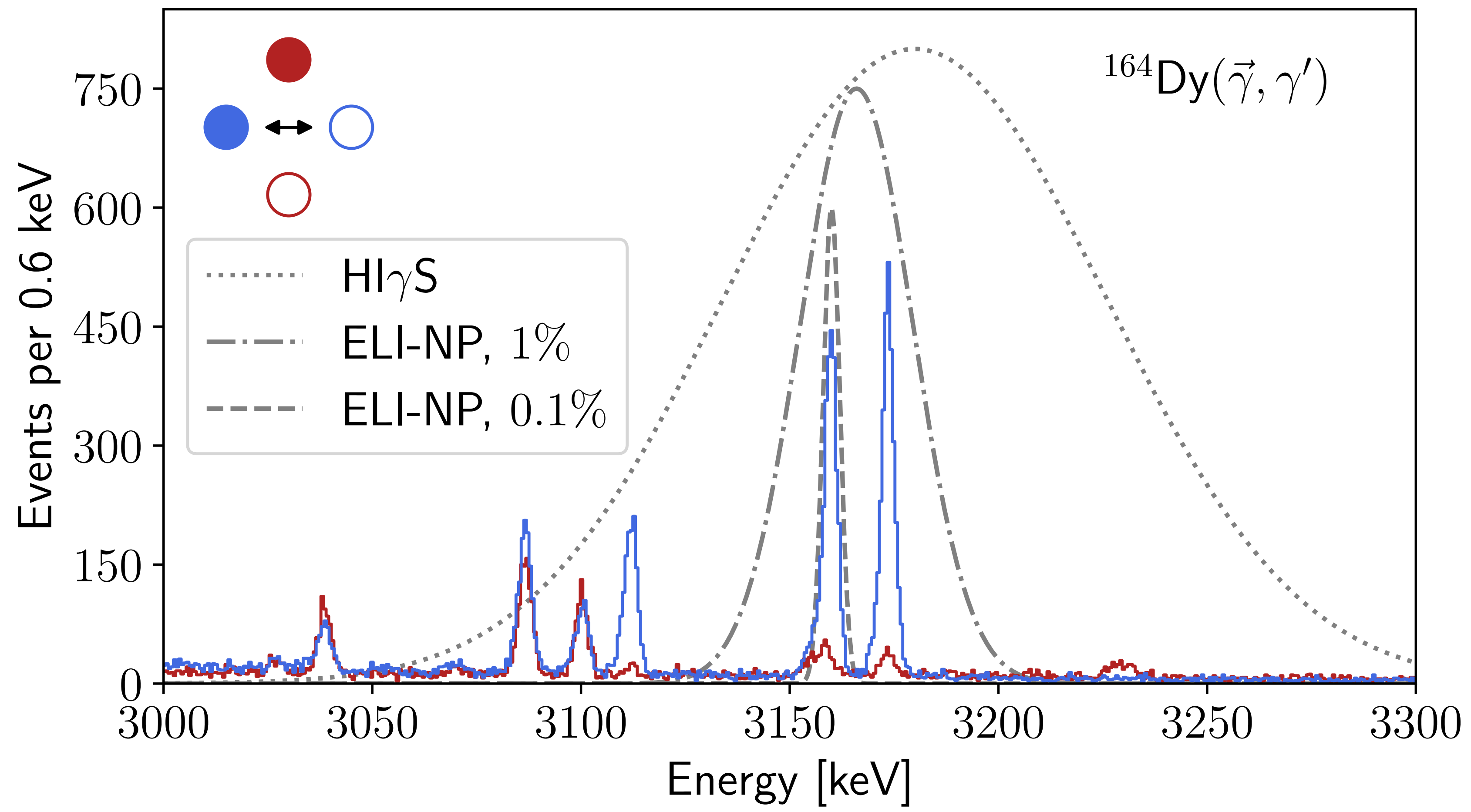

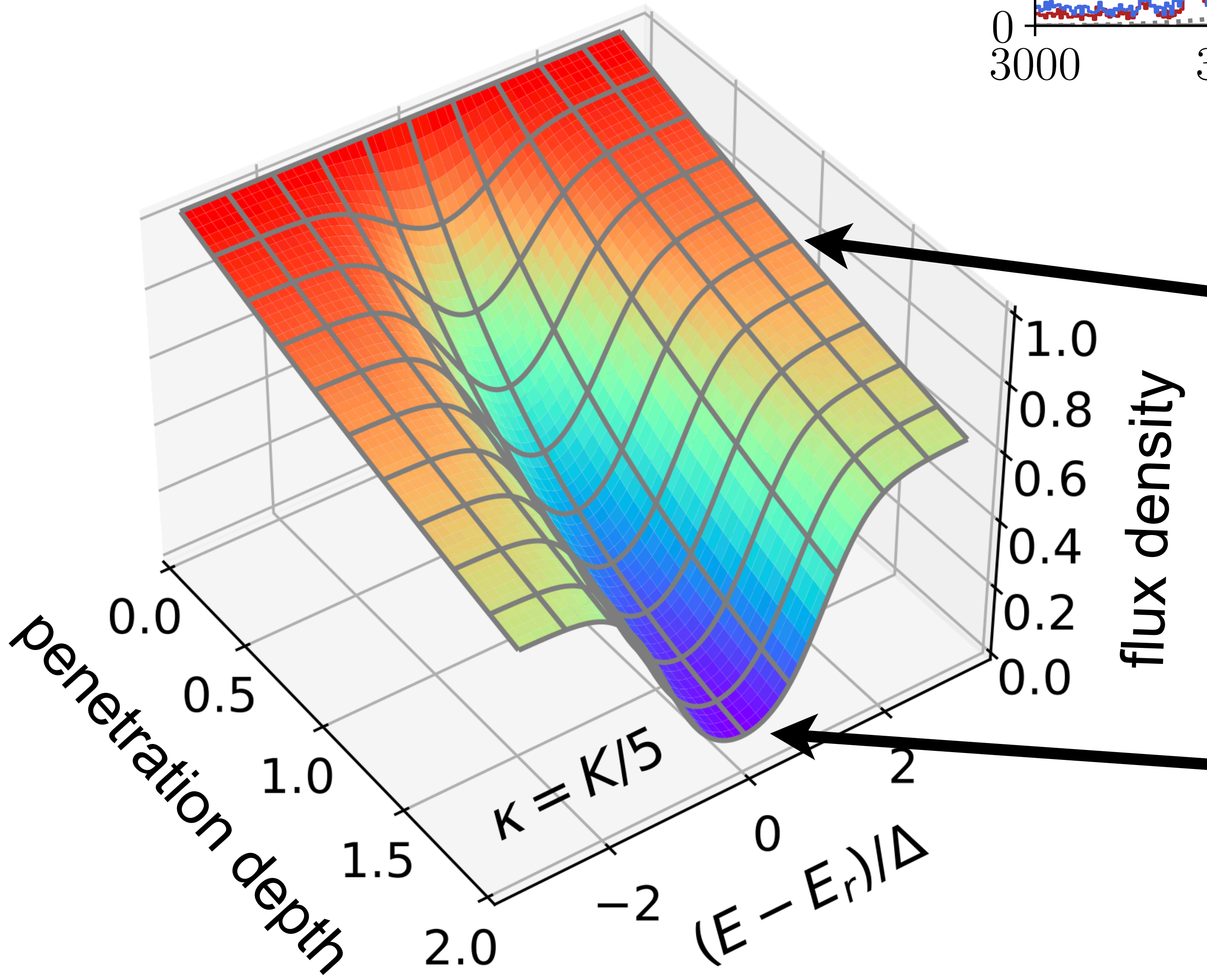

Zilges, Prog. Part. Nucl. Phys. 122, 103903 (2022)

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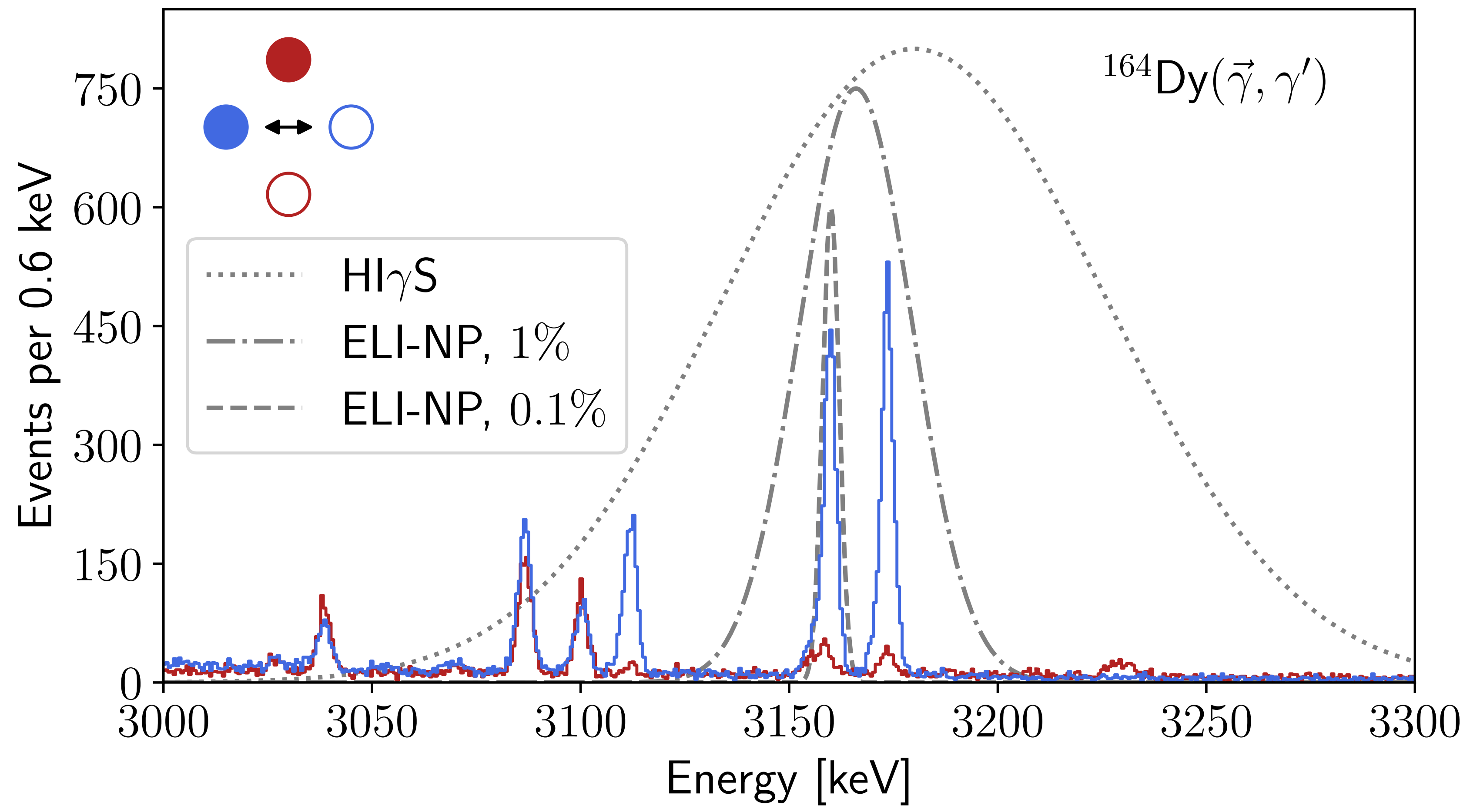

next-generation photon source

==

LCB at a multi-turn SRF-ERL

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Tobias Beck
Facility for Rare Isotope Beams,
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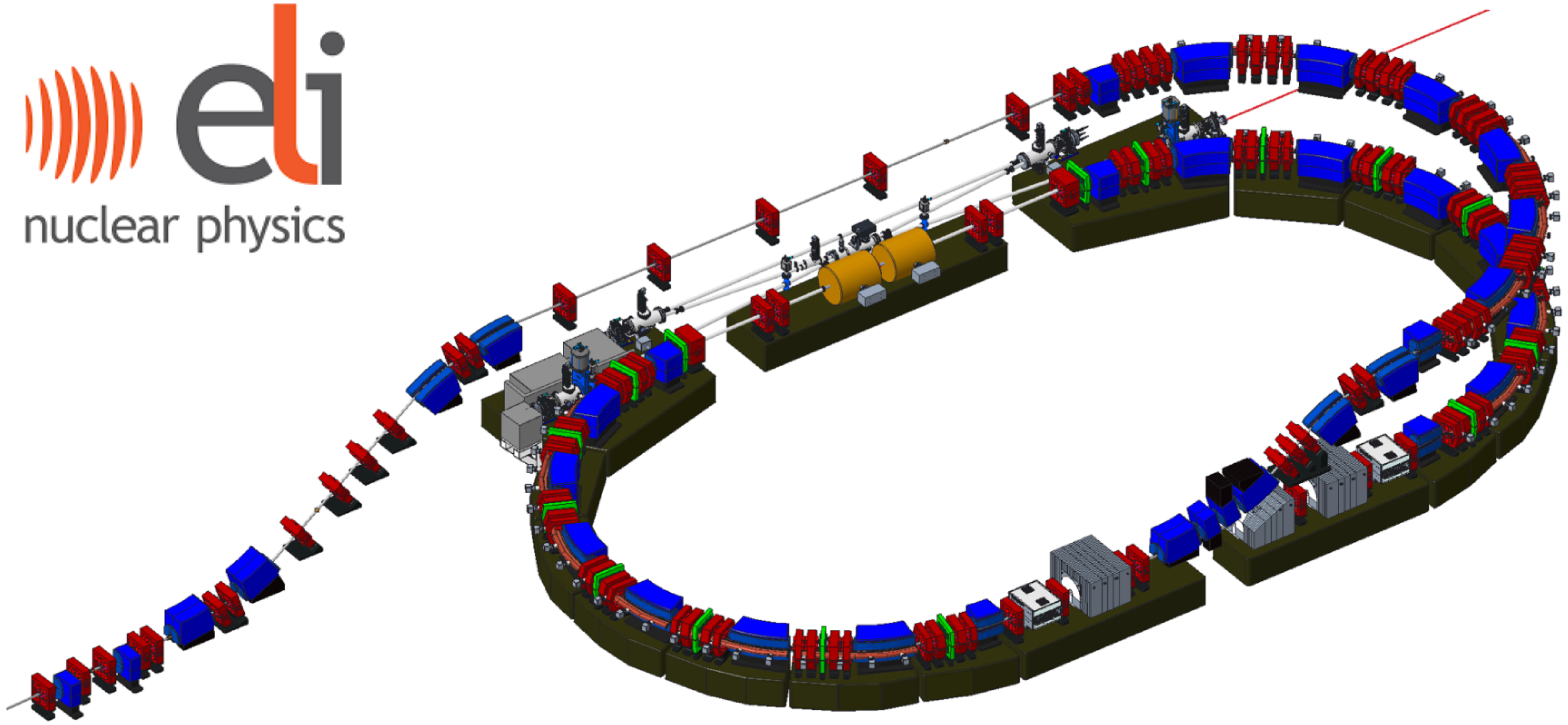
VEGA @ ELI-NP



Zilges, Prog. Part. Nucl. Phys. 122, 103903 (2022); courtesy of Lyncean Technologies

Properties:

- warm linac
- 35 MHz collision frequency
- IR and green lasers
- $E_\gamma = 1 - 20$ MeV
- photon flux $\geq 10^{11}\,\gamma s^{-1}$
- $\Delta E_\gamma / E_\gamma \leq 0.5\,\%$

Appendix “Wishlist”

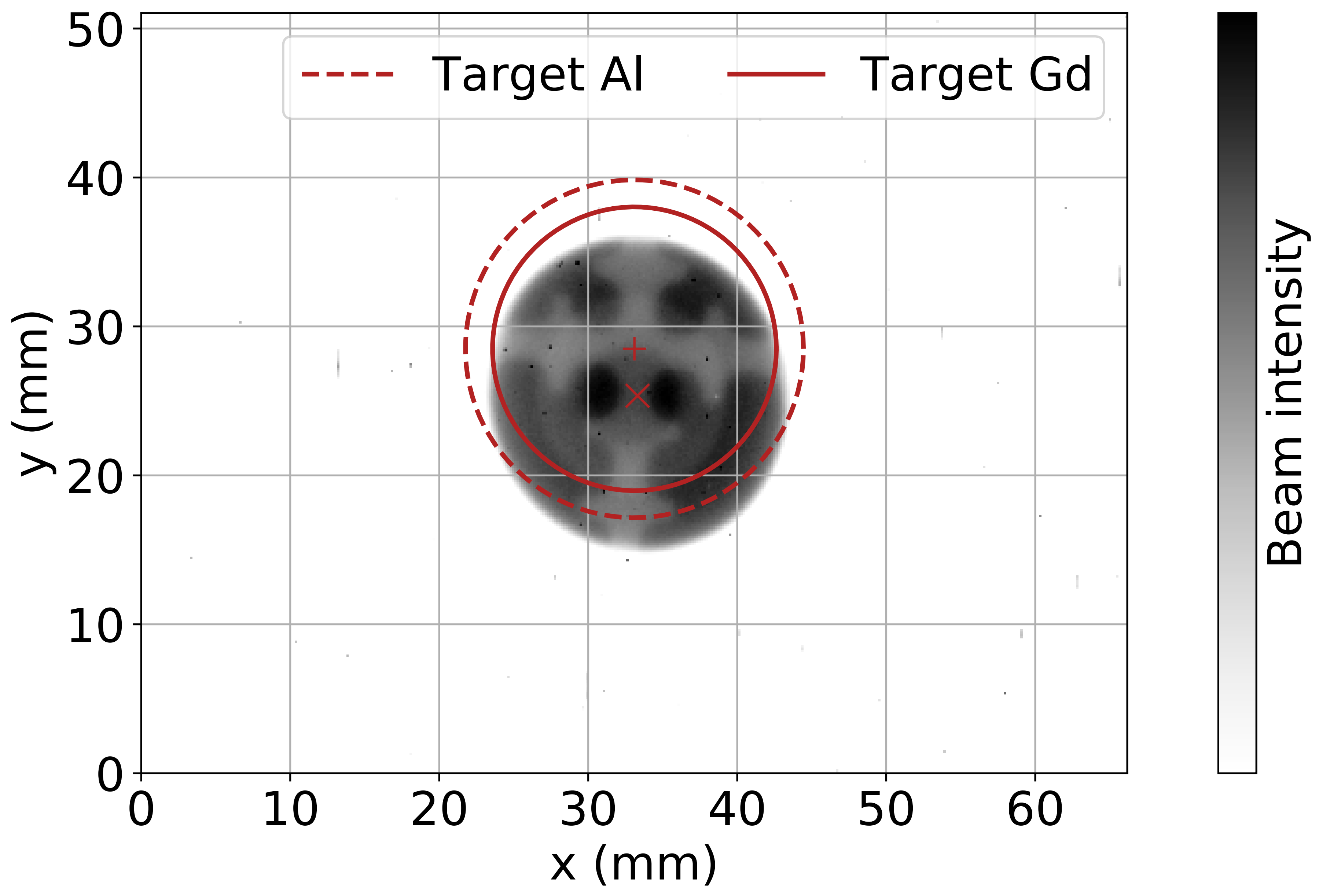
Uncertainty scattered photon energy:

$$\frac{\Delta E_\gamma}{E_\gamma} \approx \sqrt{\left(2\frac{\Delta E_e}{E_e}\right)^2 + \left(\frac{\Delta E_L}{E_L}\right)^2 + (-\gamma^2 \Delta\vartheta_f^2)^2 + \left(-\frac{1}{4}\Delta\vartheta_i^2\right)^2}$$

Requirements next-generation photon source:

- fewer bends $\longrightarrow$ Linac
- high repetition rate $\longrightarrow$ cw, SRF
- high current GeV-range electrons $\longrightarrow$ ERL

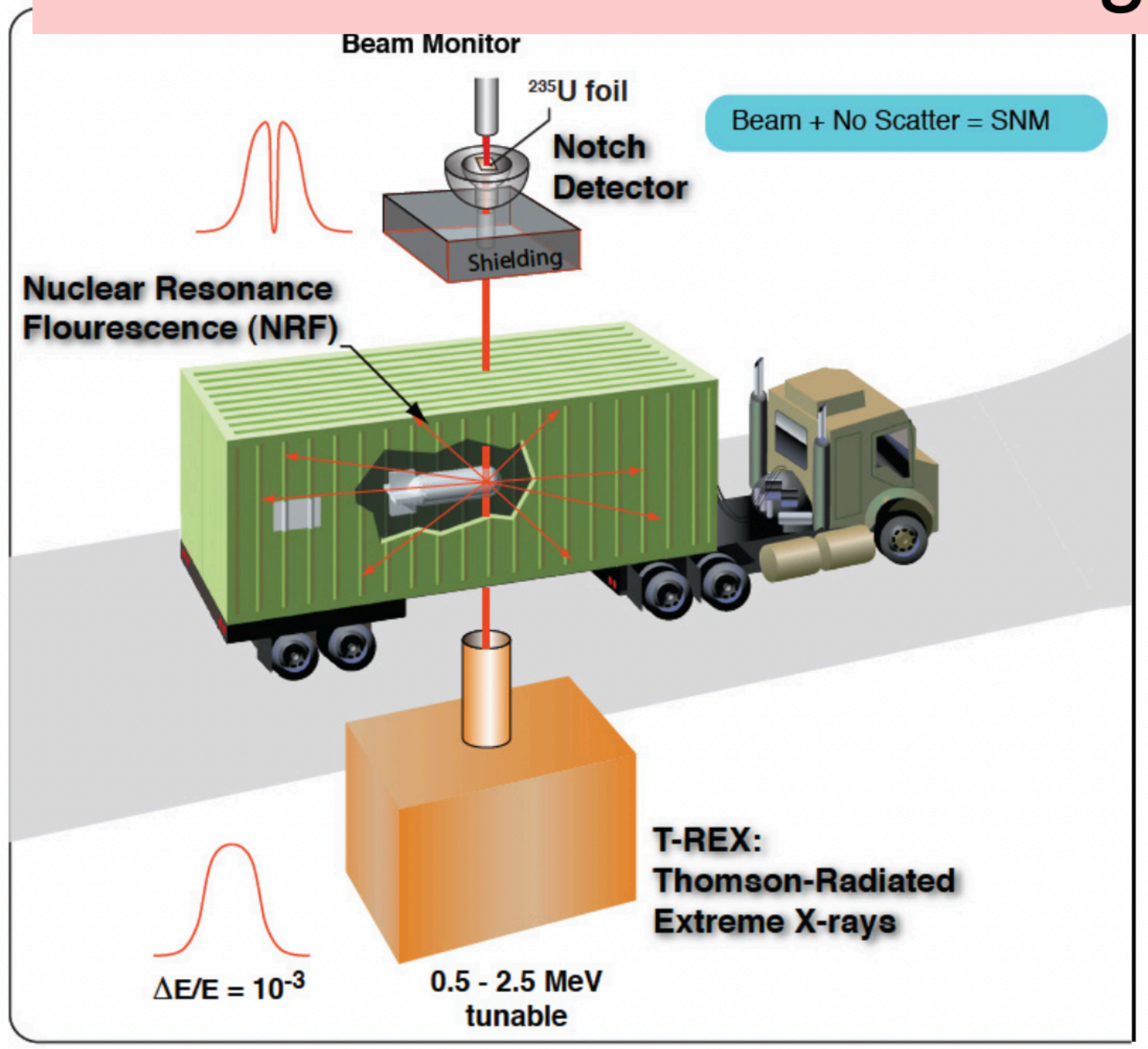
Beam-spot size:



Beck, Dissertation, TU Darmstadt (2021)

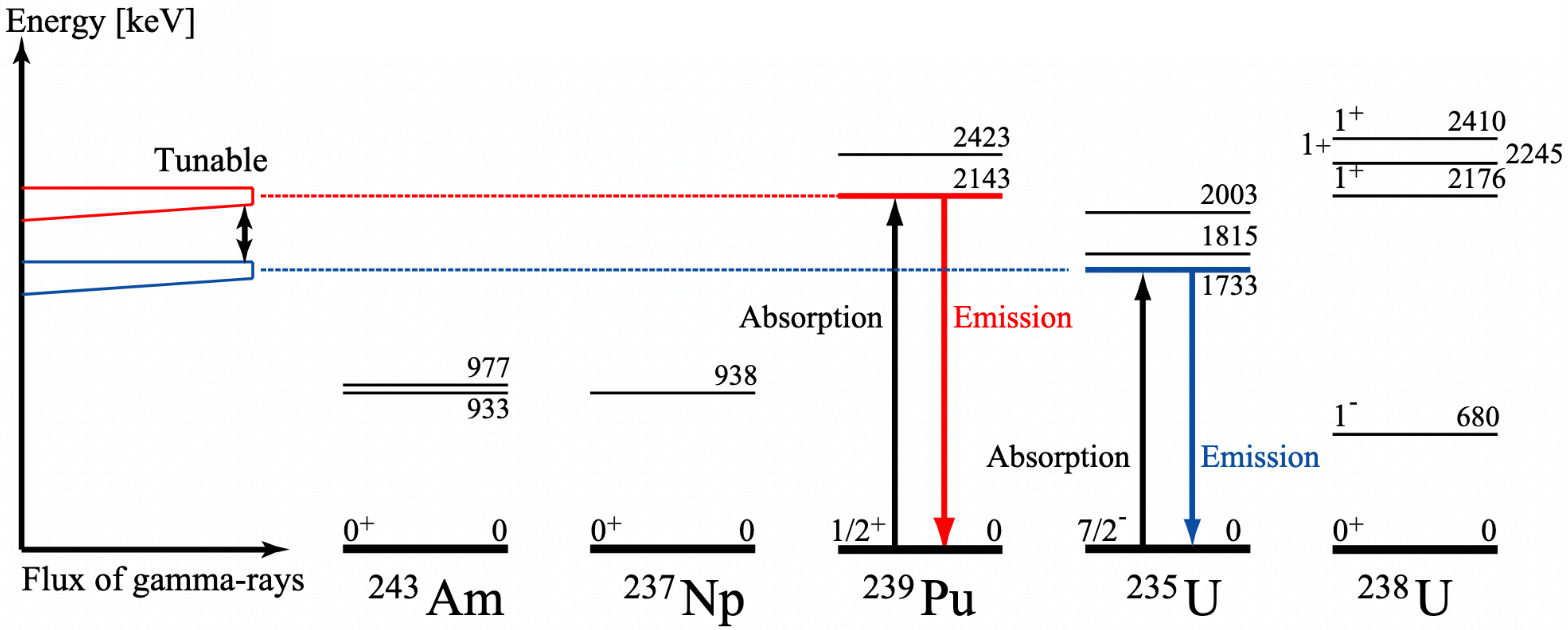
Isotope-sensitive scanning

Detection of SNM in a cargo



Hajima, FACET-II Science Opportunities Workshops (2015)

MeV-range photon beams for isotope-sensitive scanning of suspicious material.



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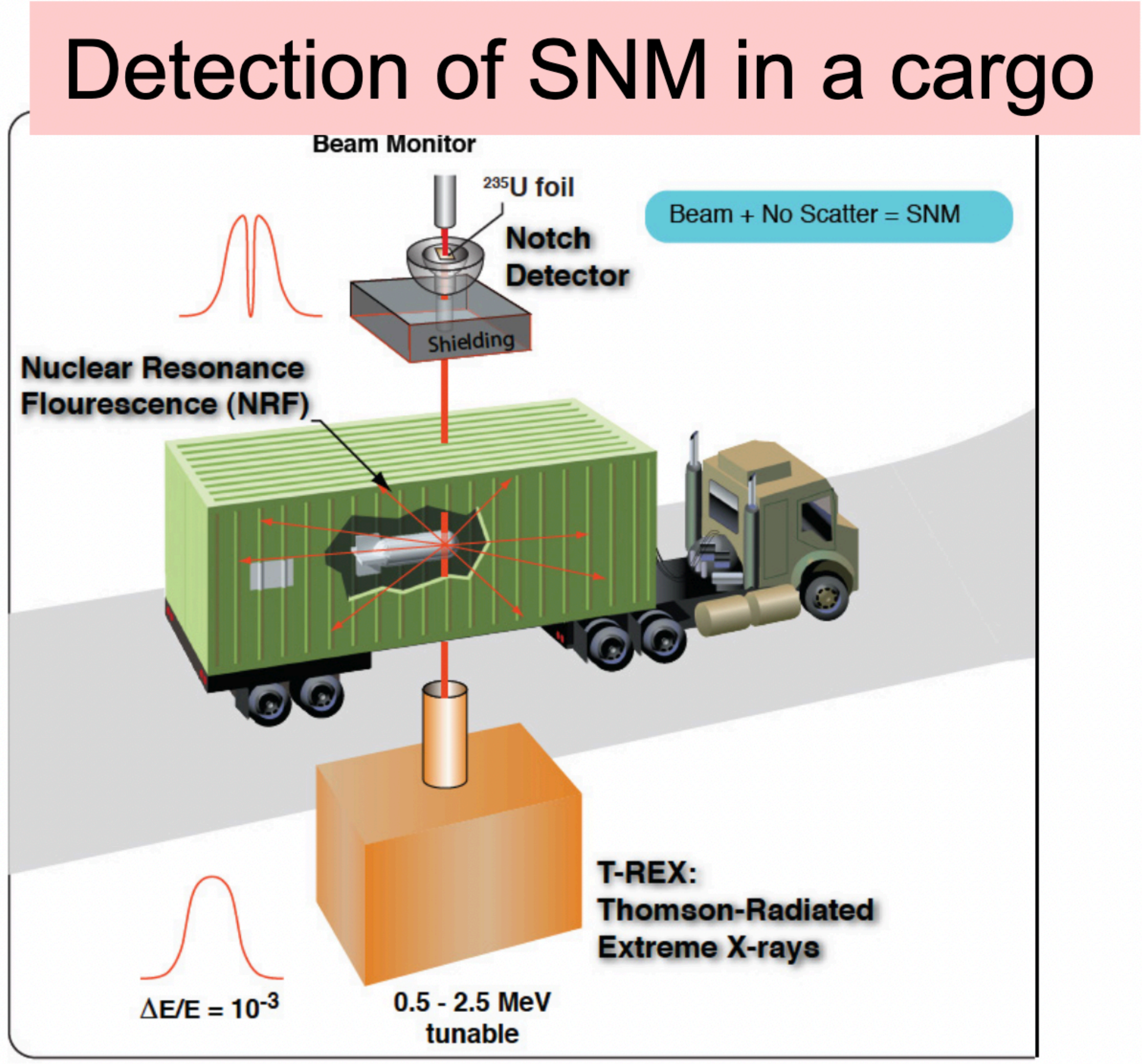

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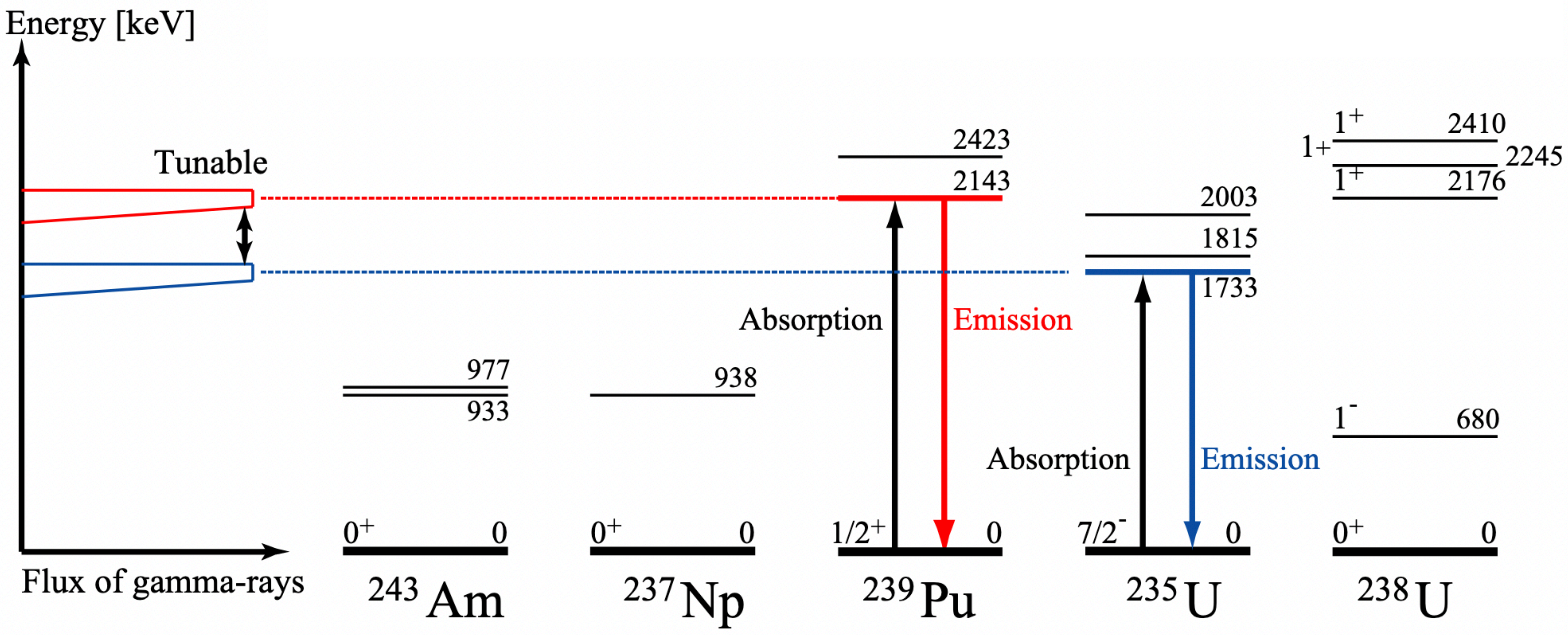

Hajima, FACET-II Science Opportunities Workshops (2015)

MeV-range photon beams for isotope-sensitive scanning of suspicious material.

Requirements:

- tunable and portable photon source
- high luminosity for fast measurements

ERL for photonuclear reactions

Tobias Beck
Facility for Rare Isotope Beams,
Michigan State University,
East Lansing, MI 48824, USA

This material is based upon work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661, the State of Michigan and Michigan State University. Michigan State University designs and establishes FRIB as a DOE Office of Science National User Facility in support of the mission of the Office of Nuclear Physics.