Nuclear Resonance Fluorescence

Renaissance of a 70-year-old Technique

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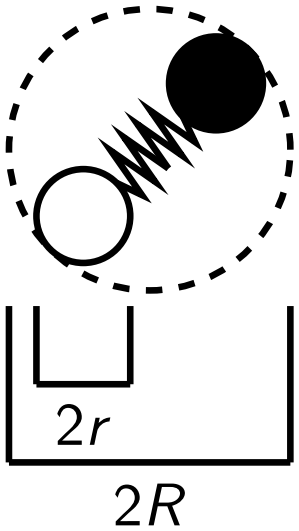
Advances in Physics Seminar, 06/18/2020

Outline

Interaction of Photons with Matter



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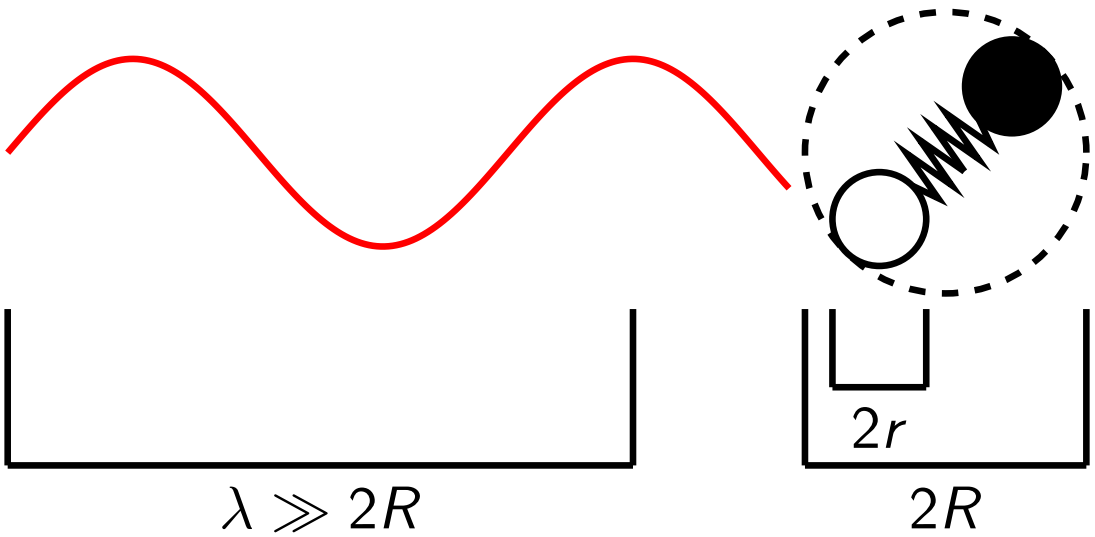

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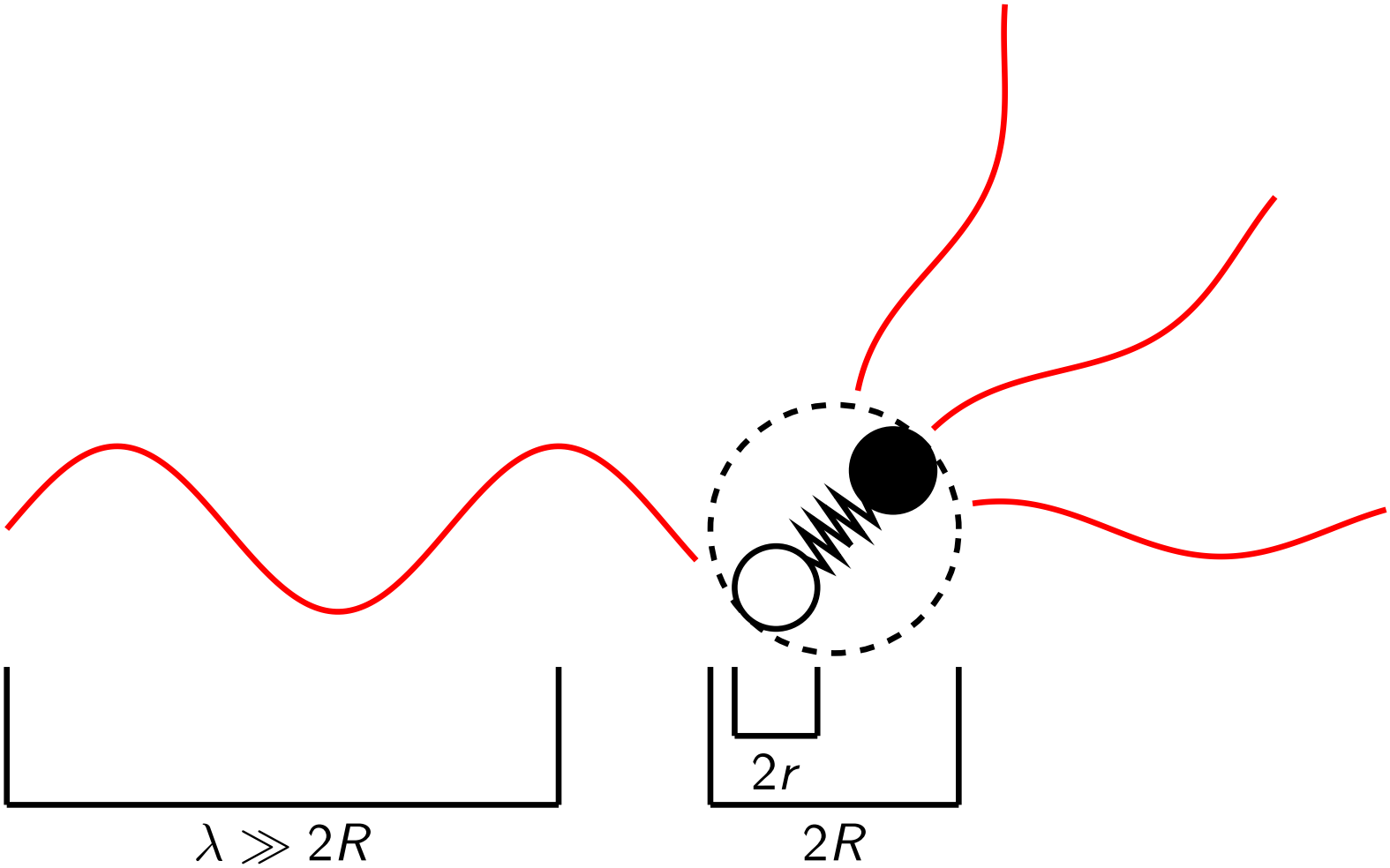

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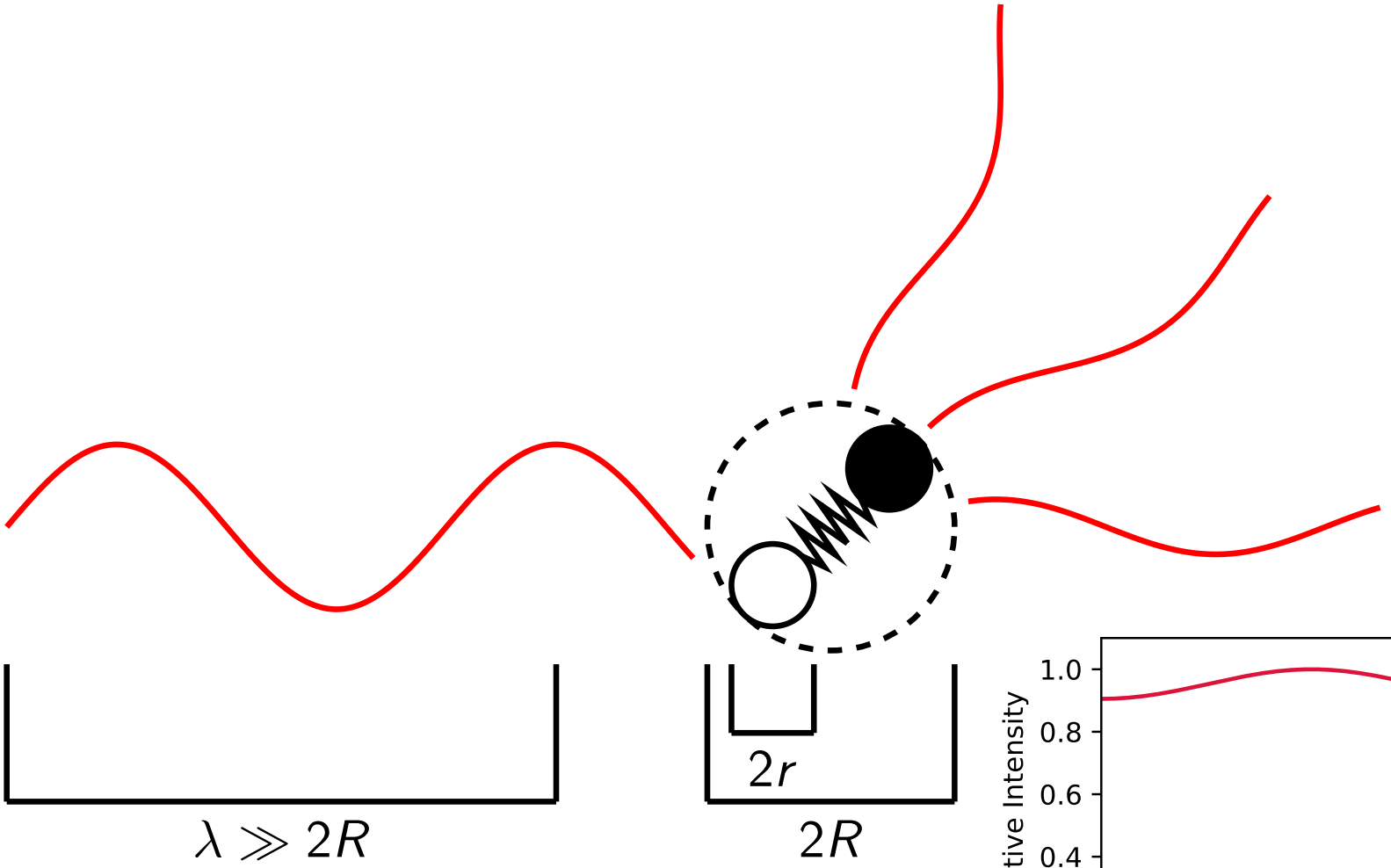

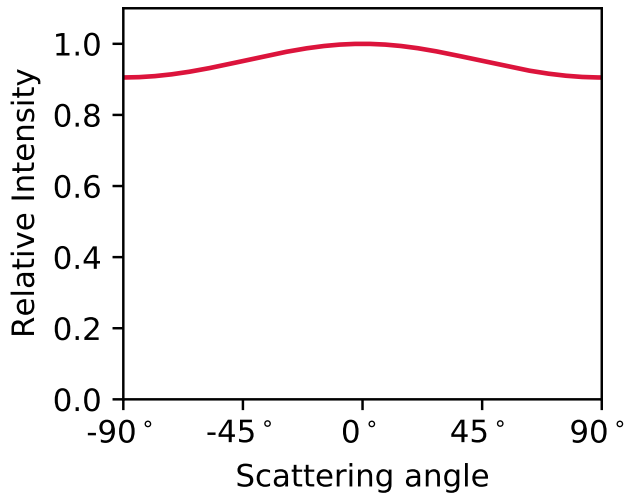

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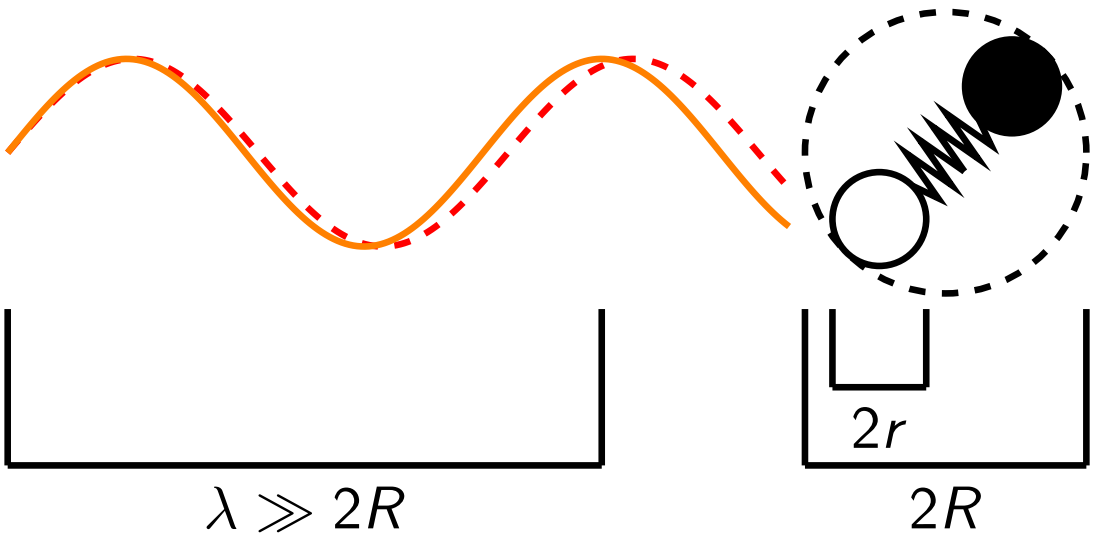

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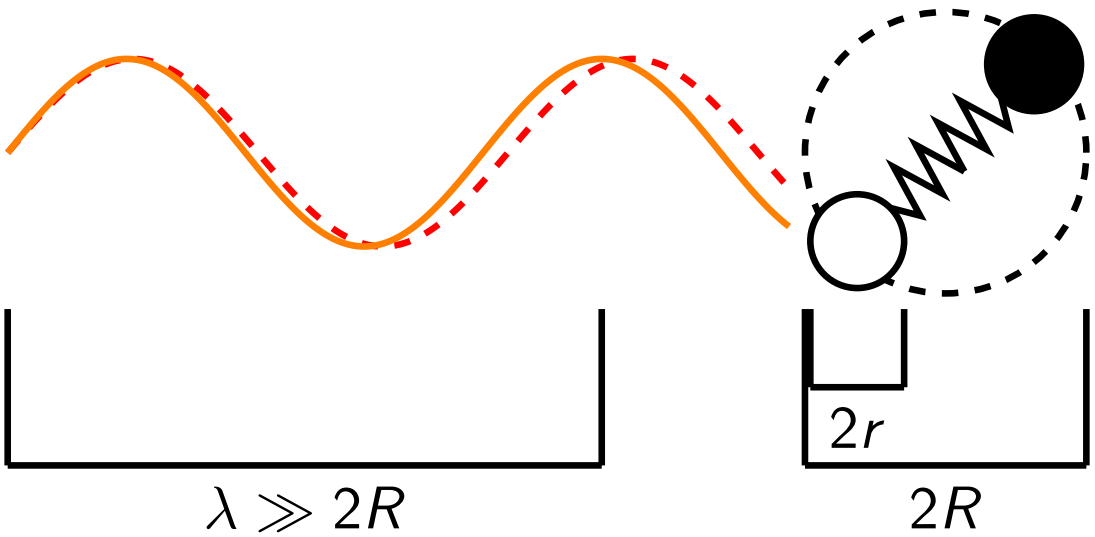

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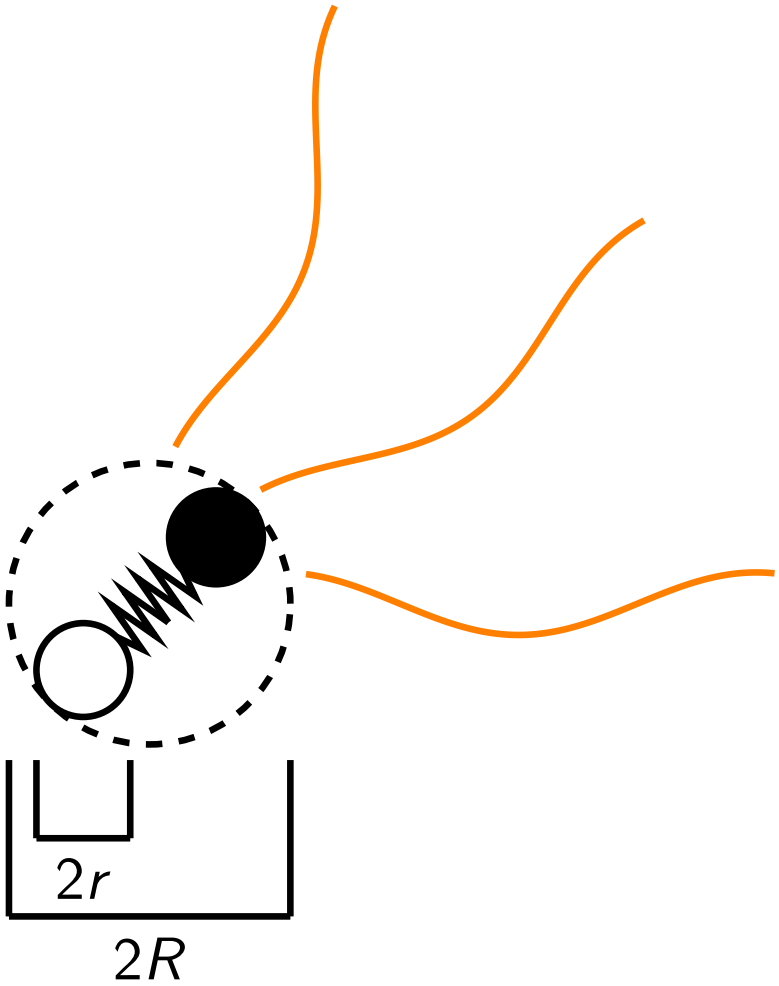

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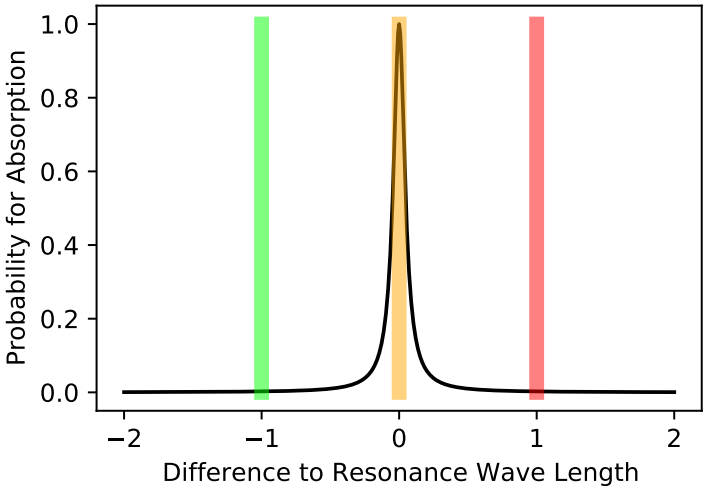

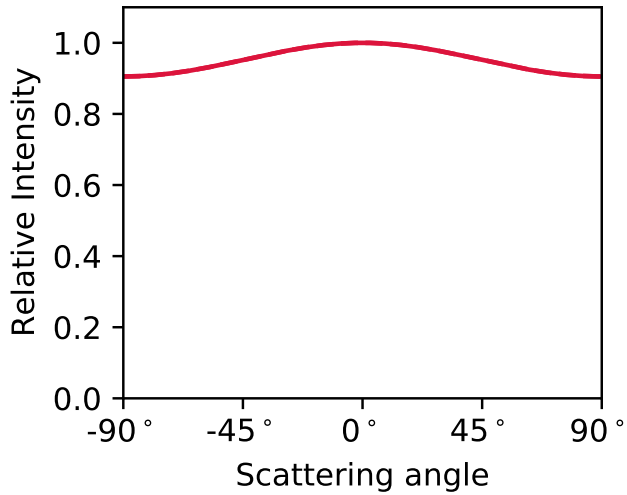

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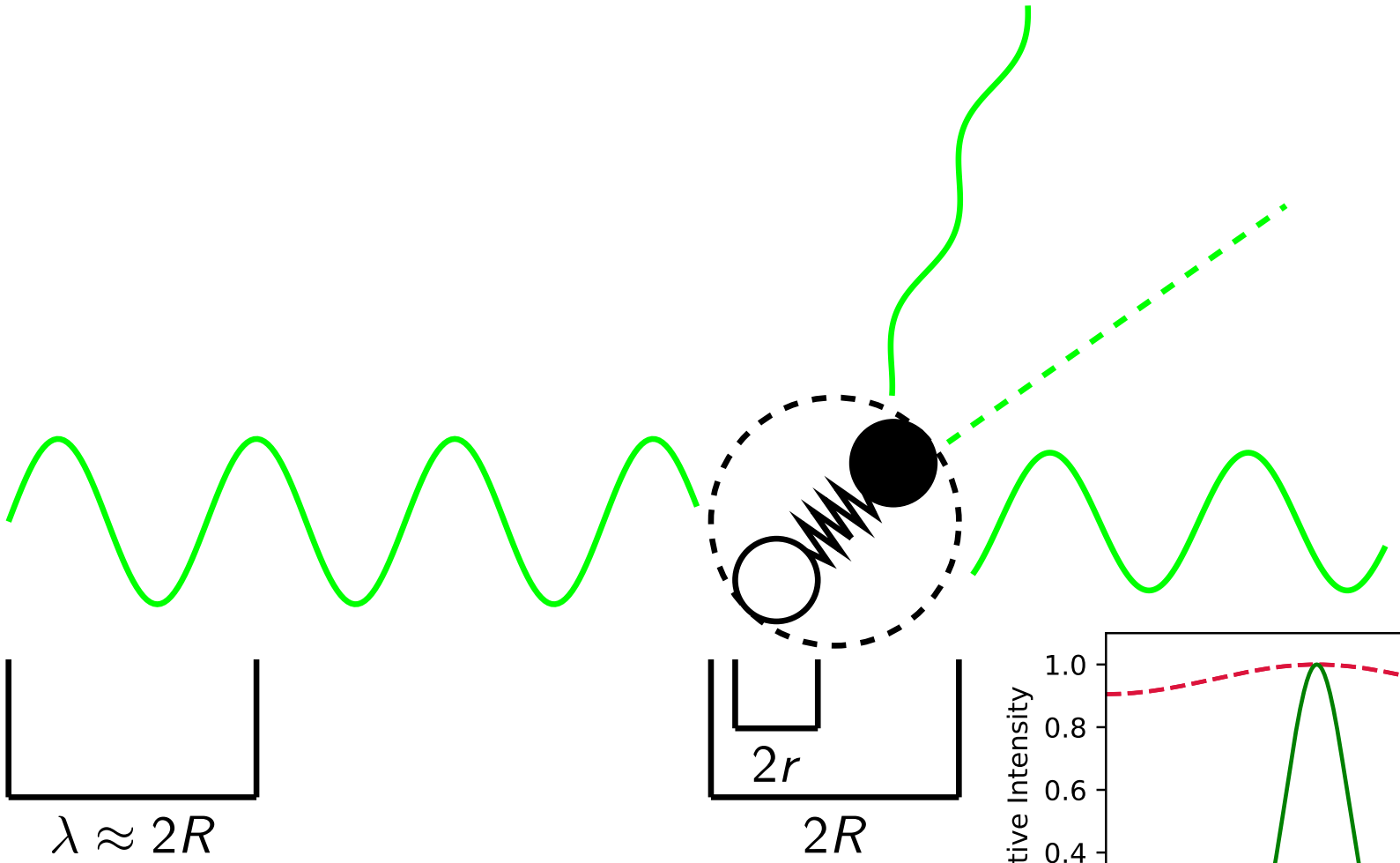

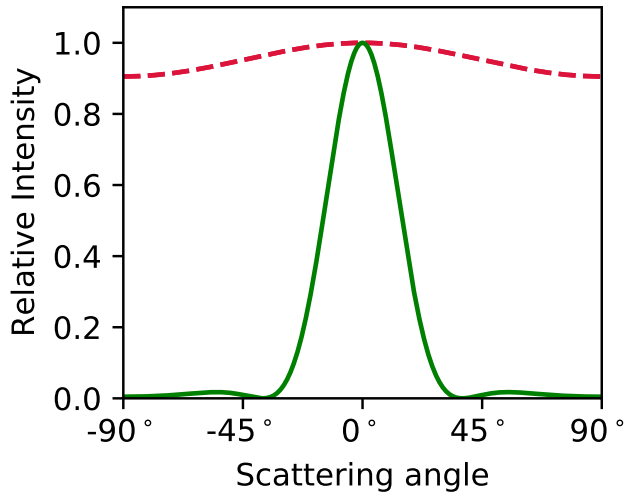

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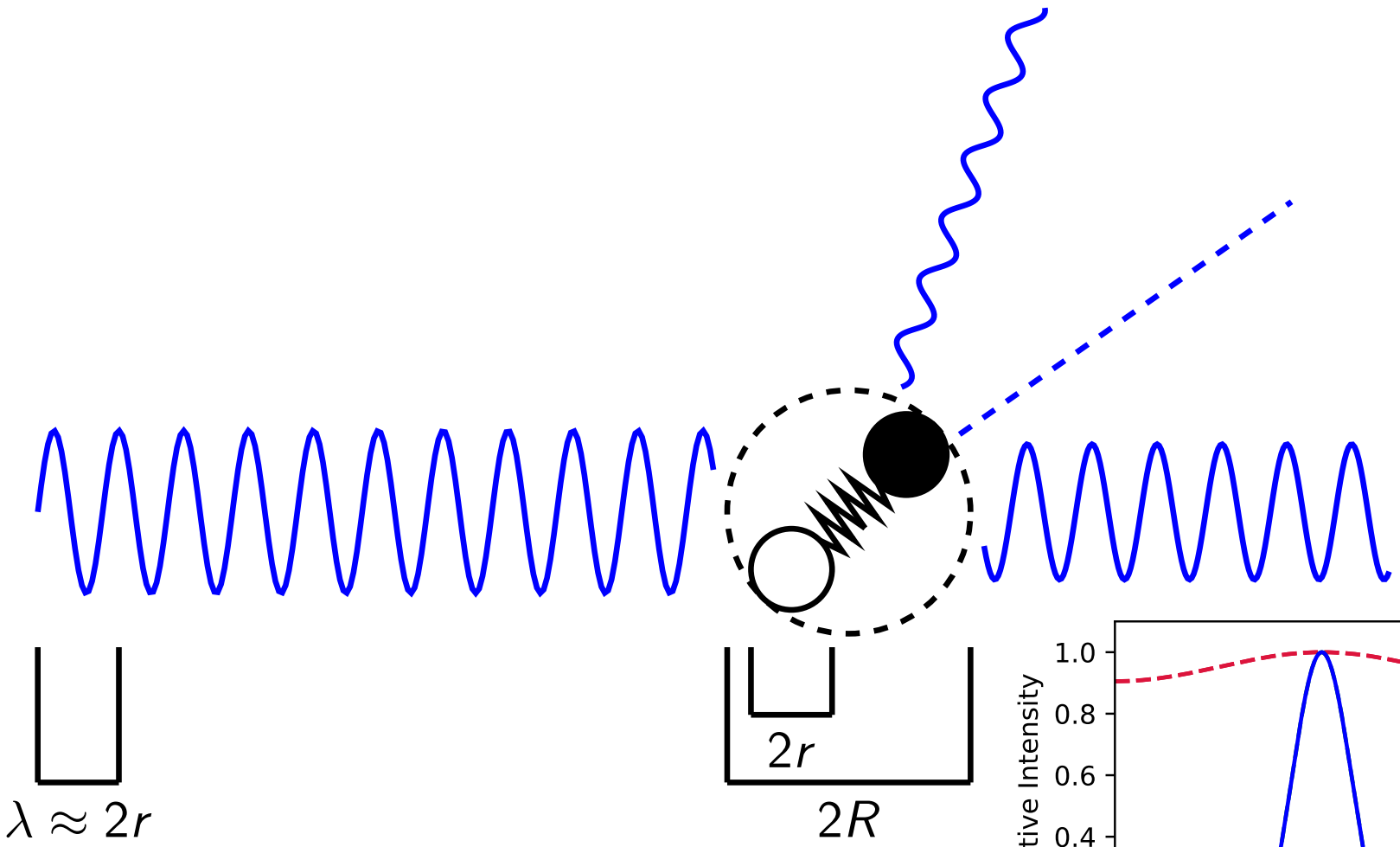

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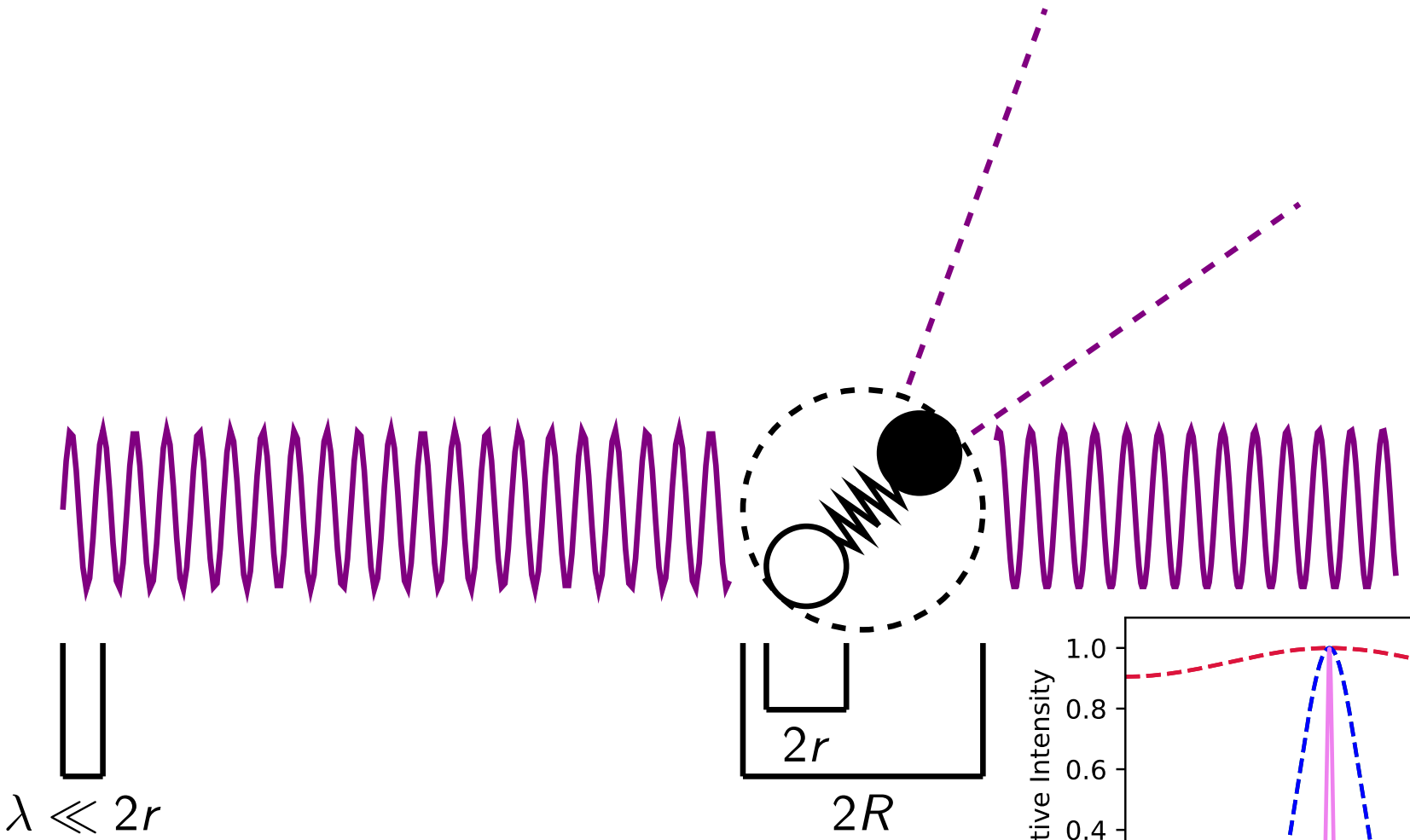

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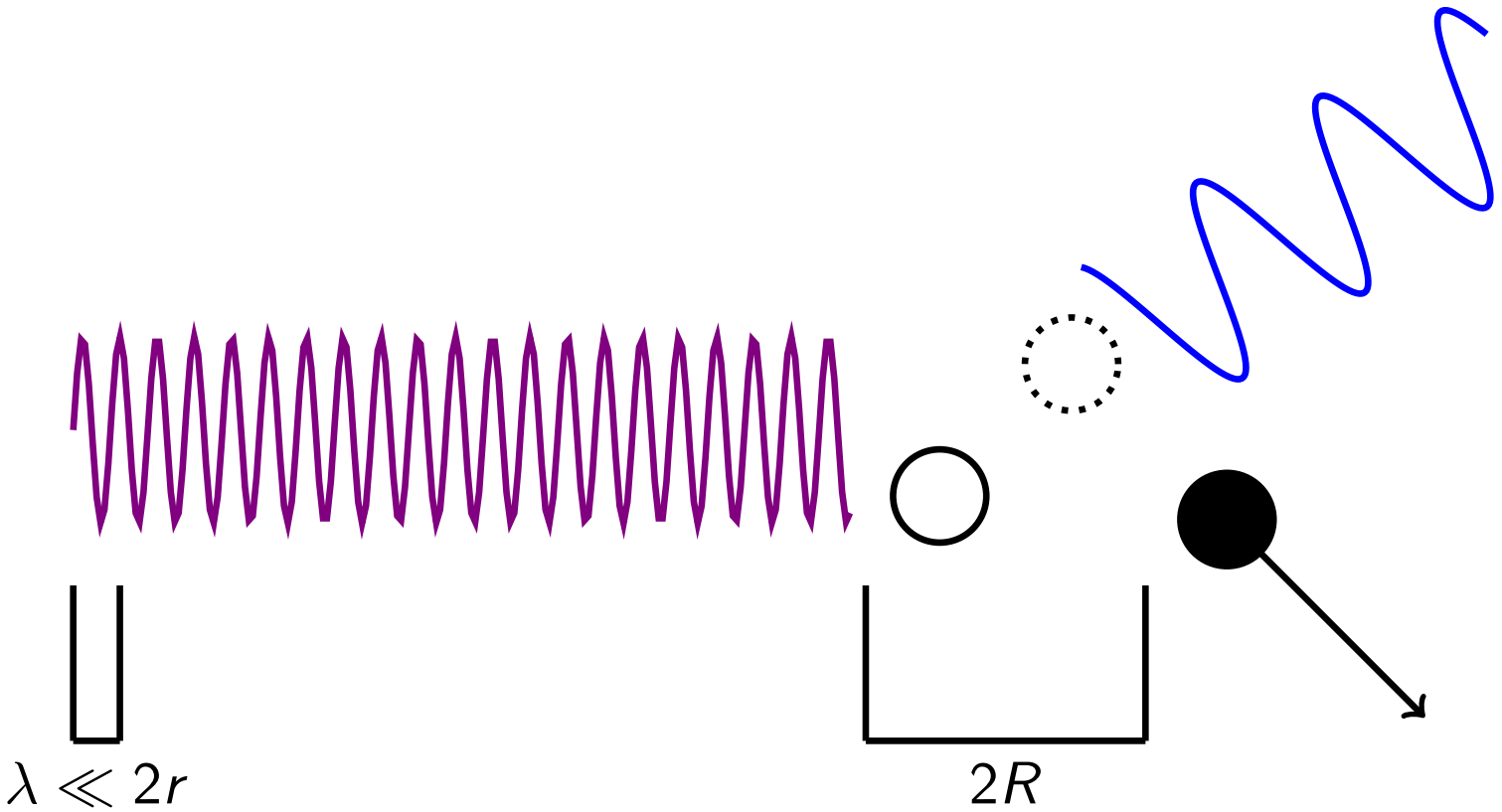
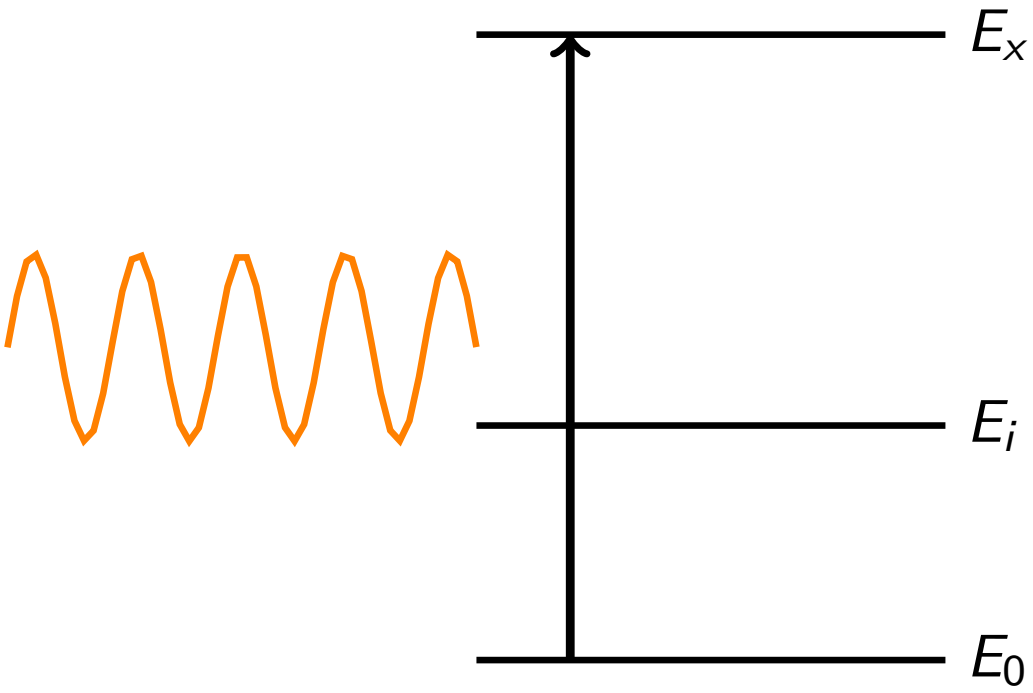


Resonance Fluorescence



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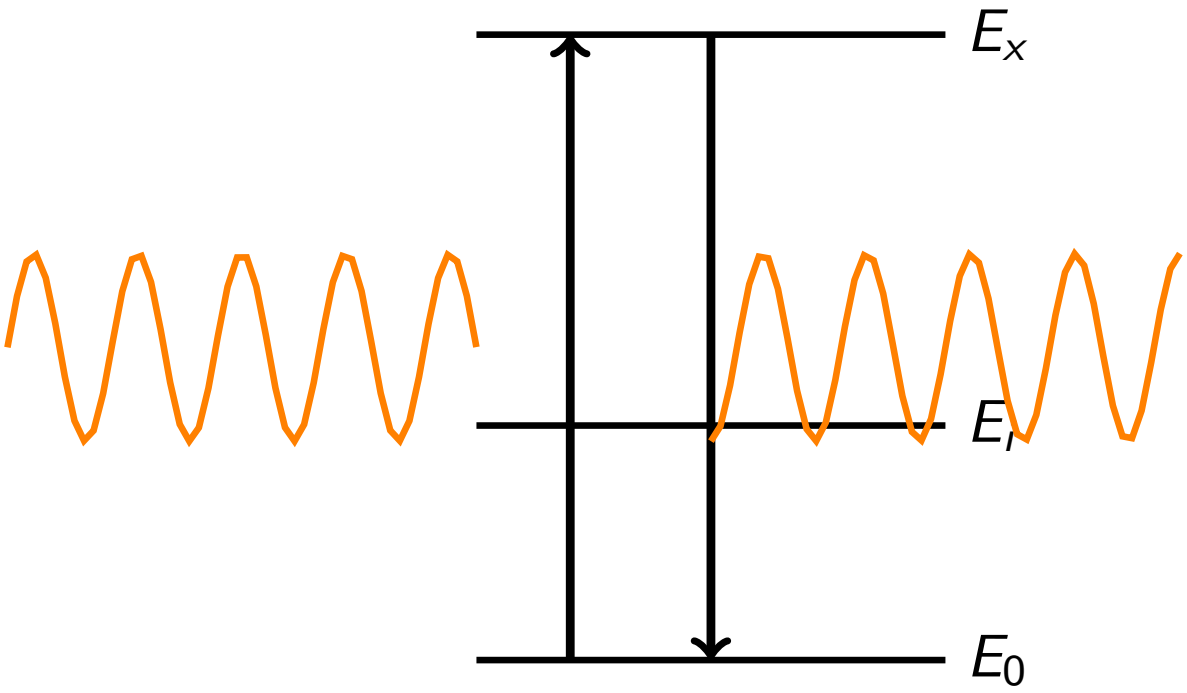

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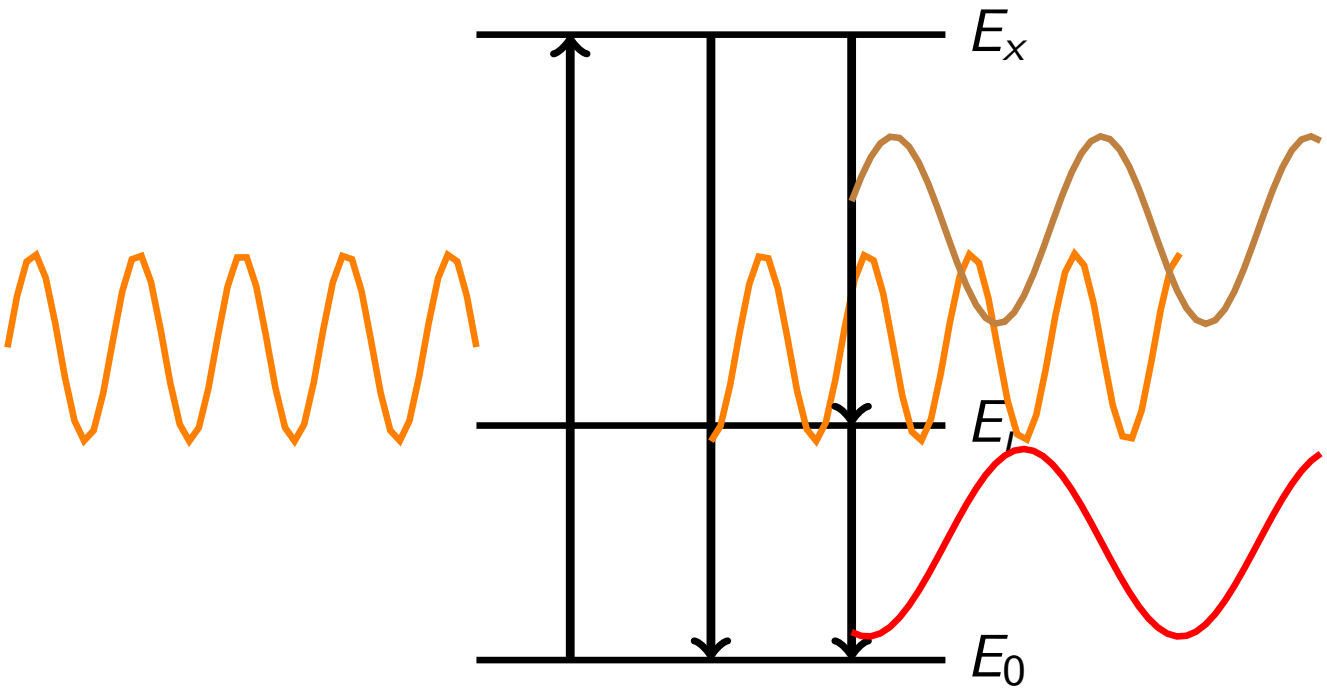
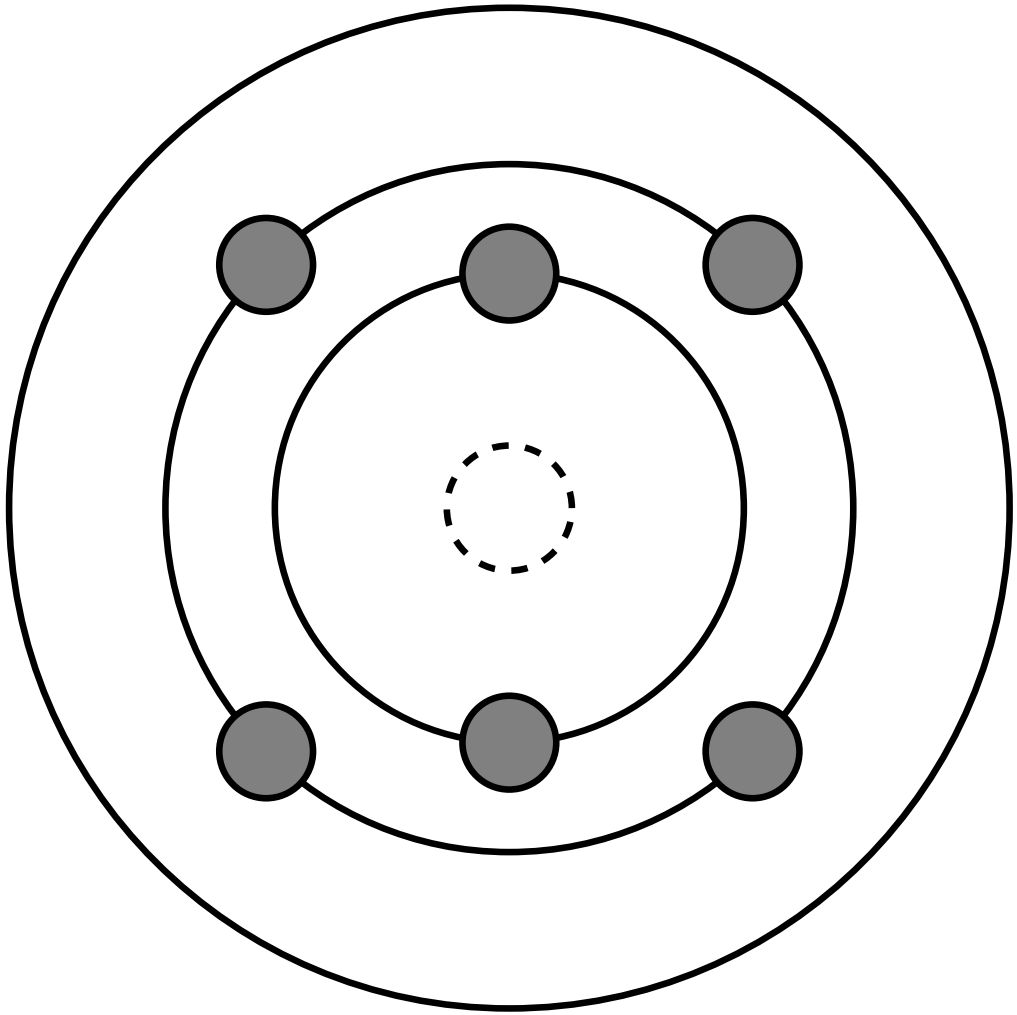
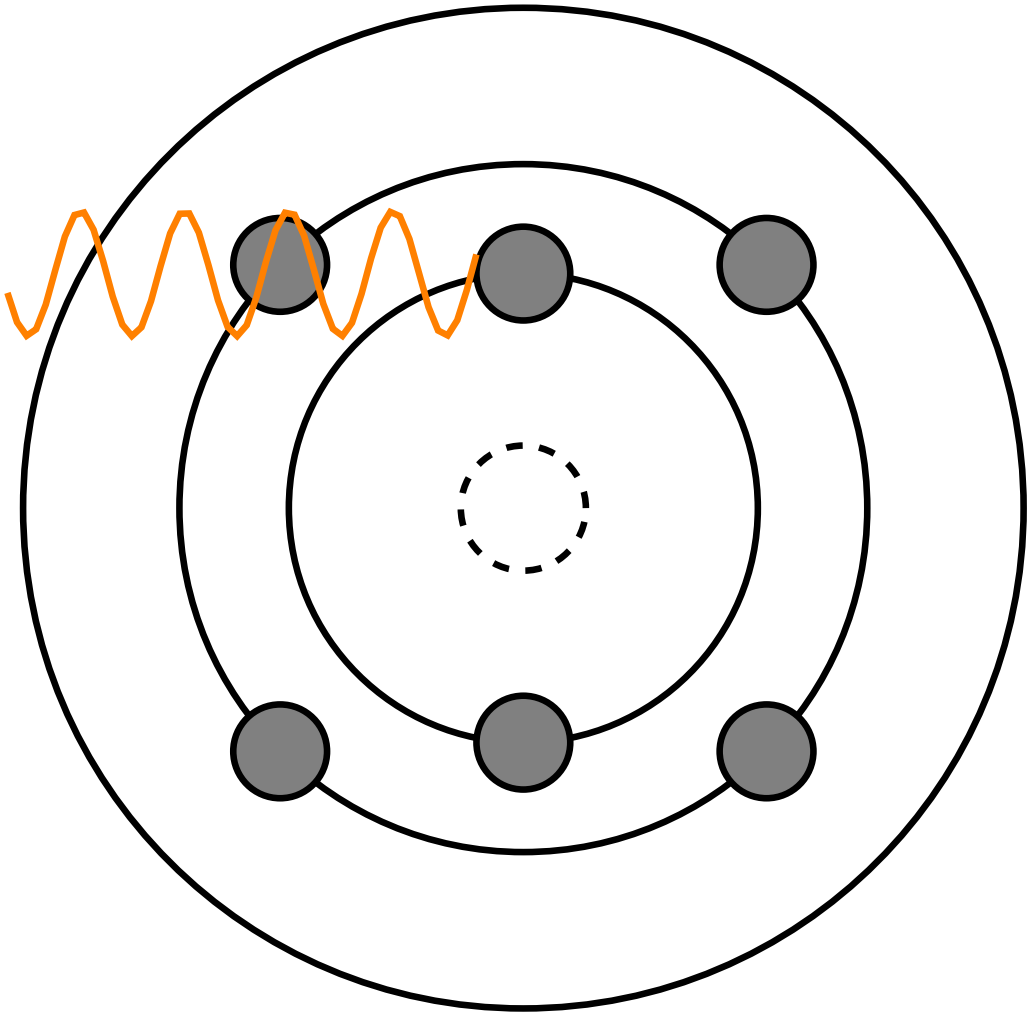


Resonance Fluorescence in Atoms



	Atom
Res. Energy	$10^0\,\mathrm{eV}$
Res. Width	$> 10^{-7}\,\mathrm{eV}$
System mass $\times c^2$	$10^9\,\mathrm{eV}$

Resonance Fluorescence in Atoms



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- **Photon source**: 'conventional' light sources, **laser**

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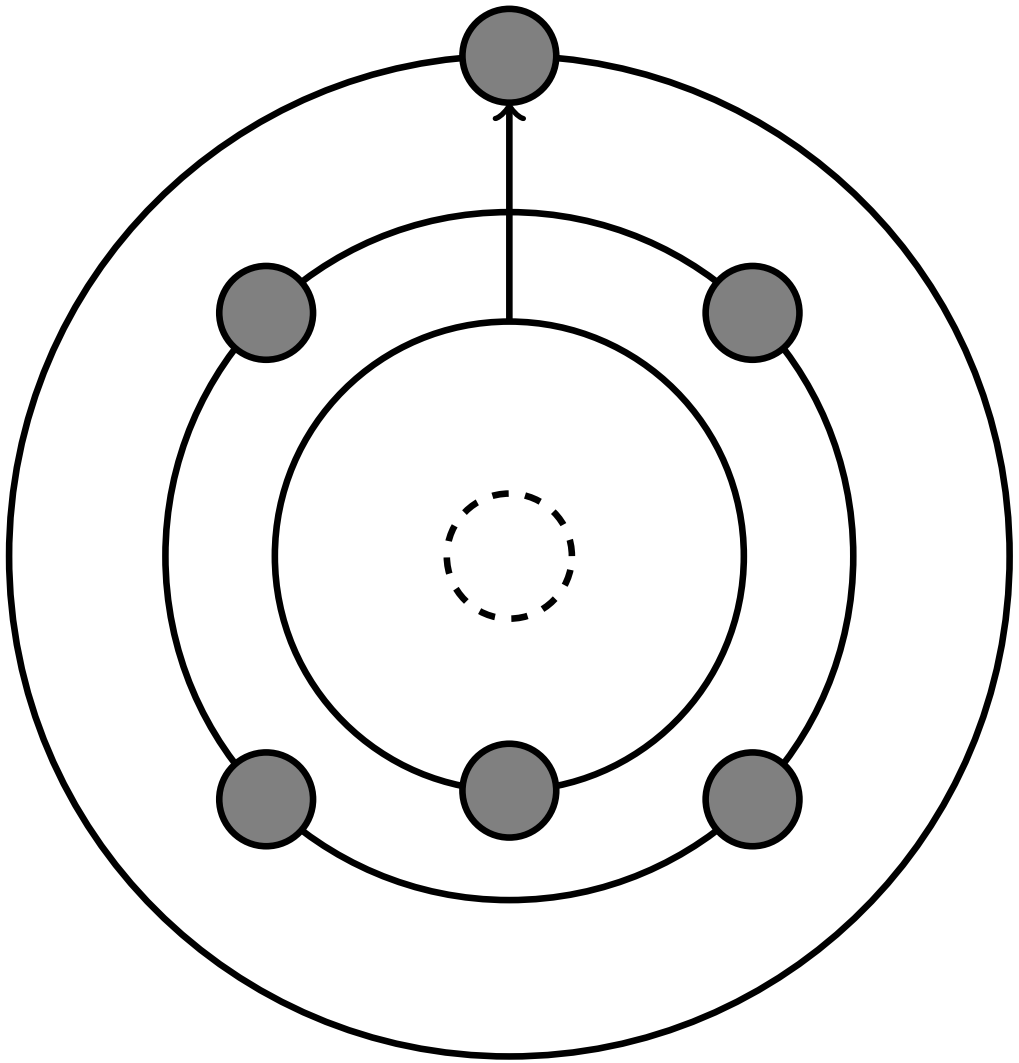

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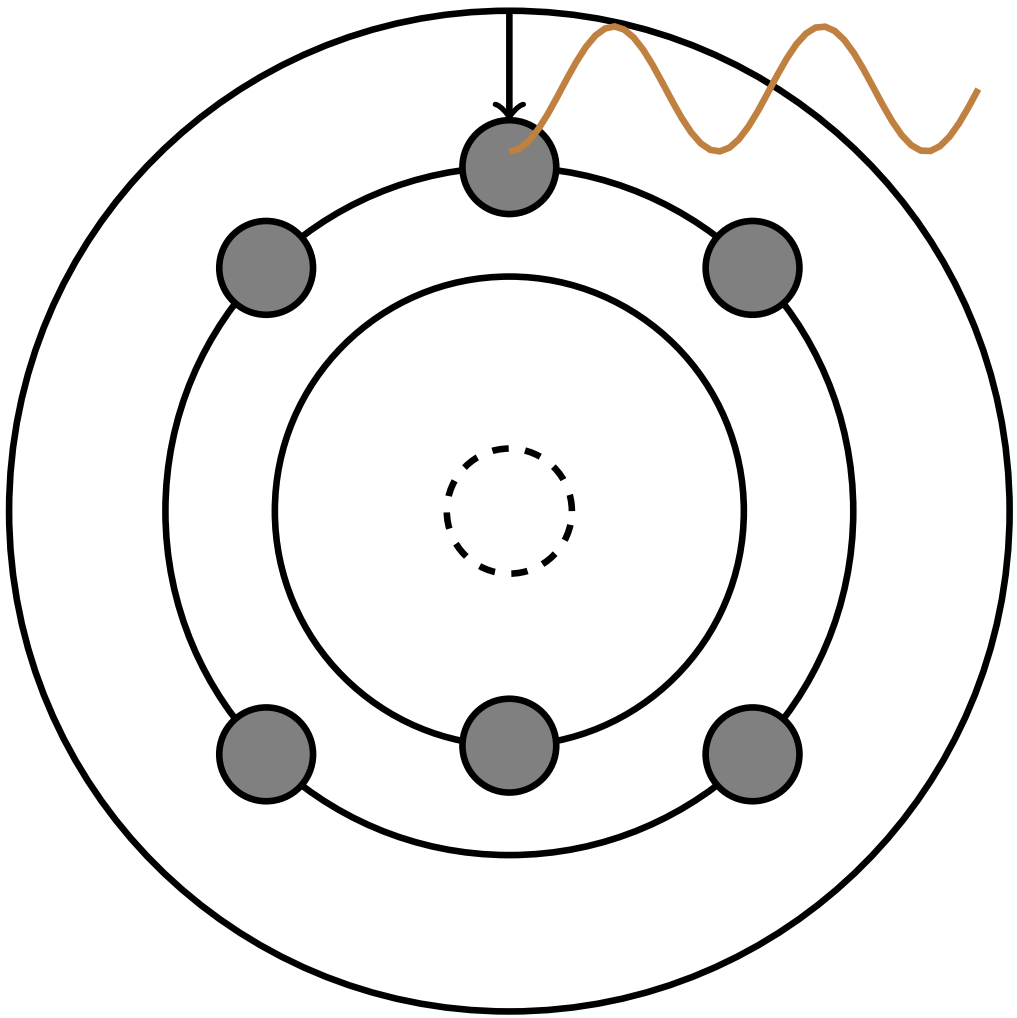

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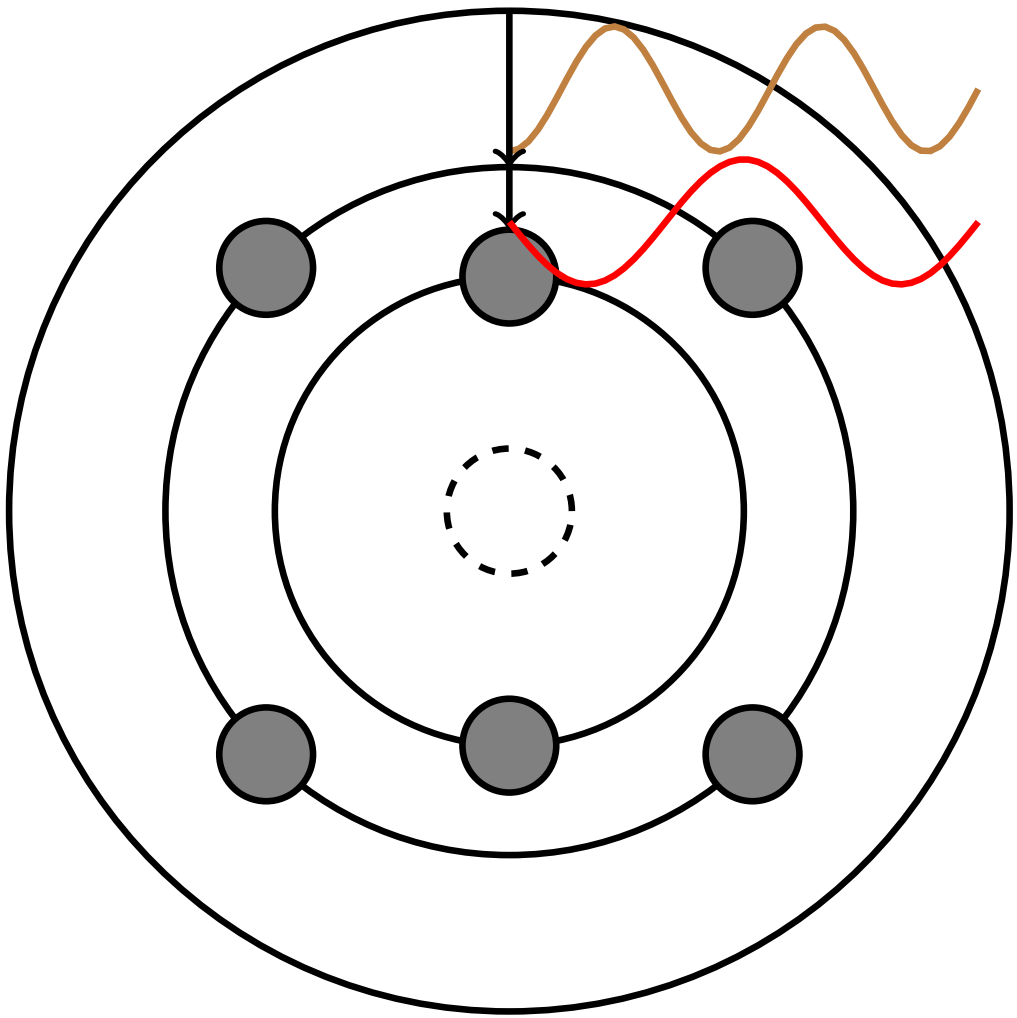
Resonance Fluorescence in Atoms



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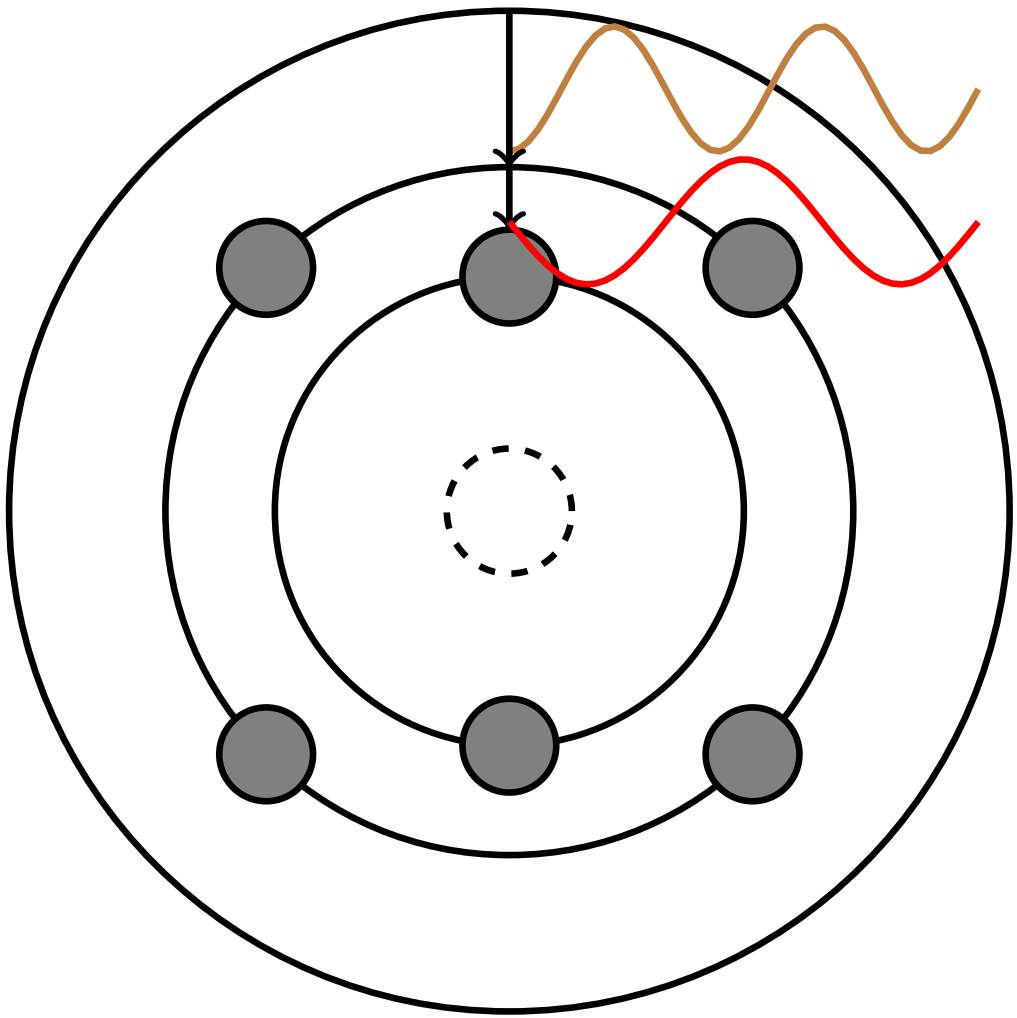

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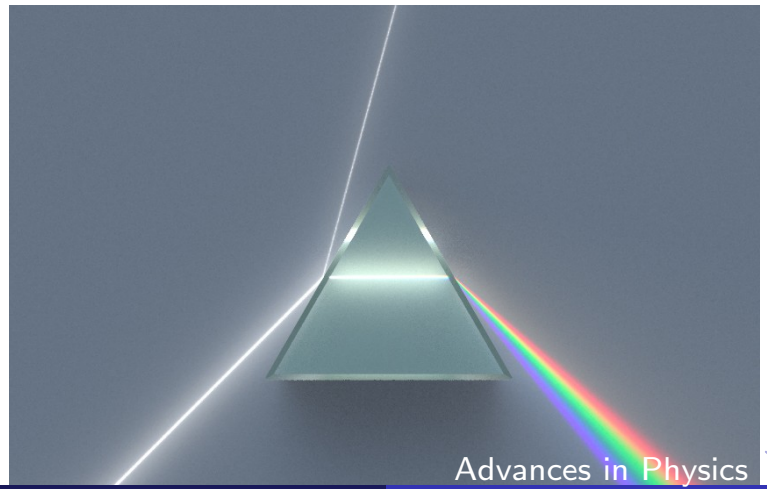
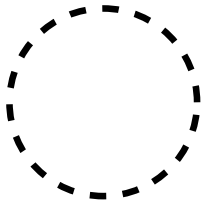
- **Photon source**: 'conventional' light sources, **laser**
- **Photon spectroscopy**: prisms, diffraction grids



Resonance Fluorescence in Nuclei

	Atom	Nucleus
Res. Energy	$10^0\,\mathrm{eV}$	$10^6\,\mathrm{eV}$
Res. Width	$10^{-7}\,\mathrm{eV}$	$10^0\,\mathrm{eV}$
System mass $\times c^2$	$10^9\,\mathrm{eV}$	$10^9\,\mathrm{eV}$



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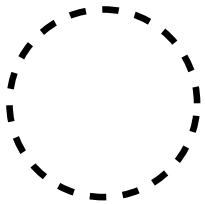

- **Photon source**: radioactive sources

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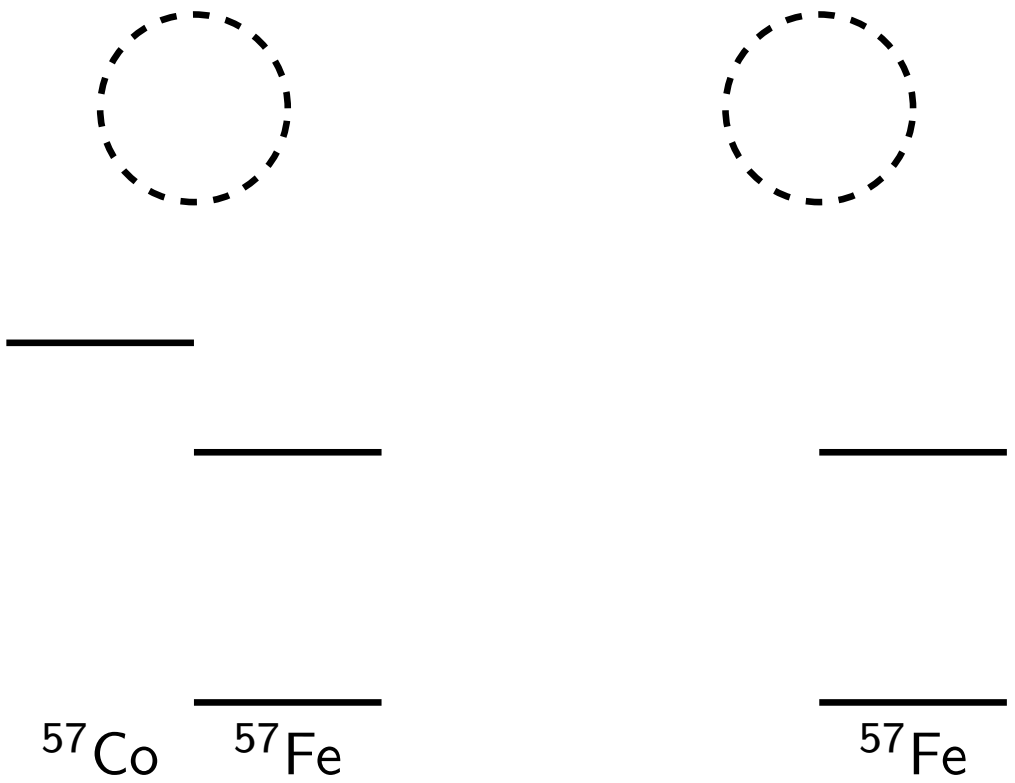

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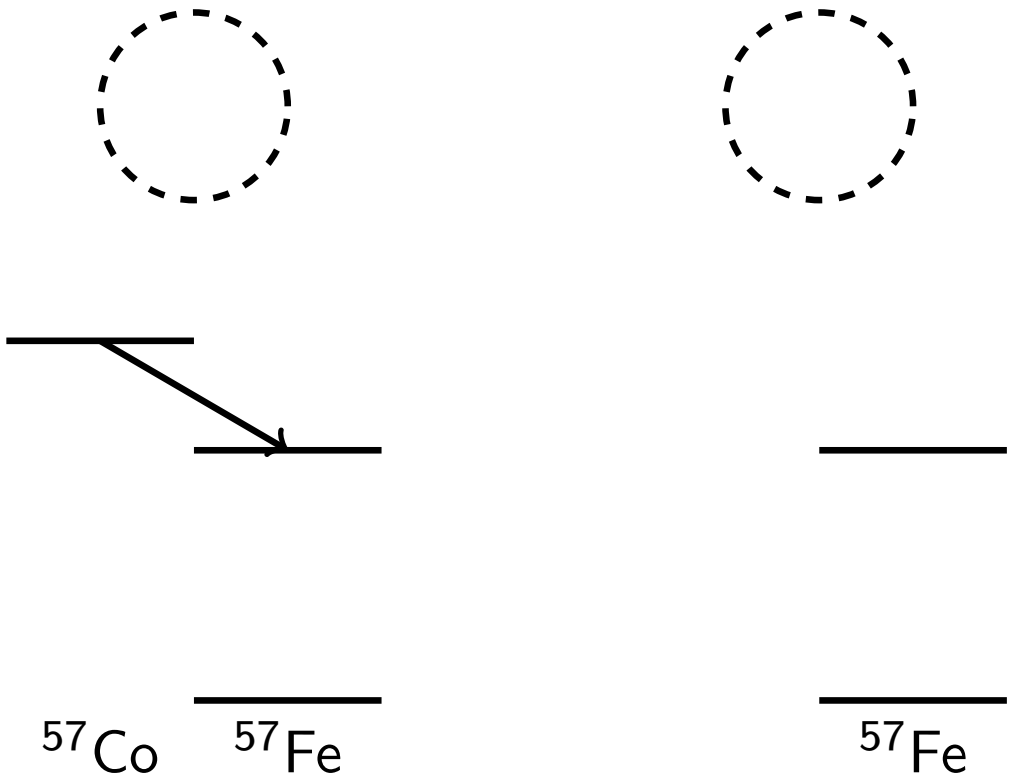

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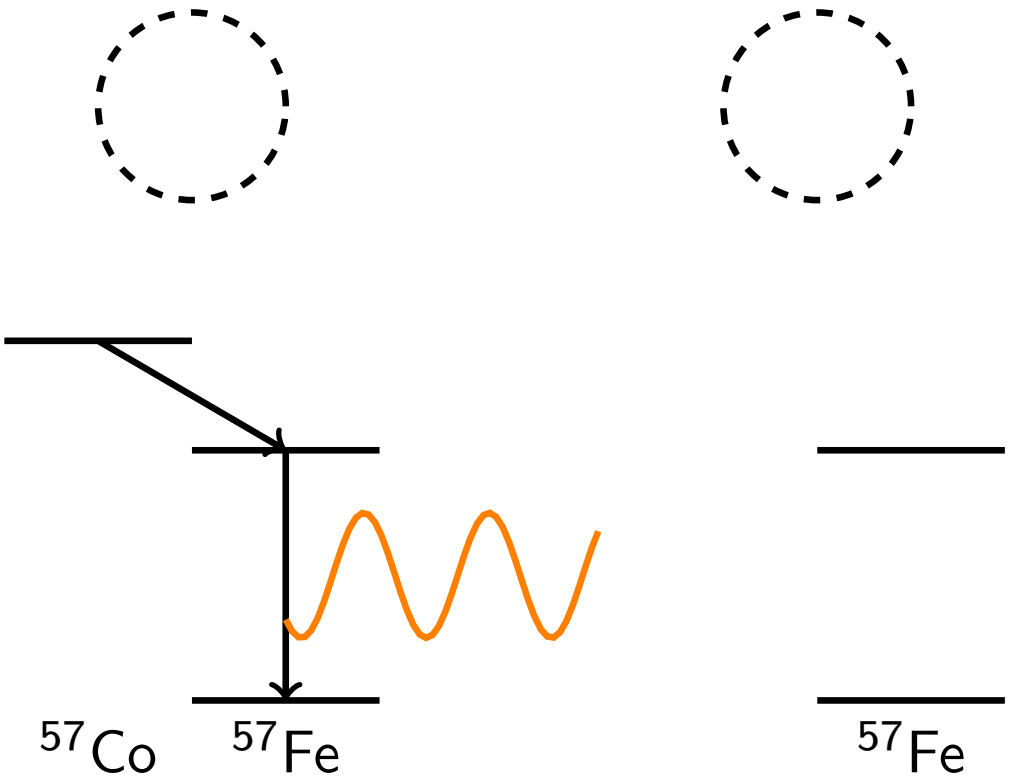

Resonance Fluorescence in Nuclei

$$\text{relative recoil} \approx \frac{\text{Photon energy}}{\text{Nuclear mass} \times c^2}$$

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Res. Width	$10^{-7}\,\mathrm{eV}$	$10^0\,\mathrm{eV}$
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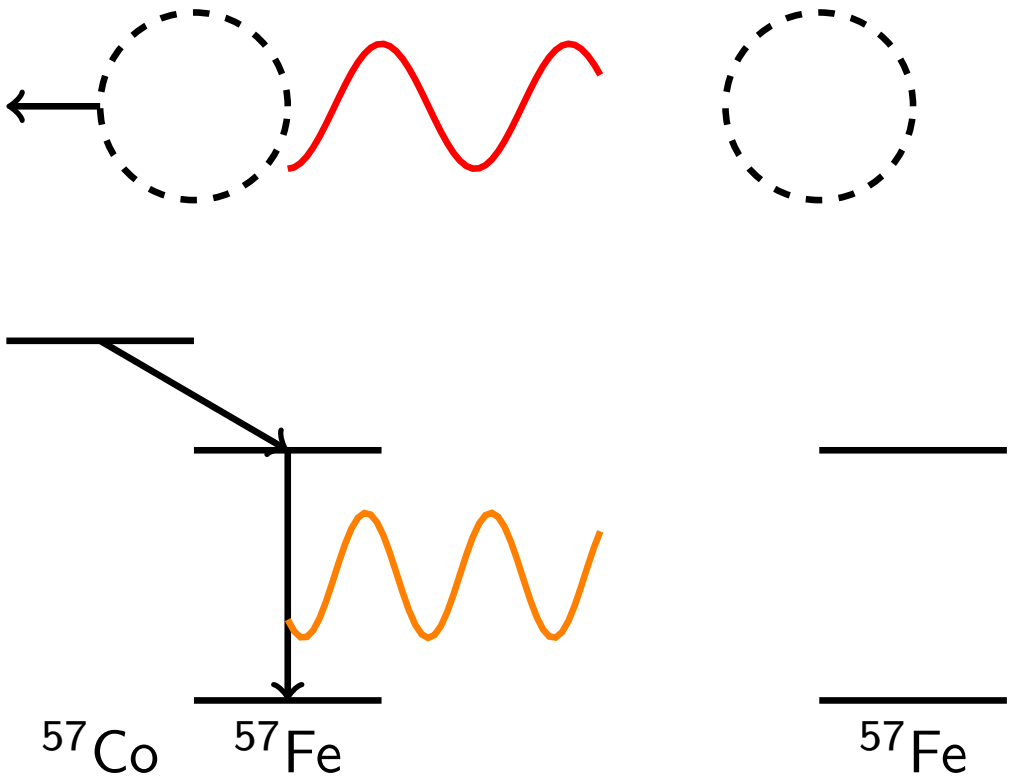

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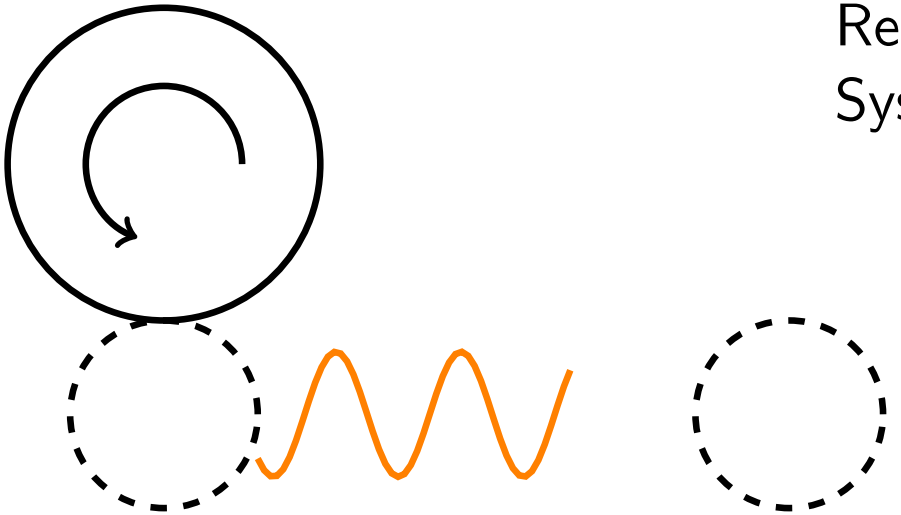
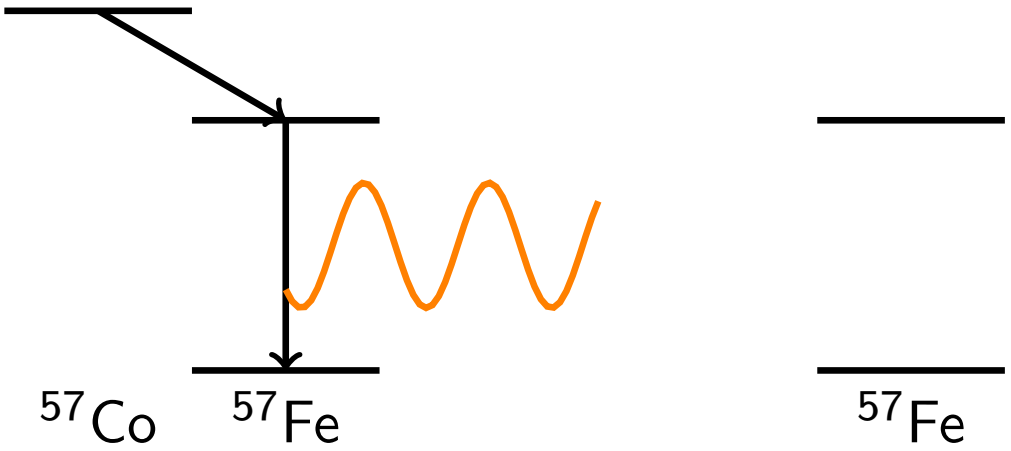


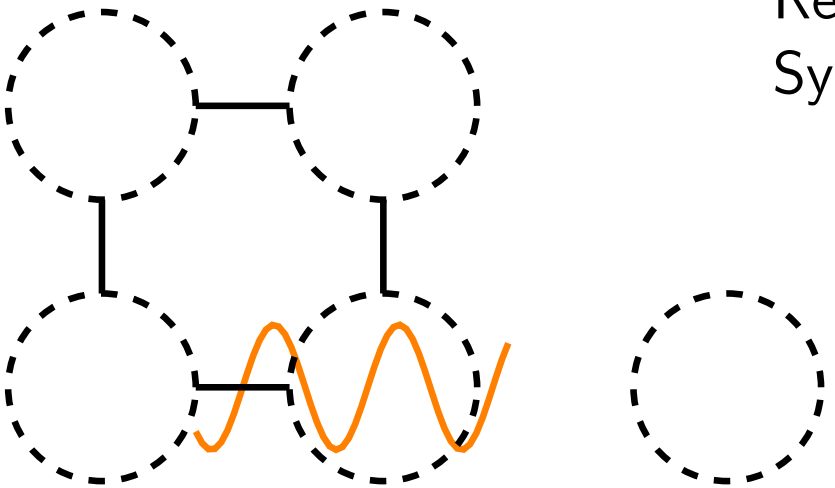
- **Photon source**: radioactive sources [Moon (1951)]



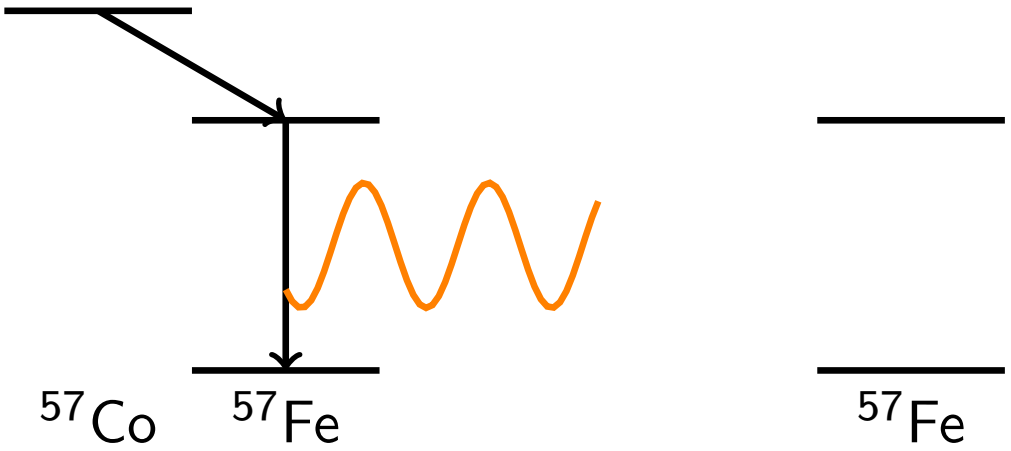
Resonance Fluorescence in Nuclei

$$\text{relative recoil} \approx \frac{\text{Photon energy}}{N \times \text{Nuclear mass} \times c^2}$$

	Atom	Nucleus
Res. Energy	$10^0\,\mathrm{eV}$	$10^6\,\mathrm{eV}$
Res. Width	$10^{-7}\,\mathrm{eV}$	$10^0\,\mathrm{eV}$
System mass $\times c^2$	$10^9\,\mathrm{eV}$	$10^9\,\mathrm{eV}$



- **Photon source**: radioactive sources [Moon (1951), Mössbauer (1958)]



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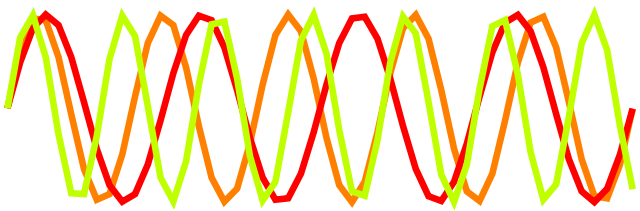

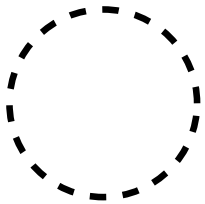

- **Photon source**: radioactive sources [Moon (1951), Mössbauer (1958)], photon beams [Hayward et al. (1957)]

Resonance Fluorescence in Nuclei

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System mass $\times c^2$	$10^9\,\mathrm{eV}$	$10^9\,\mathrm{eV}$

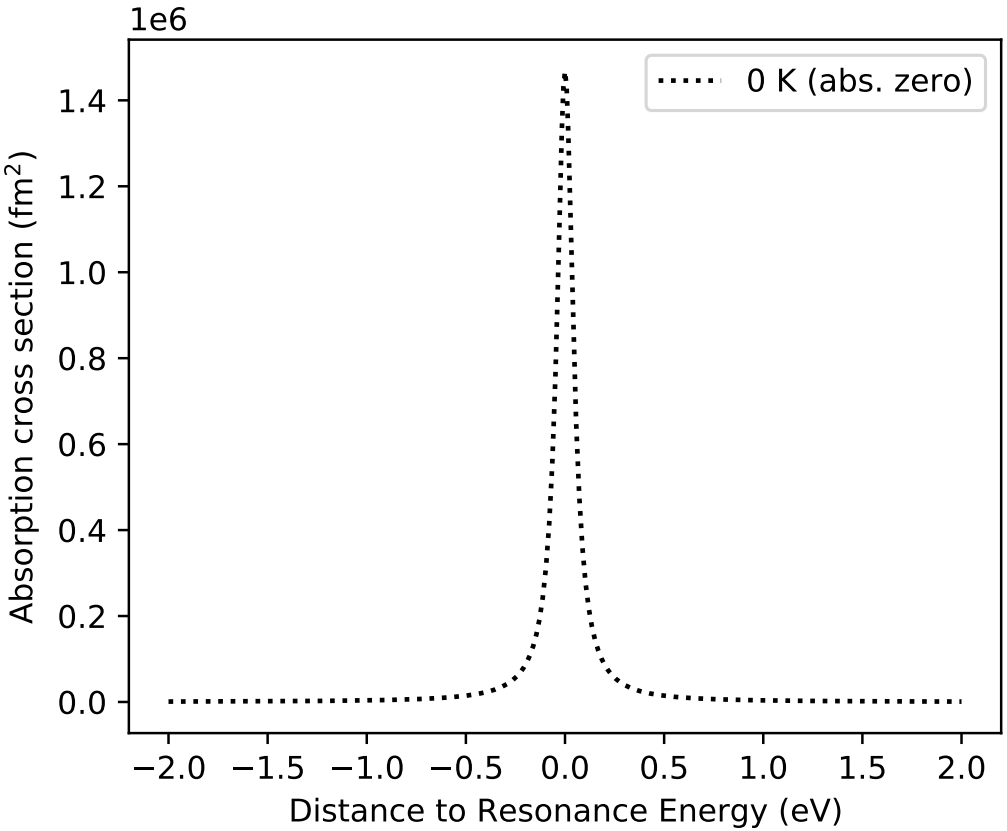
Realistic image of a gamma-ray detector with some indication of the dimensions. I used a picture of two people working on the Gammasphere detectors array, which had been shown in an earlier talk of the series.

- **Photon source**: radioactive sources [Moon (1951), Mössbauer (1958)], photon beams [Hayward et al. (1957)]
- **Photon spectroscopy**: particle detectors (, X-ray diffraction)

Best of two worlds: ^{229m}Th

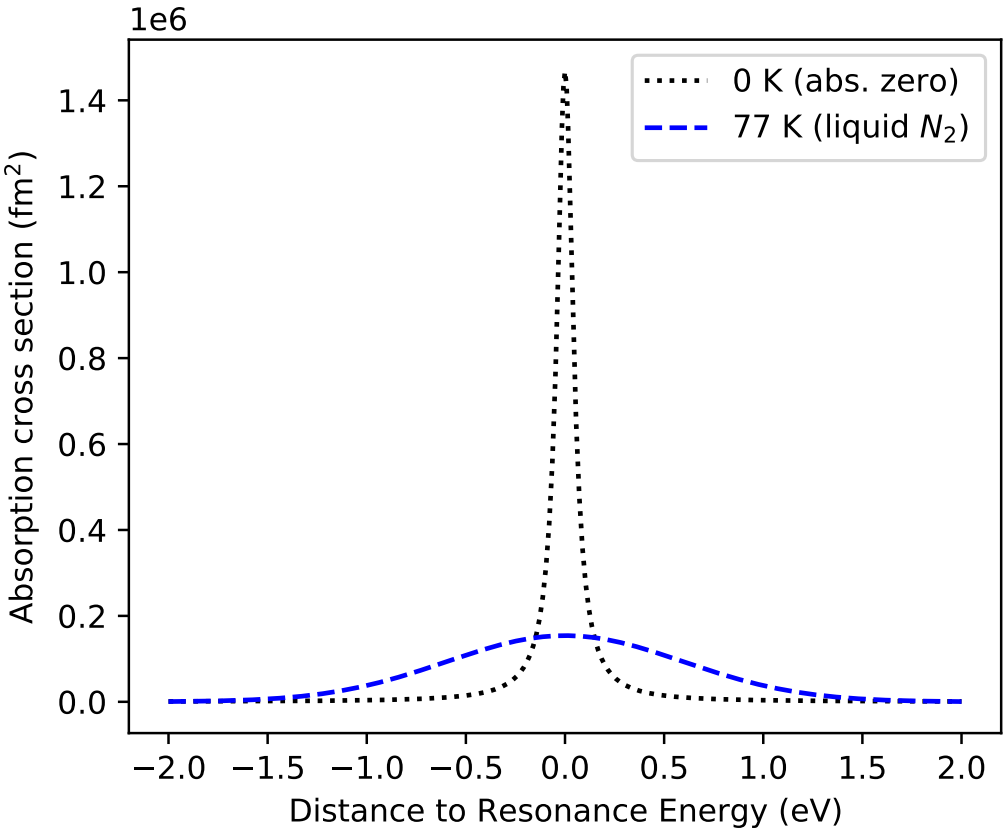
A figure that illustrates the uniqueness of the ^{229m}Th 'nuclear clock isomer'.

Doppler Broadening

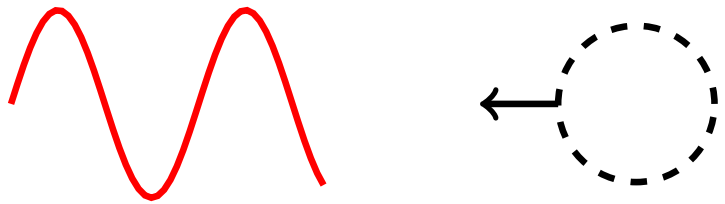


Center-of-mass frame

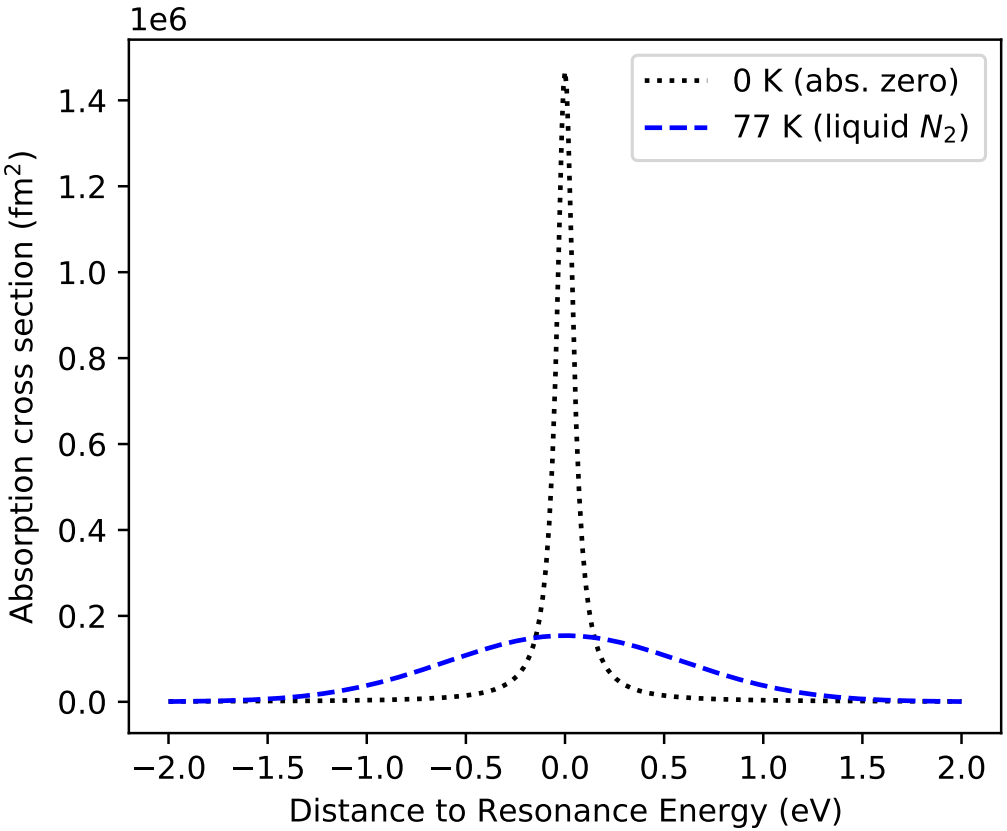
Doppler Broadening



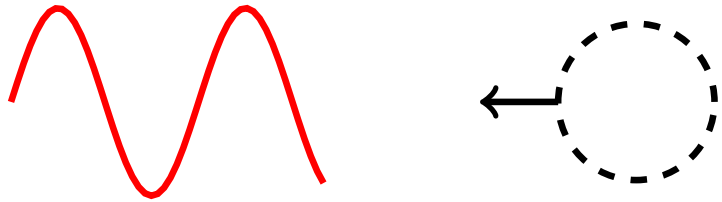
Center-of-mass frame



Doppler Broadening

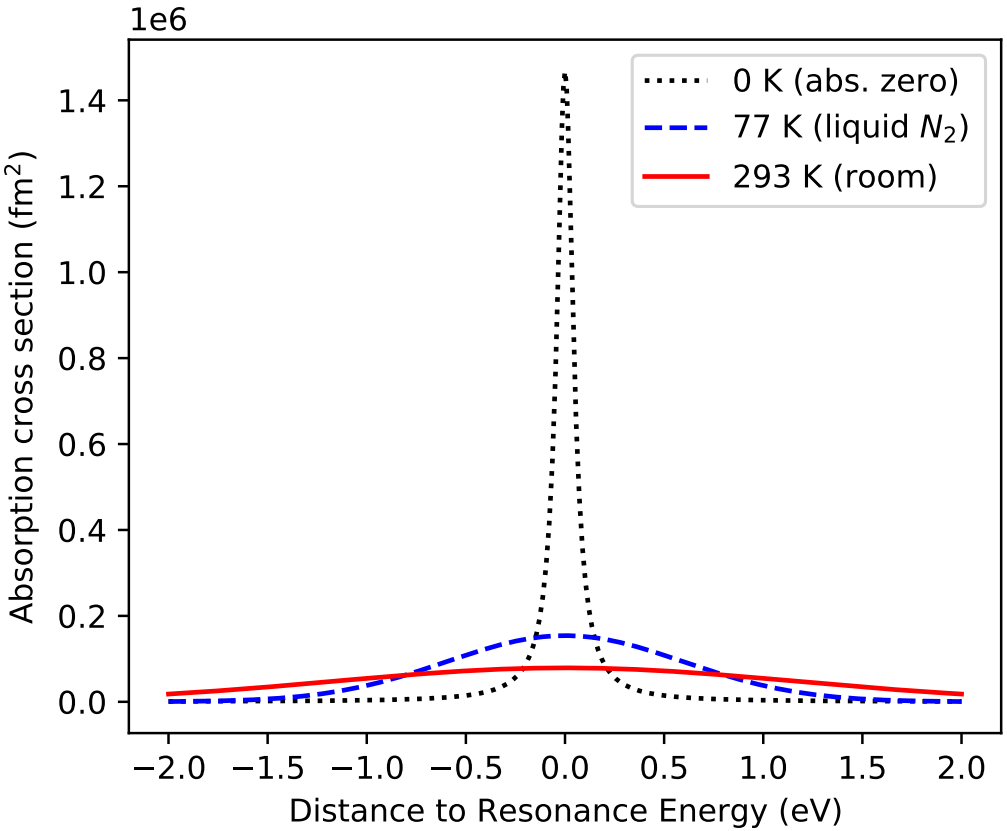


Center-of-mass frame

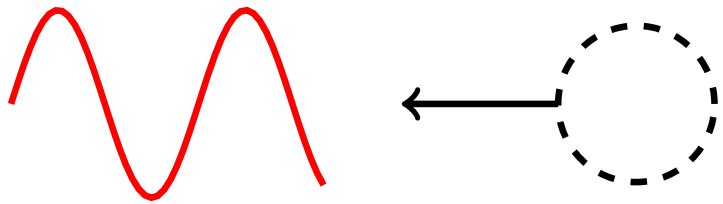


Nucleus-at-rest frame

Doppler Broadening



Center-of-mass frame



Nucleus-at-rest frame

Doppler Broadening

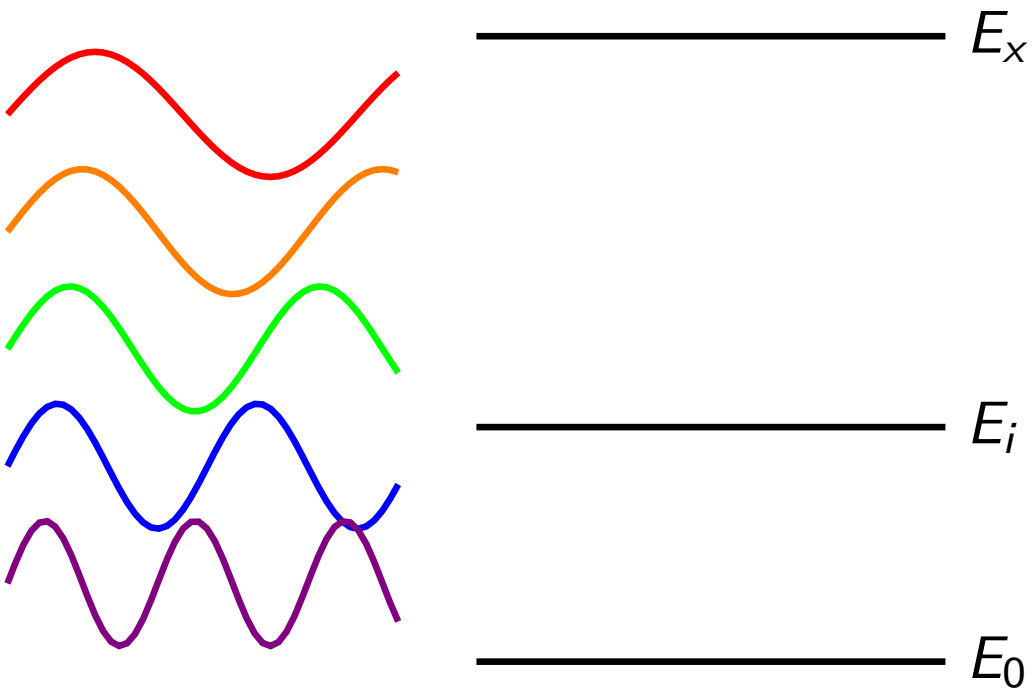
Some figure which shows that a resonance can have an arbitrary line shape due to condensed-matter effects. I used the conjecture by Lamb in his article on neutron capture by atoms in a crystal.

Center-of-mass frame

Nucleus-at-rest frame

Connection to condensed-matter physics [Lamb, (1939)]

Absorption or Scattering Spectroscopy?



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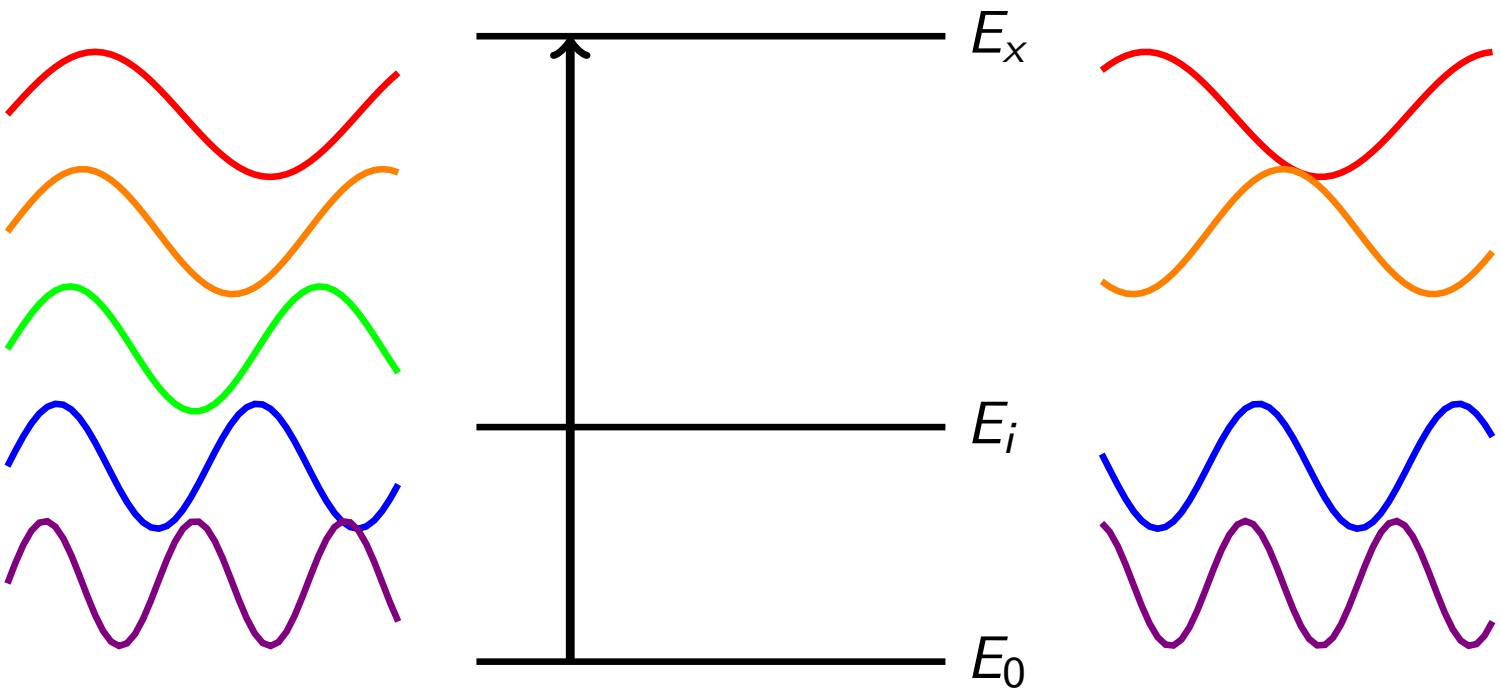
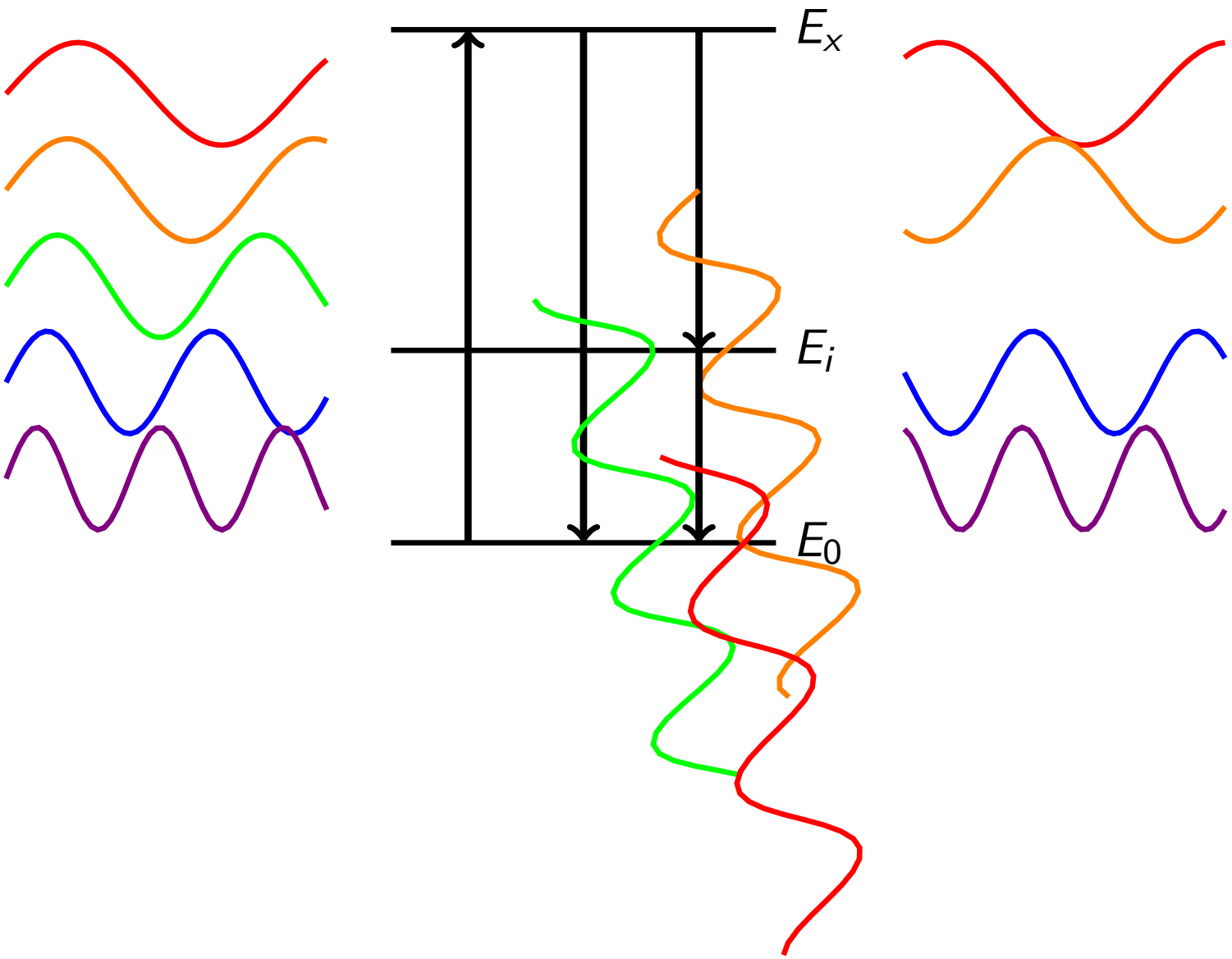
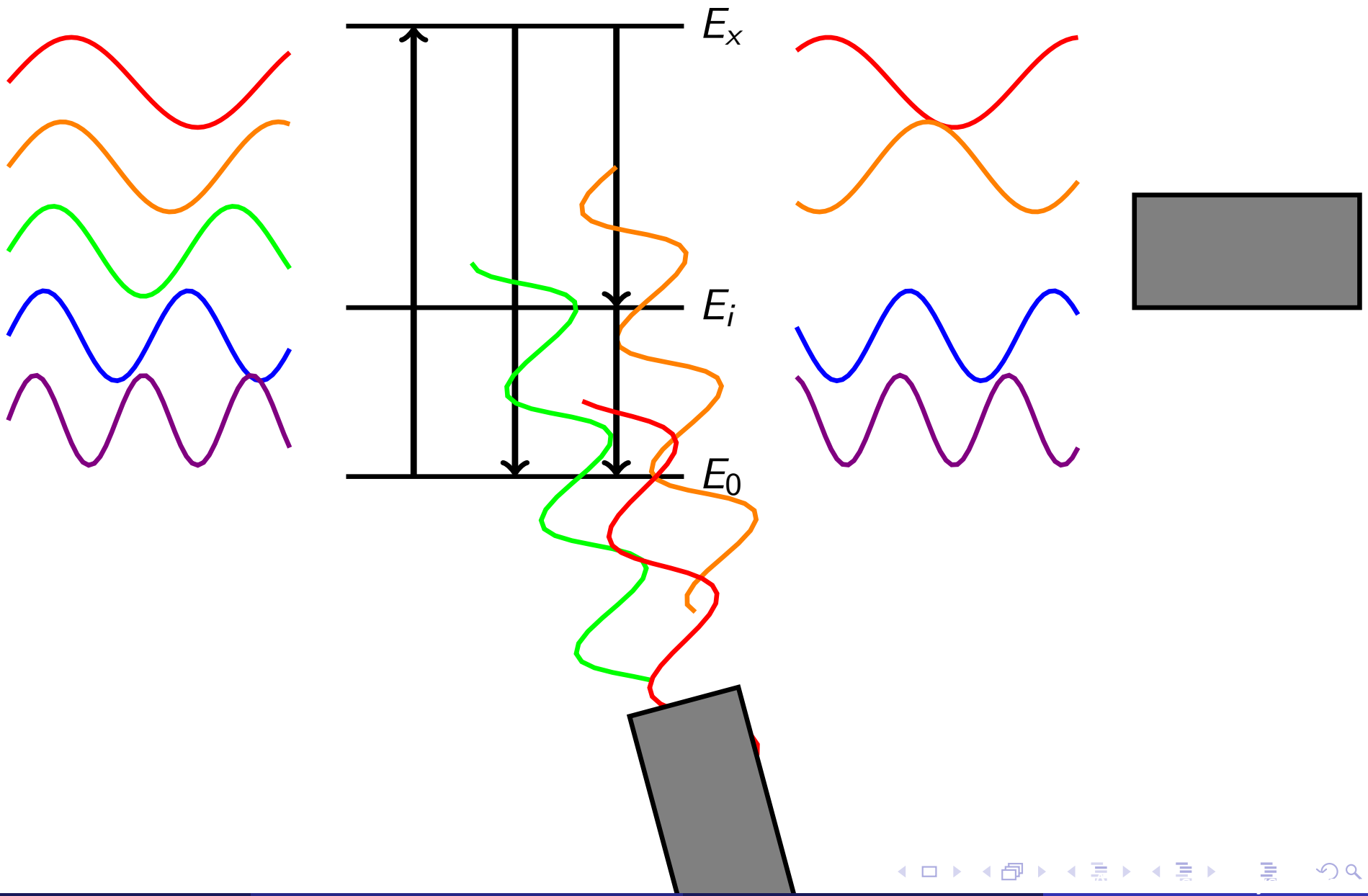


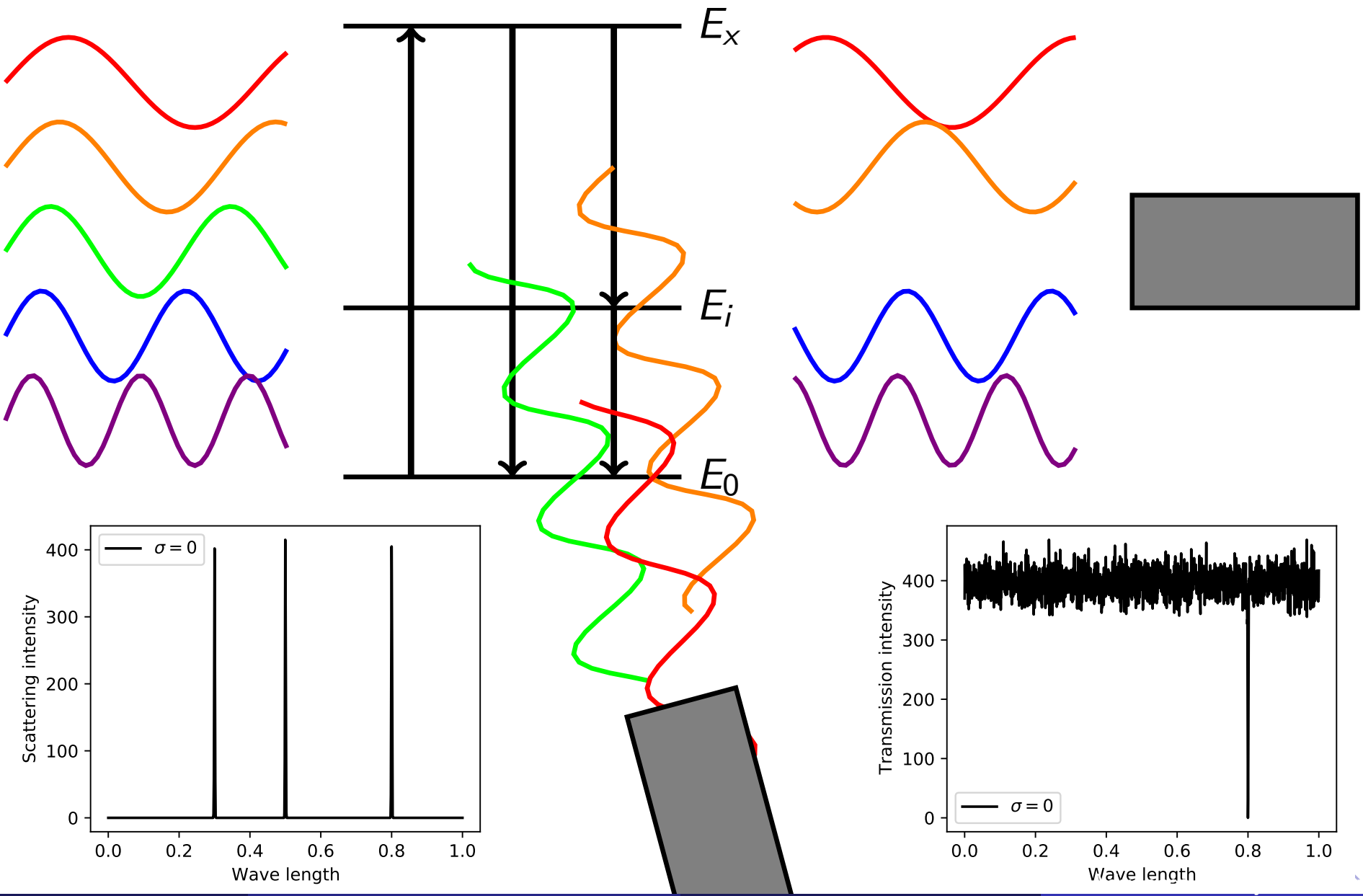
Absorption or Scattering Spectroscopy?



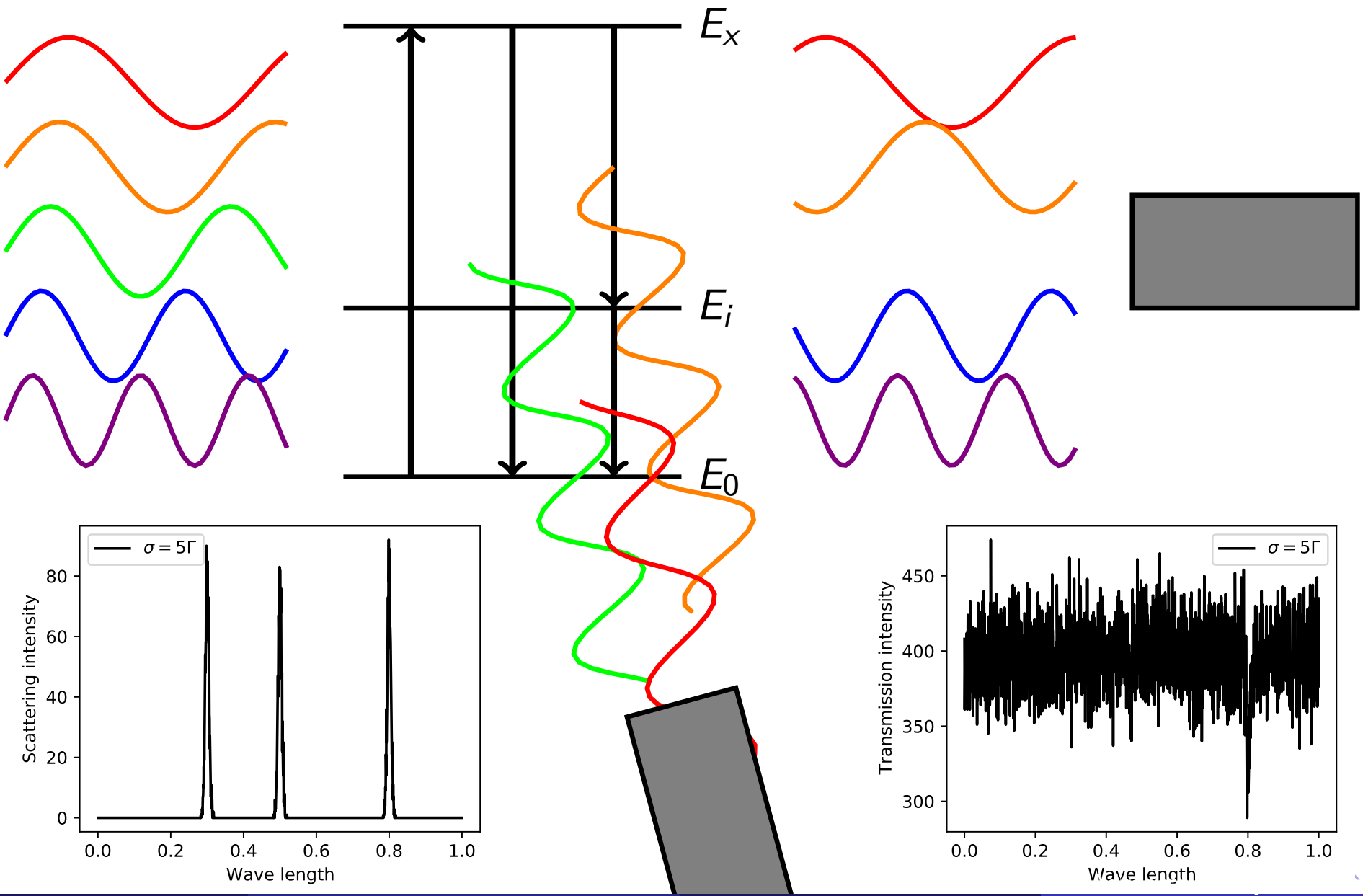
Absorption or Scattering Spectroscopy?



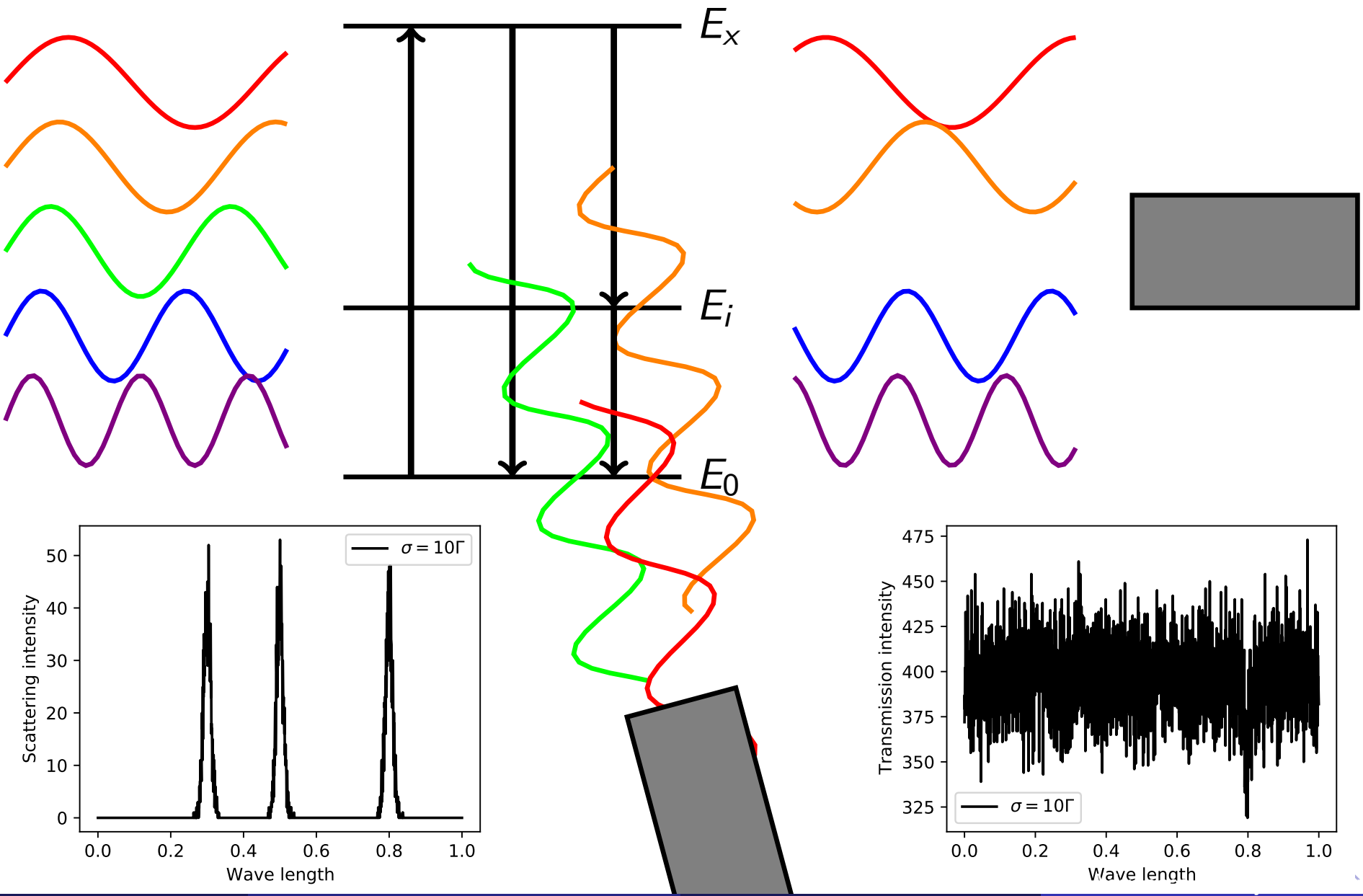
Absorption or Scattering Spectroscopy?



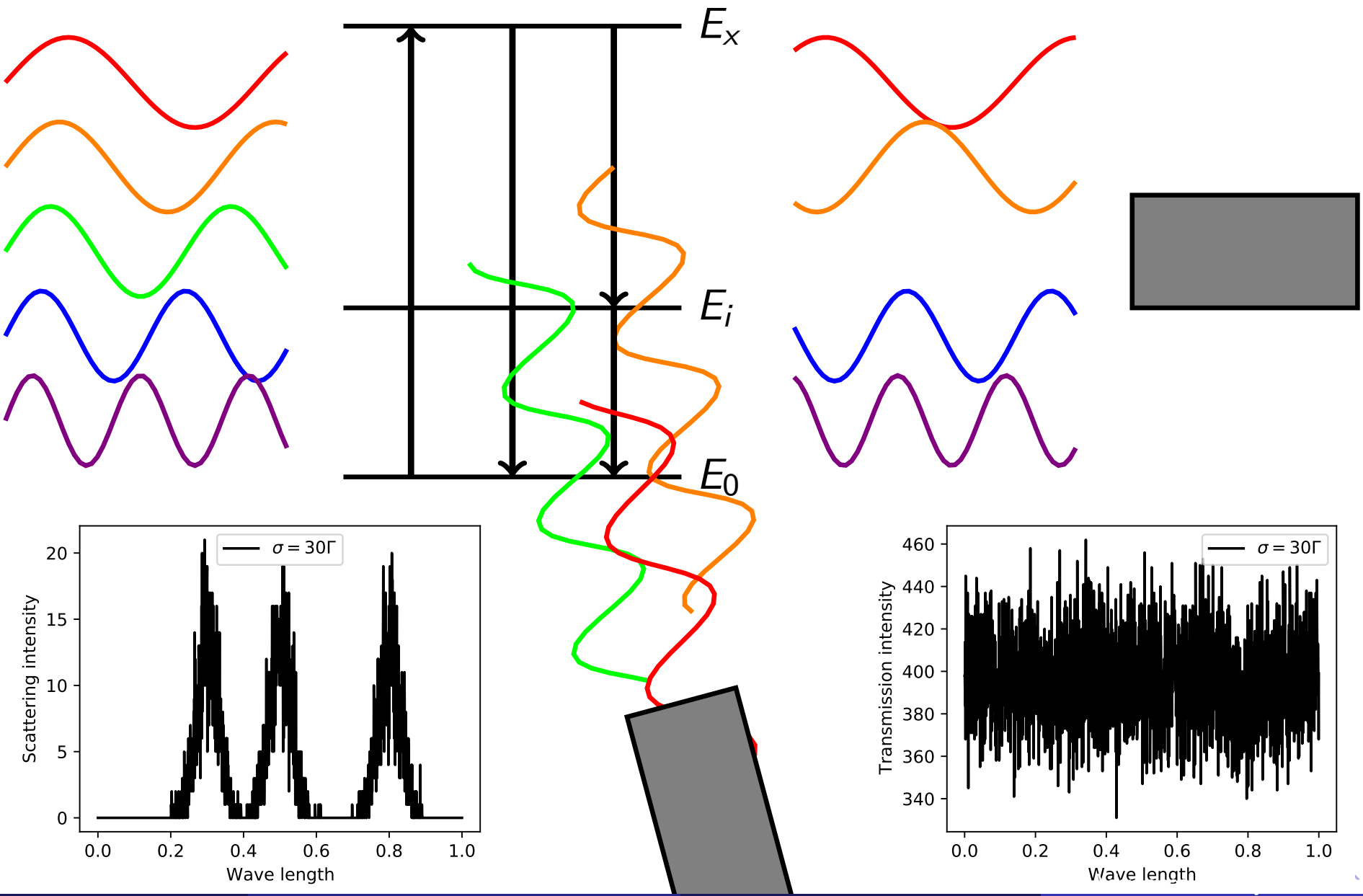
Absorption or Scattering Spectroscopy?



Absorption or Scattering Spectroscopy?



Absorption or Scattering Spectroscopy?



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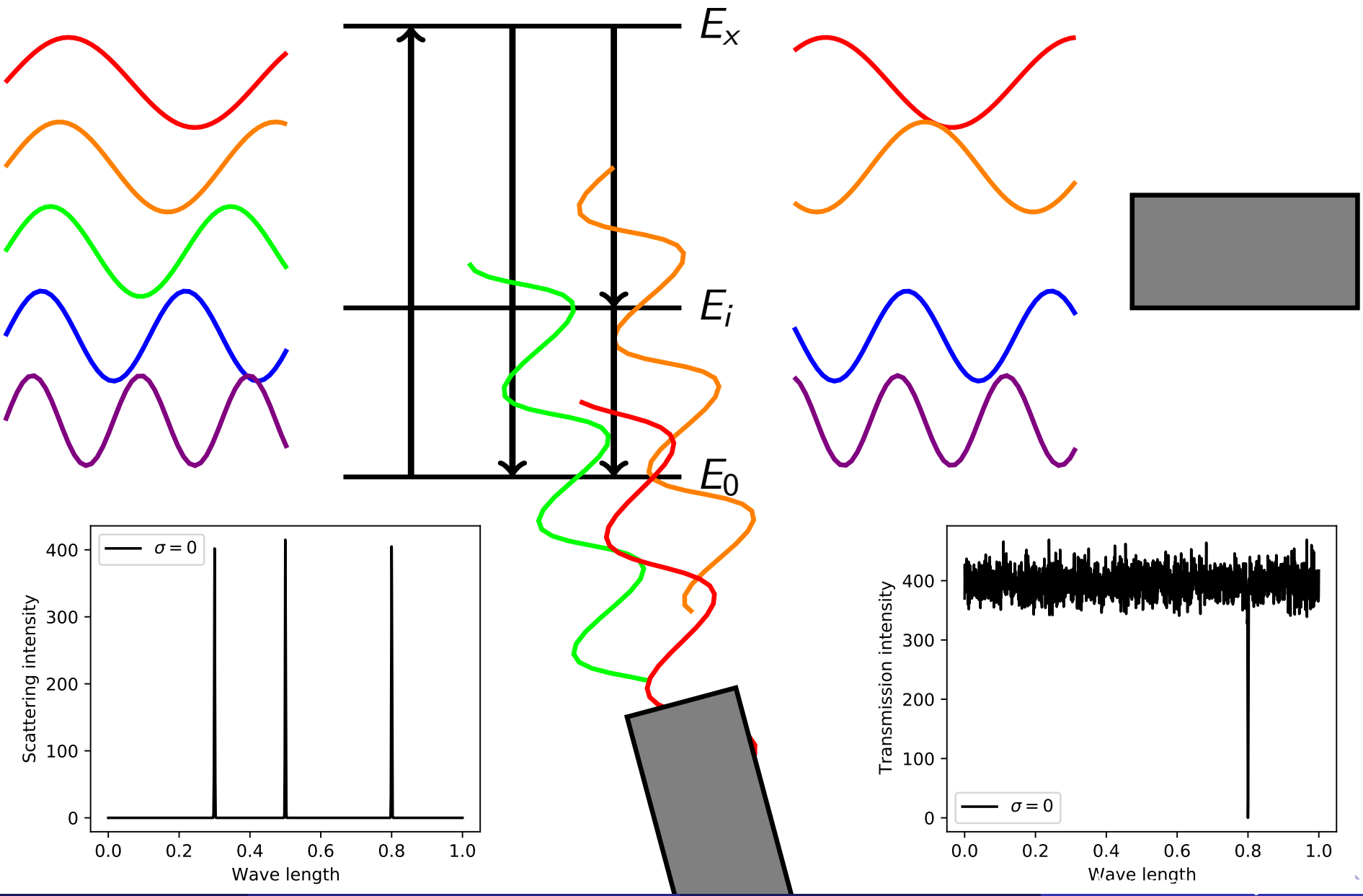

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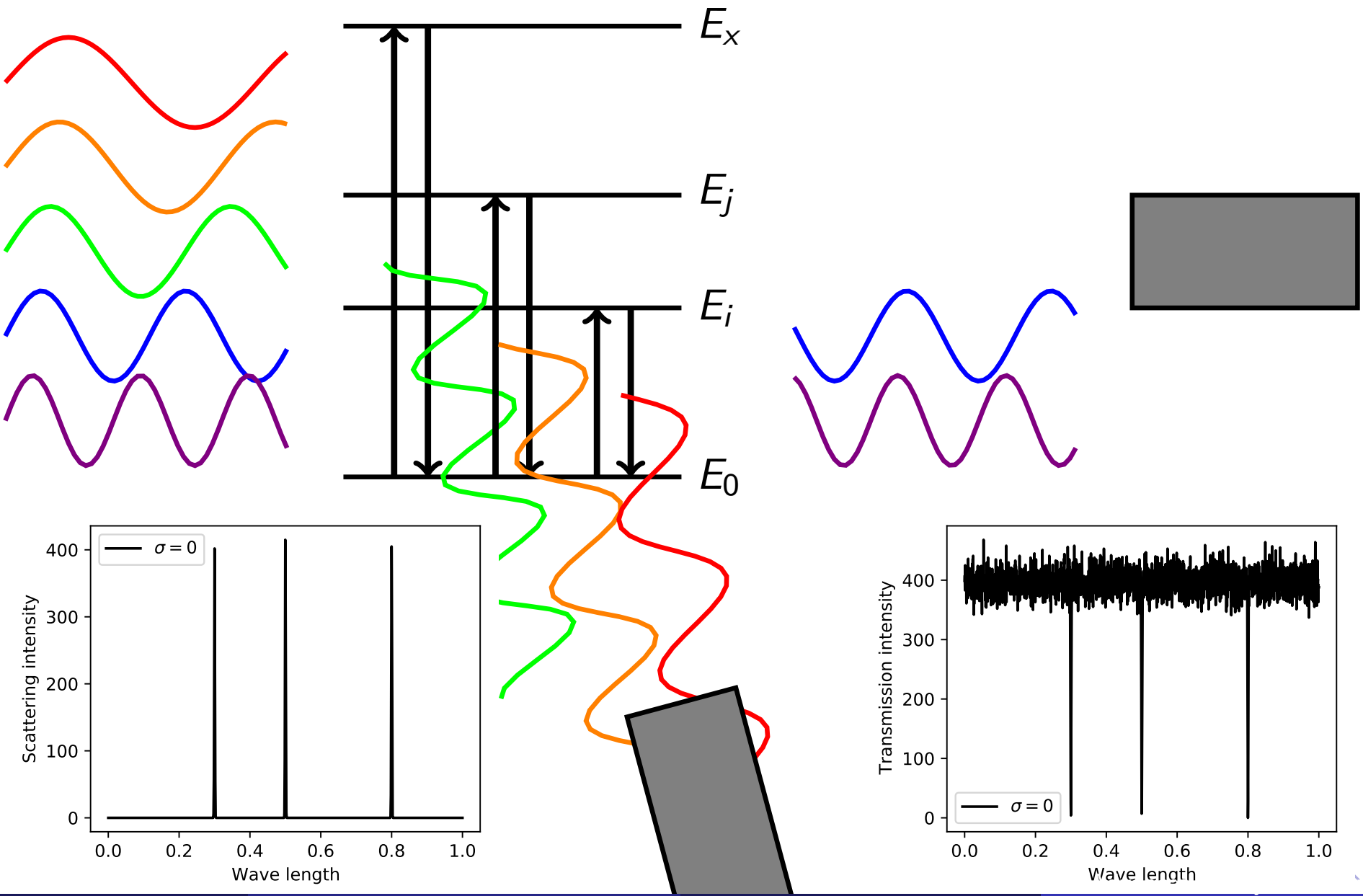

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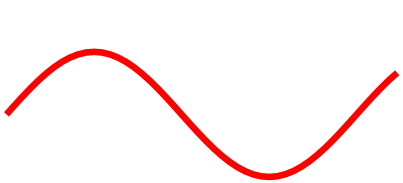

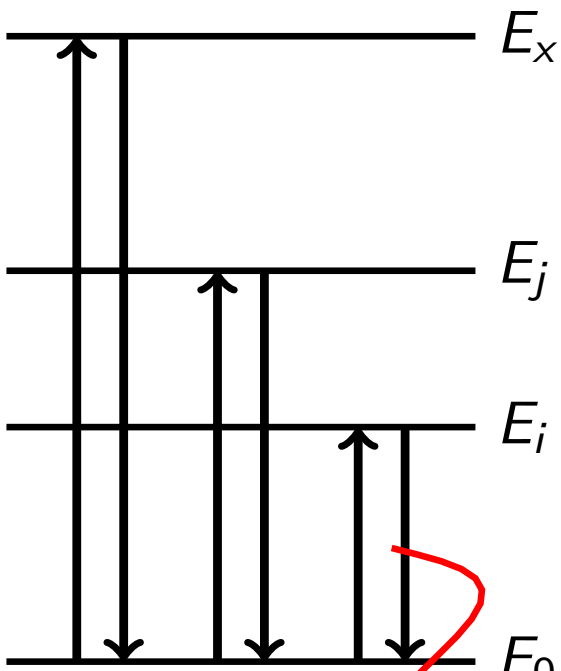

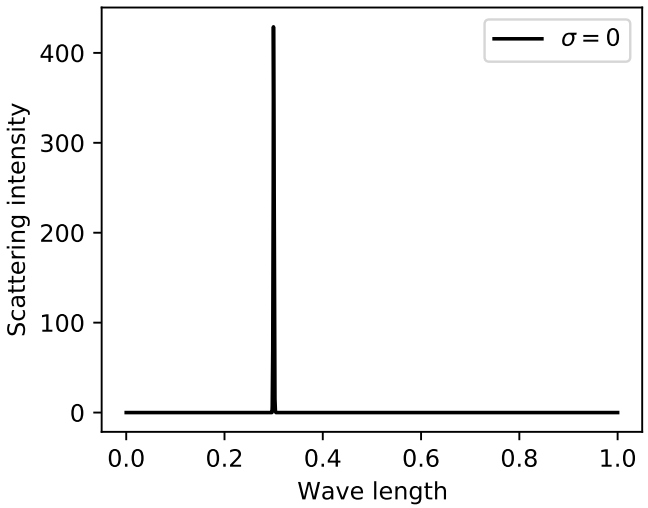

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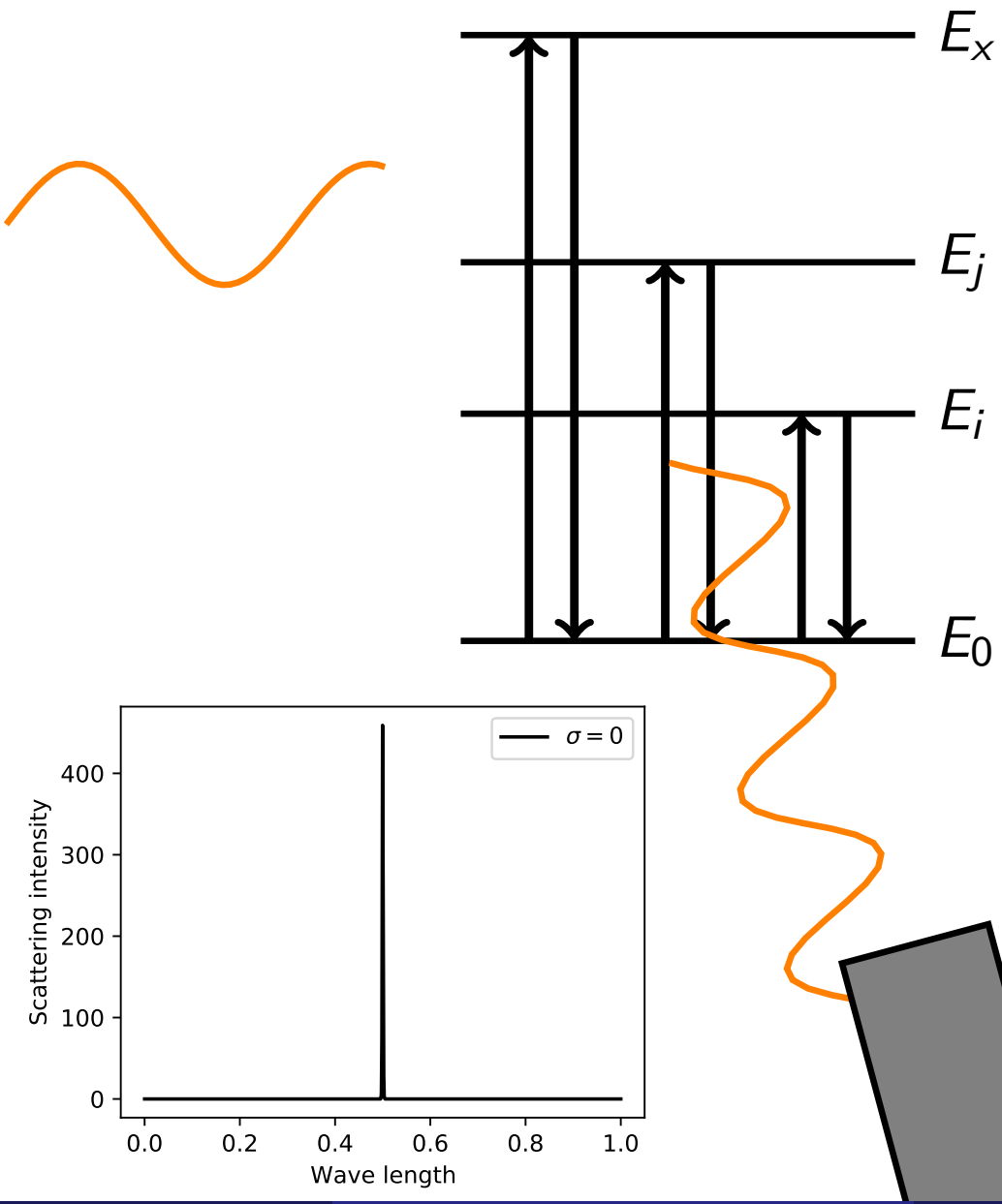

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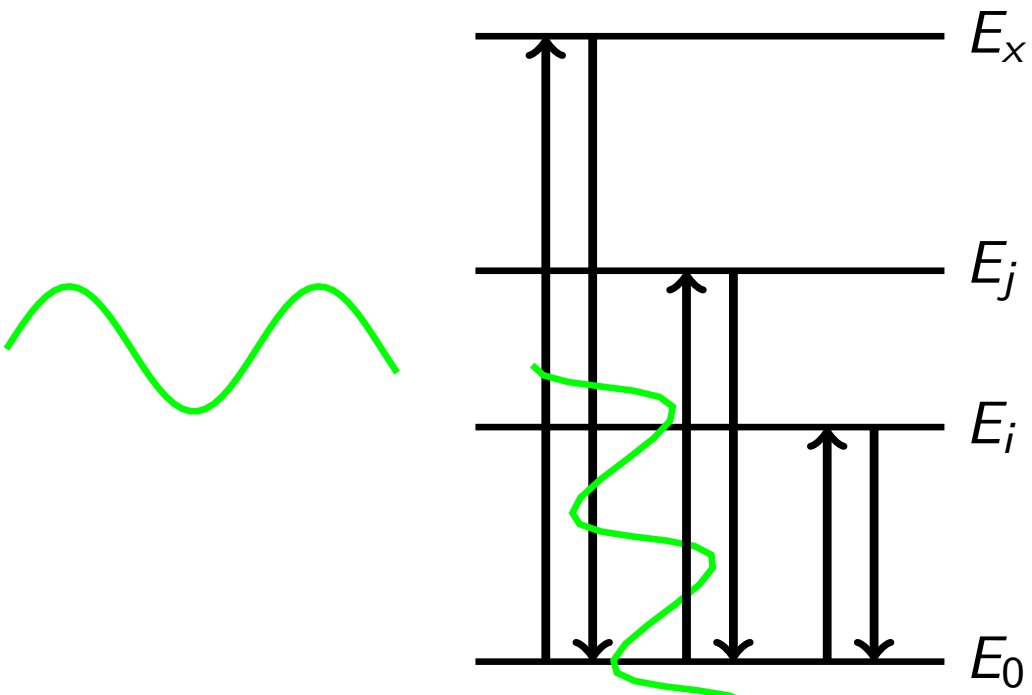
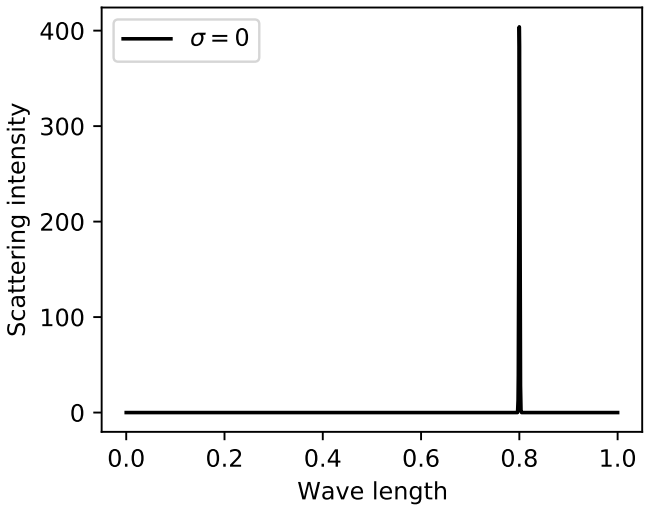
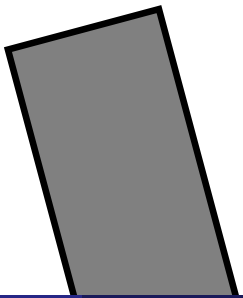
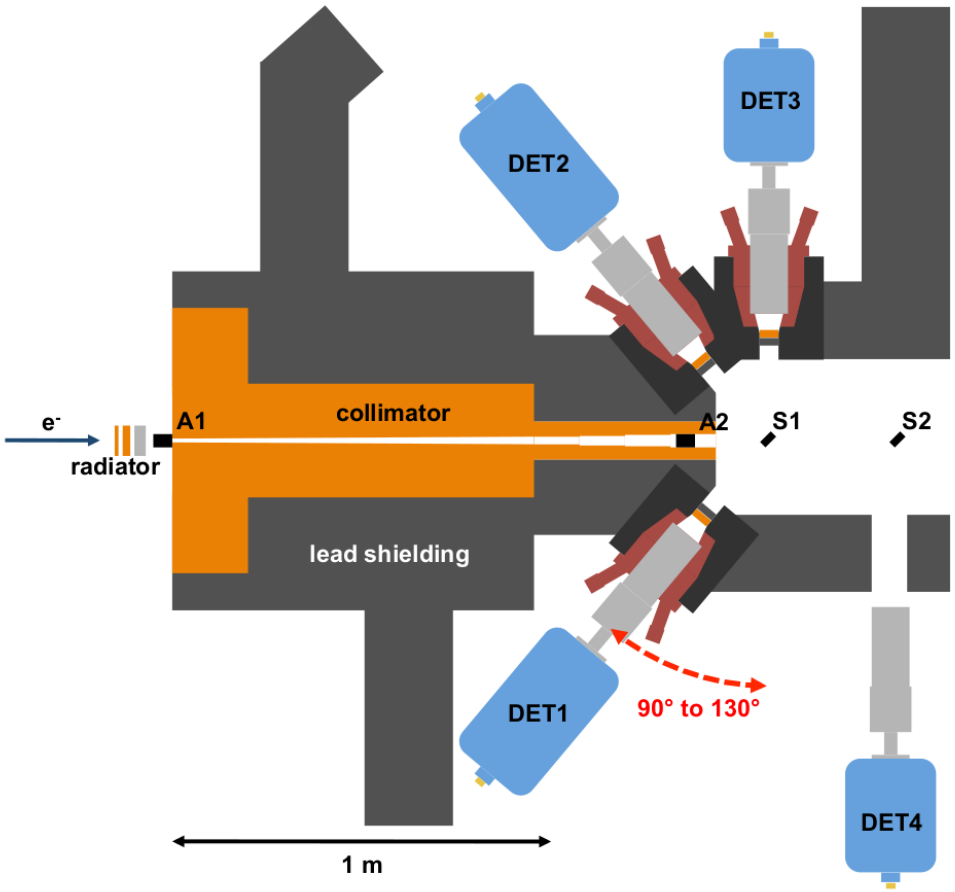




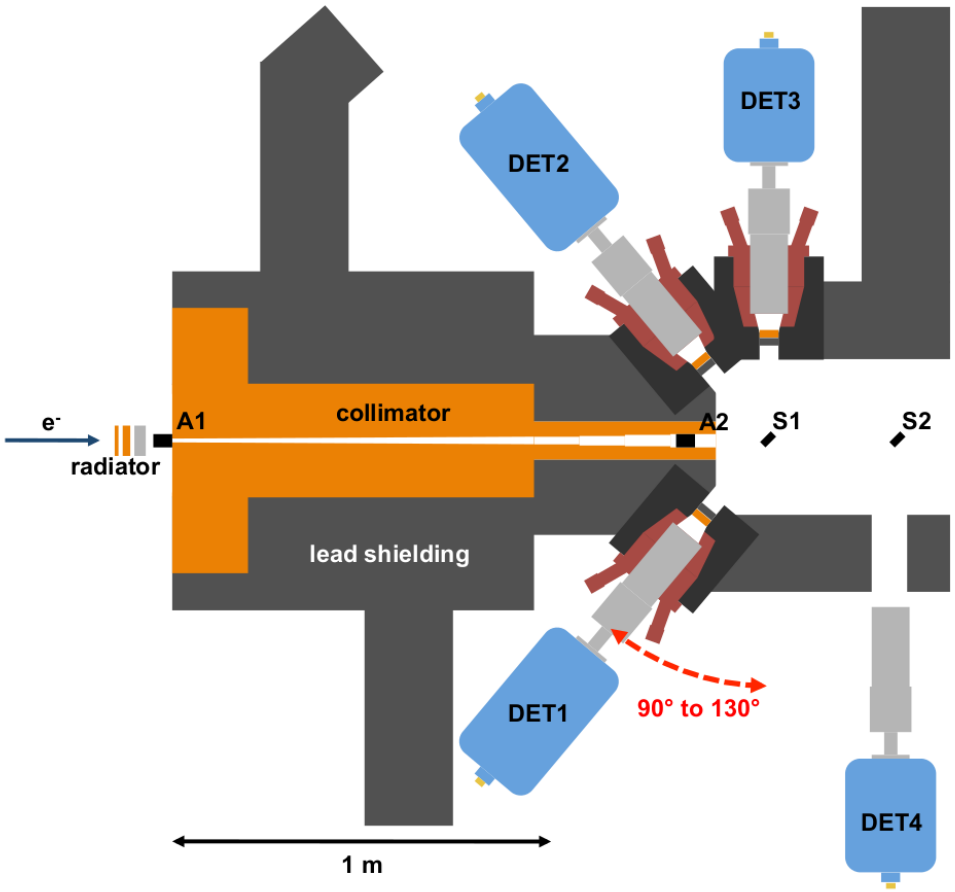


Bremsstrahlung



- Hayward et al. (1957)
- Continuous spectrum of photons up to the maximum electron energy

Bremsstrahlung



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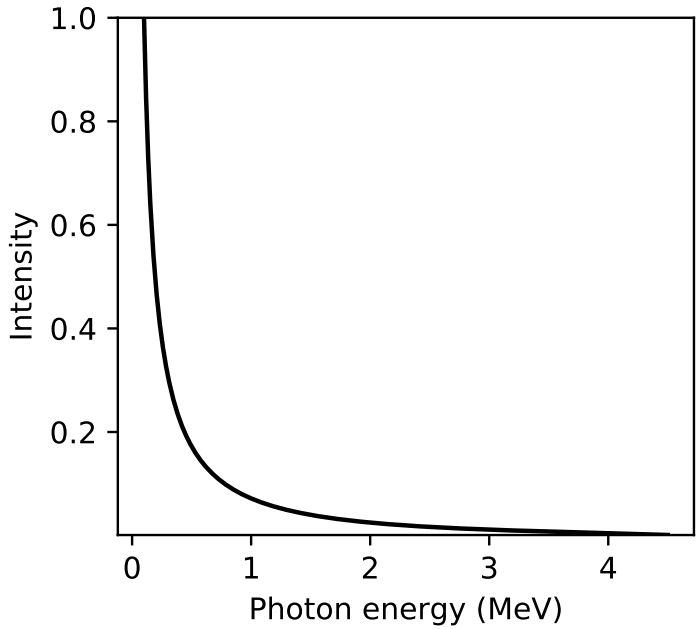
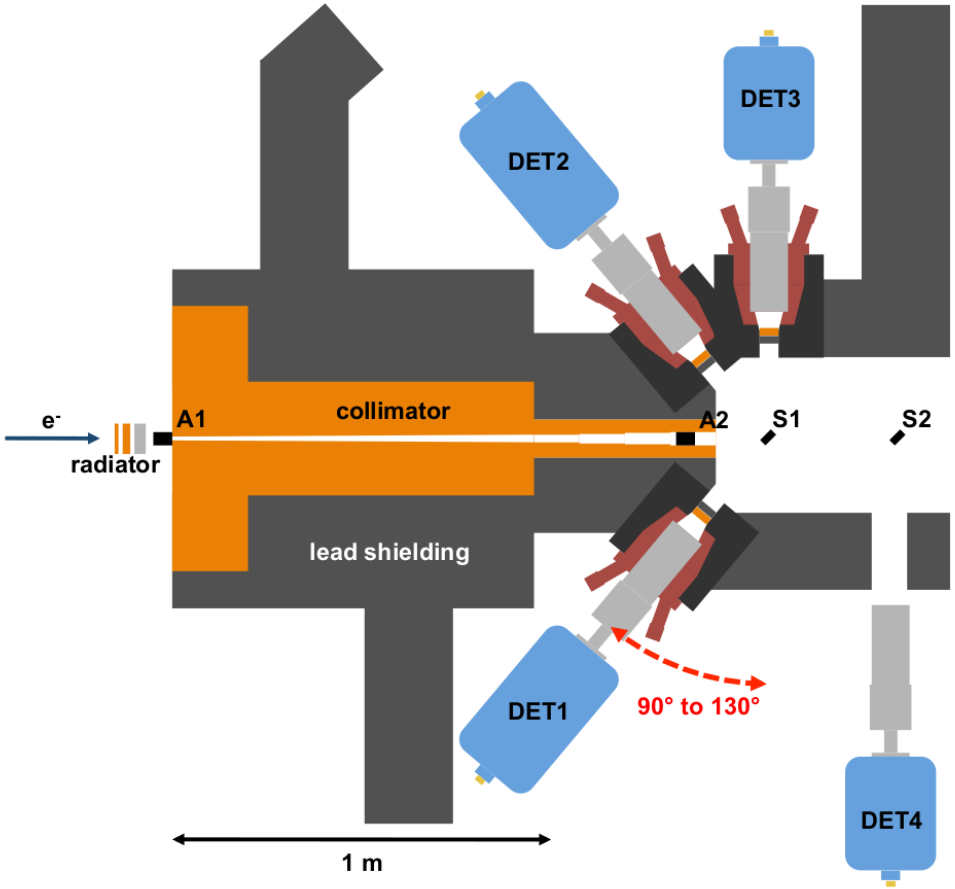


Bremsstrahlung



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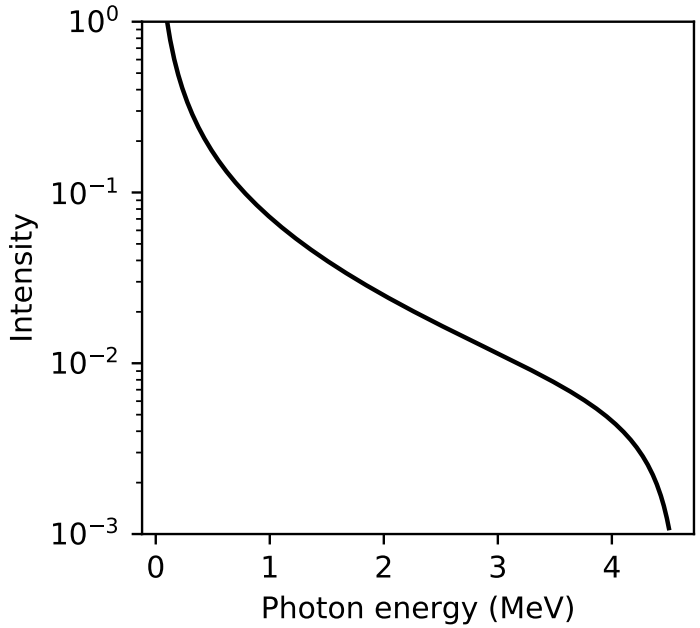
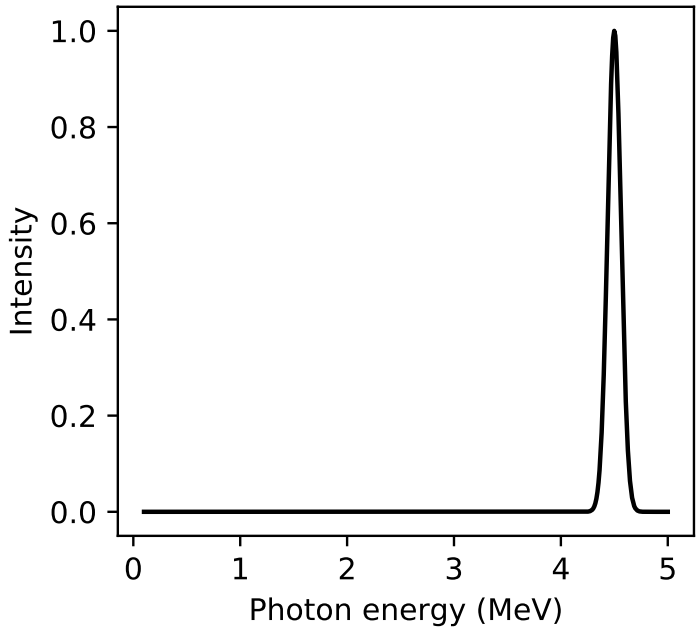


Quasimonochromatic (Polarized) Photon Beams

Schematic view of the HIγS facility.

- Pietralla, Ahmed et al. (2002)
- Quasi-monochromatic spectrum of photons with tunable energy
- High polarization



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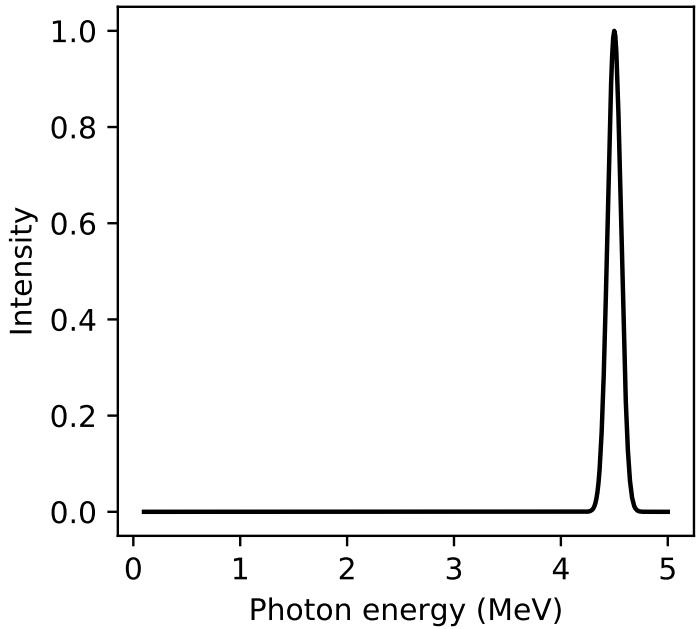
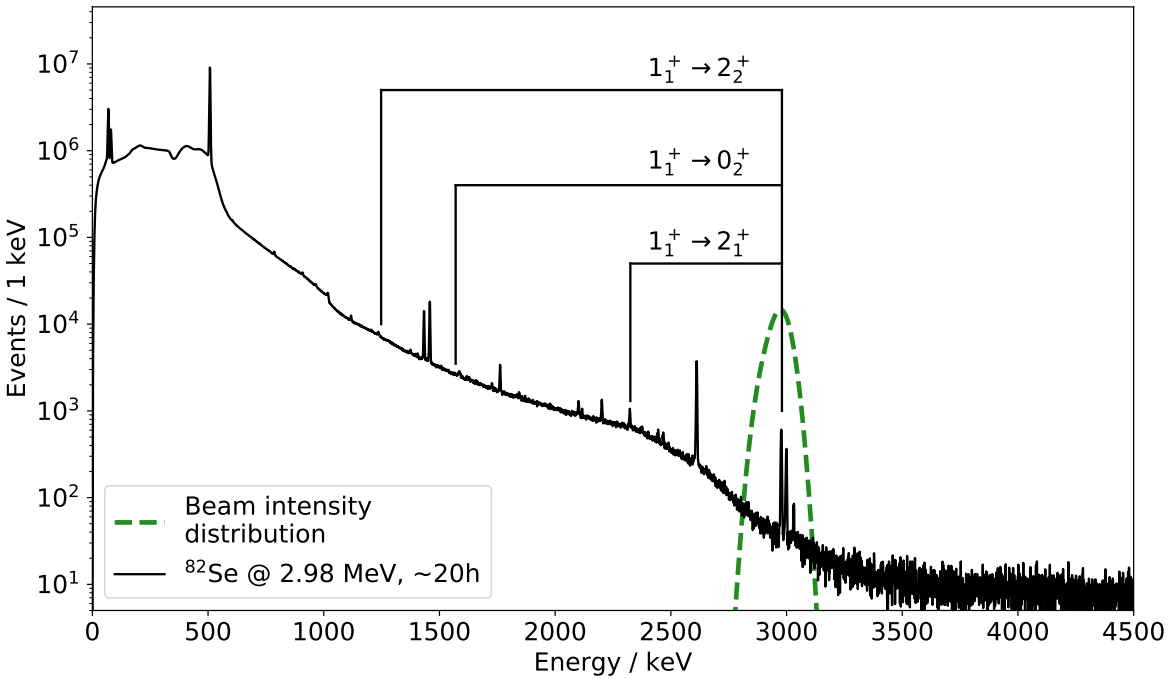


- European effort

Logo of the ELI-NP project.

Spectrum



Advantages of the NRF technique

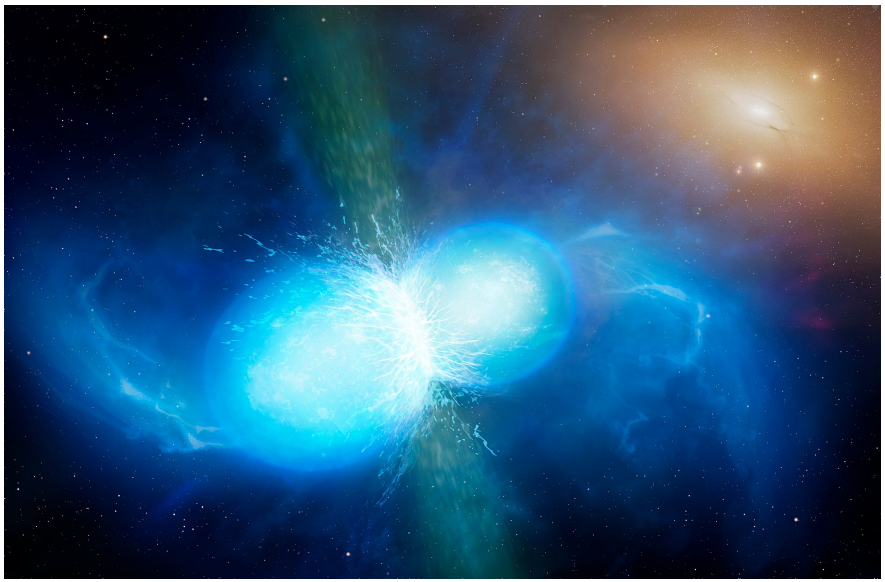
- Model-independent
- High resolution
- (Selectivity)

Disadvantages

- Nonresonant background
- Low cross section (long experiments, large samples, stable isotopes)
- Inefficient detection

r-Process Nucleosynthesis

- Synthesis of heavy elements in the universe
- Competition between photoabsorption (photodisintegration) and neutron capture



Schematic figure that shows the competition between neutron capture and photodisintegration in the r-process. I chose a figure from a textbook by C. Iliadis.

Isotope-selective Scanning

A schematic figure which show the application of the NRF method for isotope-sensitive scanning of materials. I chose a figure from a talk by R. Hajima that I found on the web. It shows how a truck is scanned for ^{235}U using a compact few-MeV gamma-ray source.

- Narrow nuclear resonances $\rightarrow$ high sensitivity to isotopic composition
- Non-destructive and highly penetrative

Literature

This slide lists the primary literature that was used for the preparation of this talk, ordered by topic.

- Nuclear Resonance Fluorescence
  - F. R. Metzger, Resonance Fluorescence in Nuclei, Prog. Nucl. Phys. **7** (1959) 53-88
  - U. Kneissl, H. H. Pitz, and A. Zilges, Prog. Part. Nucl. Phys. **37** (1996) 349-433
    `https://doi.org/10.1016/0146-6410(96)00055-5`
- Wave Optics and Atomic Physics
  - W. Demtröder, Experimentalphysik 2, Elektrizität und Optik, dritte Auflage, Springer-Verlag Berlin Heidelberg (2004)
  - W. Demtröder, Experimentalphysik 3, Atome, Moleküle und Festkörper, dritte Auflage, Springer-Verlag Berlin Heidelberg (2004)

Figures I

This slide lists all figures from external sources that were used in the original version of the presentation. All websites were accessed on 06/18/2020.

- Prism: Second figure in `https://de.wikipedia.org/wiki/Prisma_(Optik)`
- Gammasphere: `https://www.phy.anl.gov/gammasphere/`
- ^{229m}Th: Figure 1 in L. von der Wense et al., Direct detection of the ^{229}Th nuclear clock transition, Nature **533** (2016) 47-51 `https://doi.org/10.1038/nature17669`
- Resonance shape for a crystal: Figure 2 in W. E. Lamb, Capture of Neutrons by Atoms in a Crystal, Phys. Rev. **55** (1939) 190-197 `https://doi.org/10.1103/PhysRev.55.190`

Figures II

- DHIPS: Figure 6.2 in C. Romig, Investigation of Nuclear Structure with Relative Self-Absorption Measurements, Dissertation, Technische Universität Darmstadt (2015) https://tuprints.ulb.tu-darmstadt.de/4446/
- HIγS: Figure 2 in H. R. Weller et al., Research opportunities at the upgraded HIγS facility, Prog. Part. Nucl. Phys. **62** (2009) 257-303 https://doi.org/10.1016/j.ppnp.2008.07.001
- ELI-NP logo: https://www.eli-np.ro/
- Spectrum: Modified from U. Friman-Gayer, Probing Nuclear Structure Relevant for Neutrinoless Double-Beta Decay with Nuclear Resonance Fluorescence, Dissertation, Technische Universität Darmstadt (2020) https://tuprints.ulb.tu-darmstadt.de/11385/

Figures III

- Schematic r-Process: Part (b) of Figure 5.75 in C. Iliadis, Nuclear Physics of Stars, Wiley-VCH (2015)
- Neutron star merger: First figure on `https://en.wikipedia.org/wiki/Neutron_star_merger`
- Isotope-selective scanning: Bottom left figure on slide 5 of `https://portal.slac.stanford.edu/sites/conf_public/facet_ii_wk_2015/Lists/Agenda1/Attachments/302/Hajima-NRF-NDA-FACET-II.pdf`