Outline: Photo nuclear reaction

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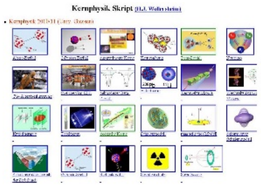
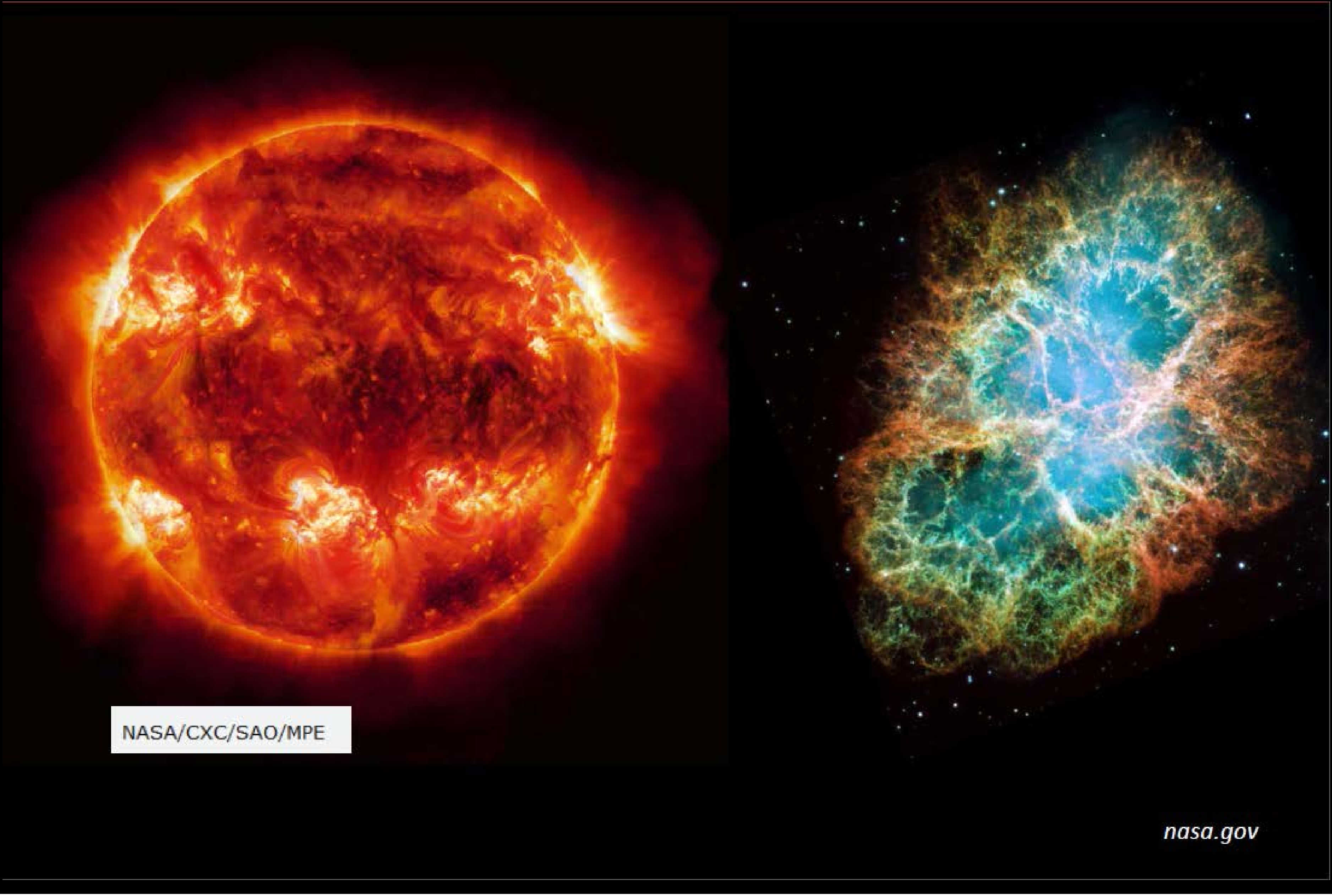


1. photons in the universe
2. nuclear resonance fluorescence
3. inverse Compton scattering
4. laser Compton backscattering (ELI)
5. Thomson scattering

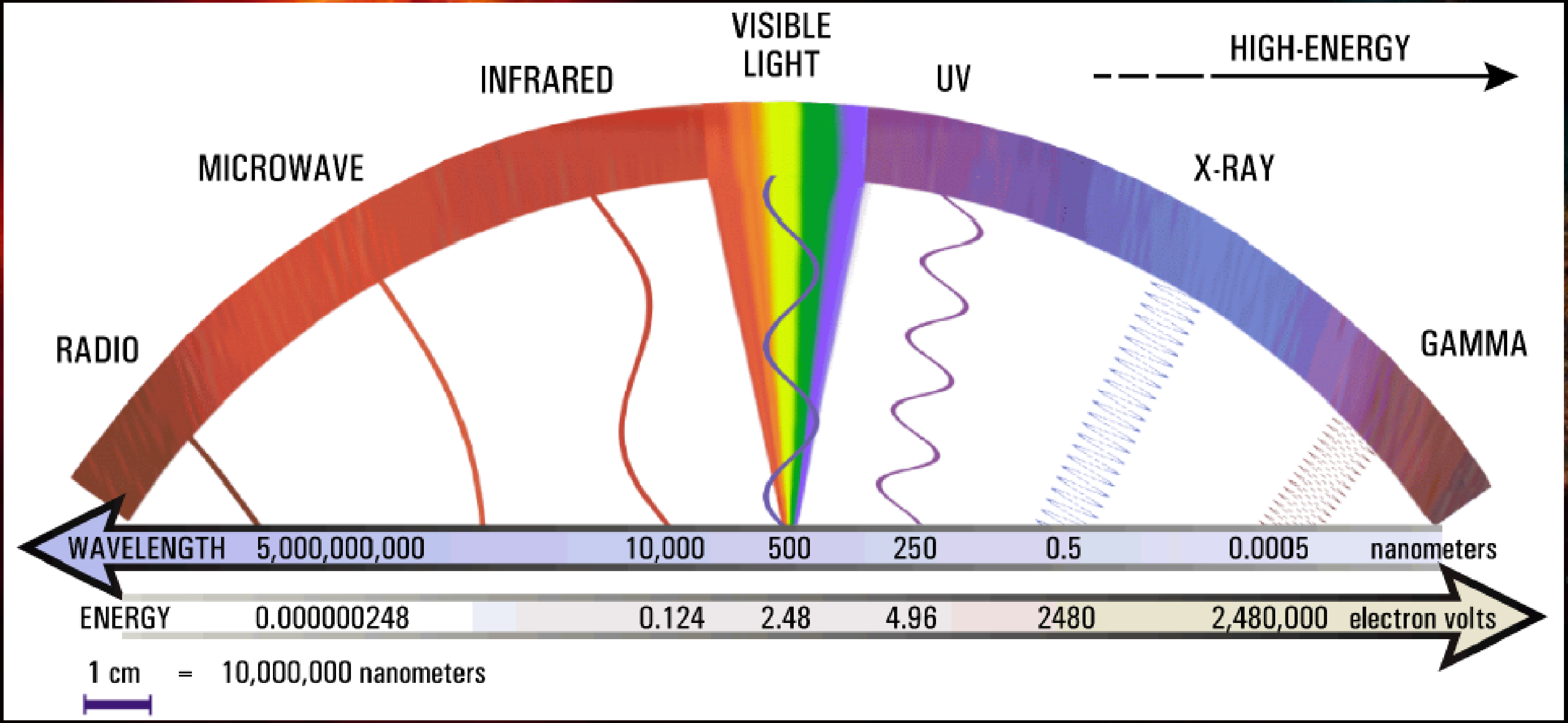
Photons in the universe



NASA/CXC/SAO/MPE

nasa.gov

Photons in the universe



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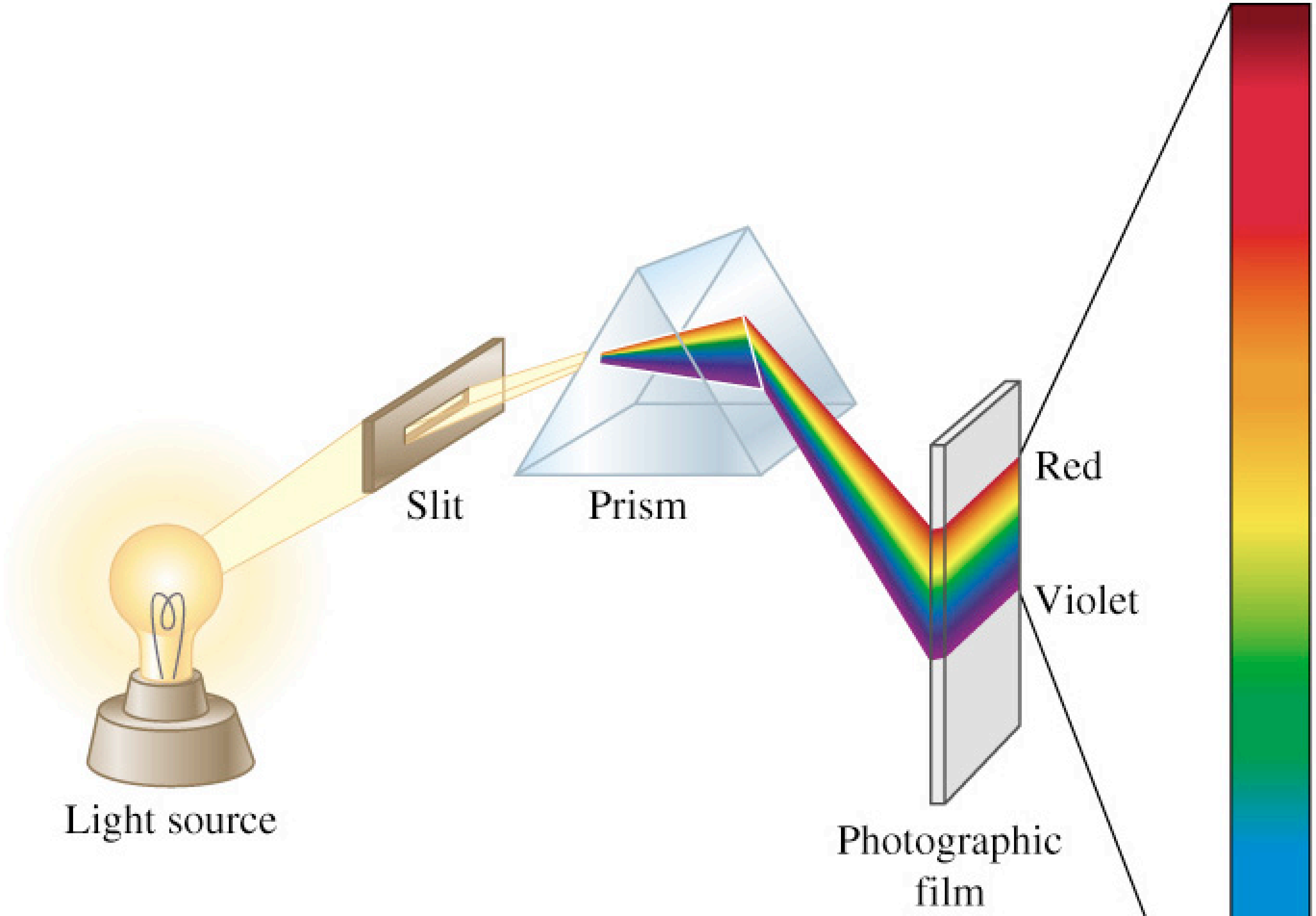
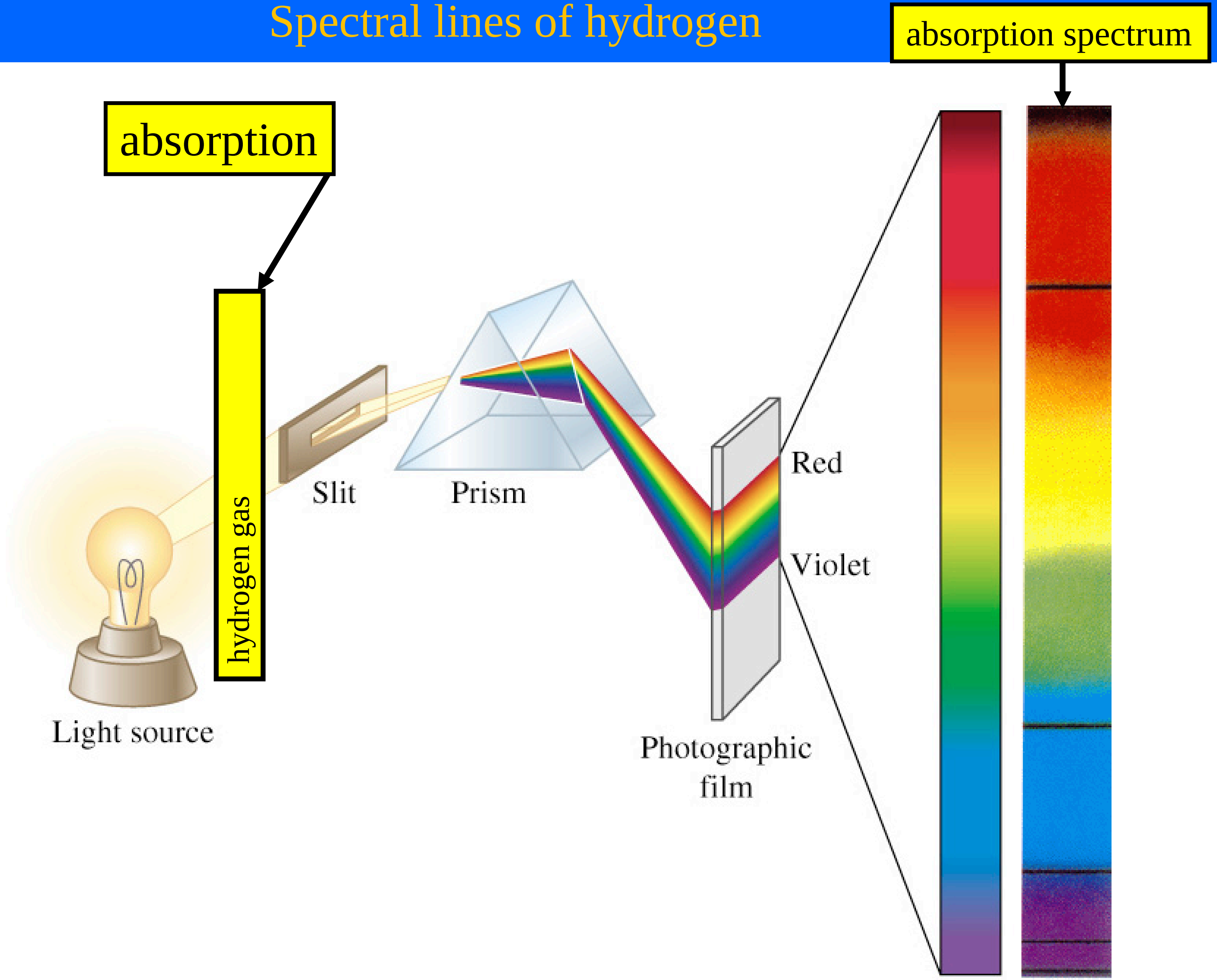
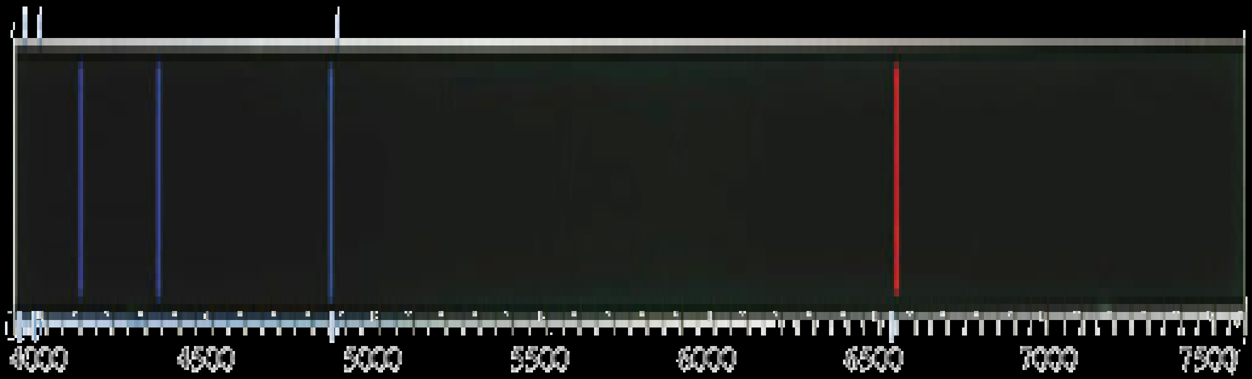
Element production on the sun



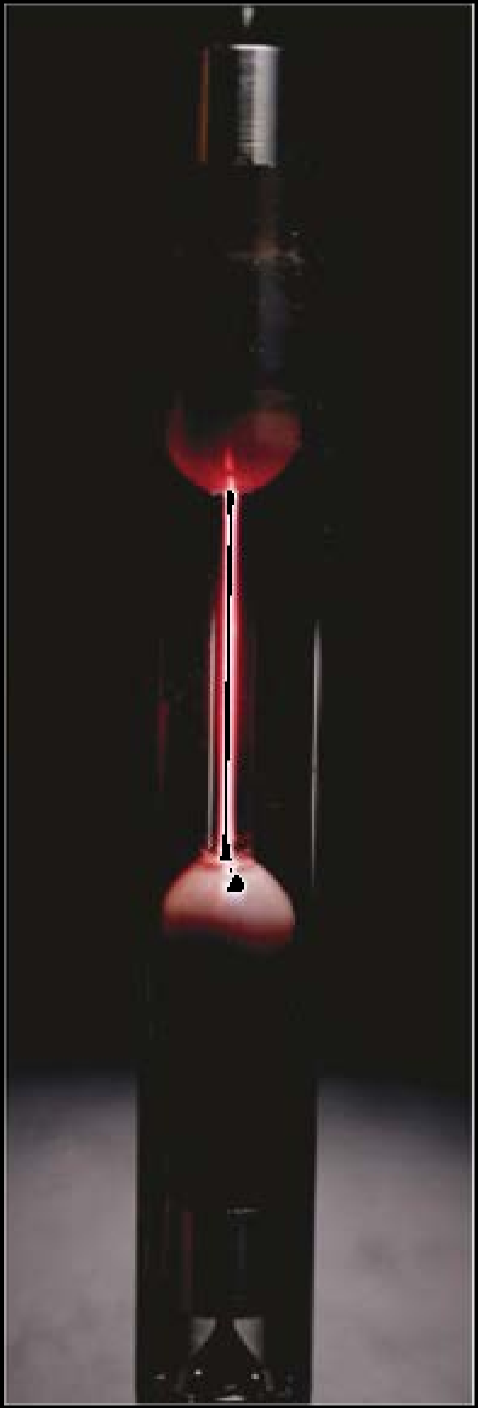
Spectral lines of hydrogen



Hydrogen emission spectrum

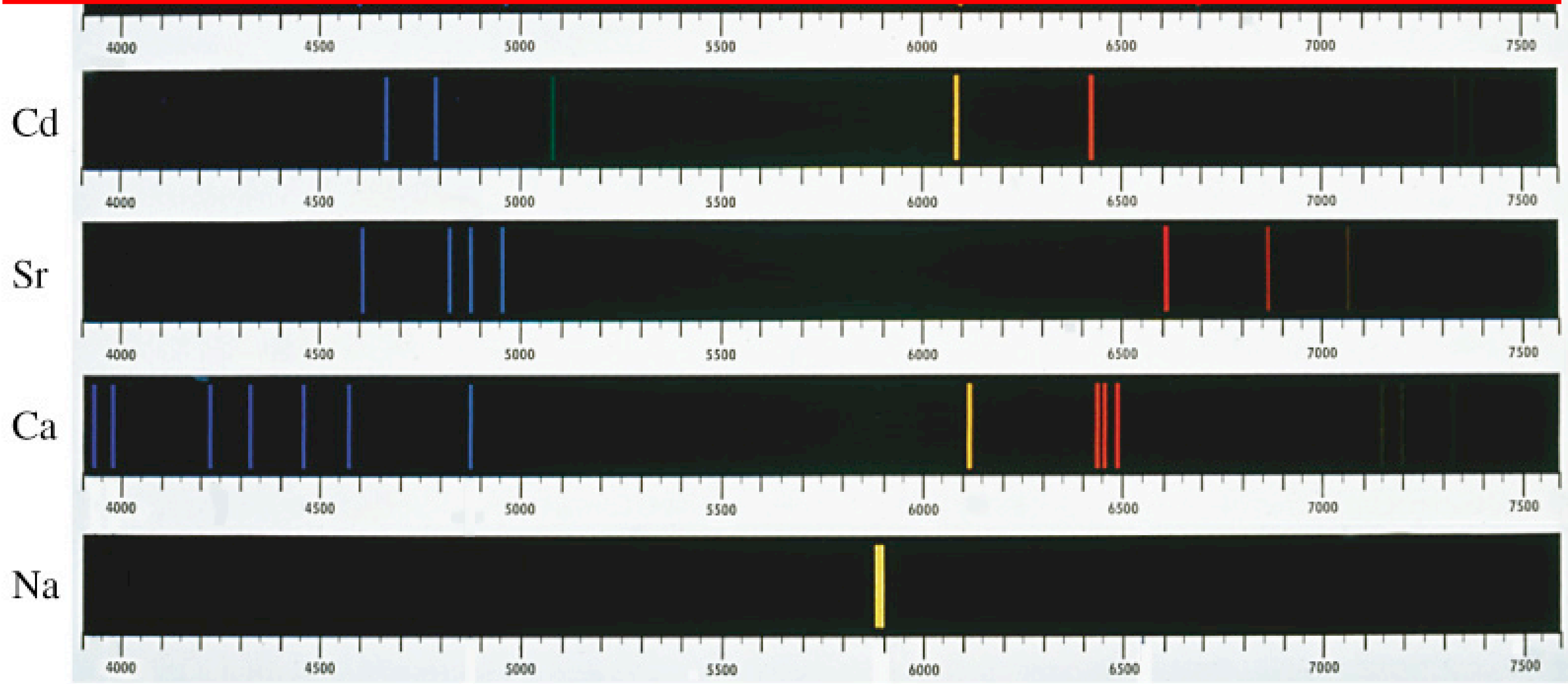


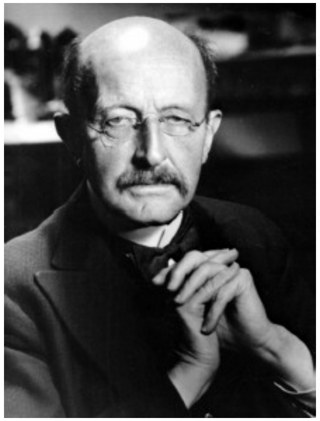
wave length nm



Spectral analysis

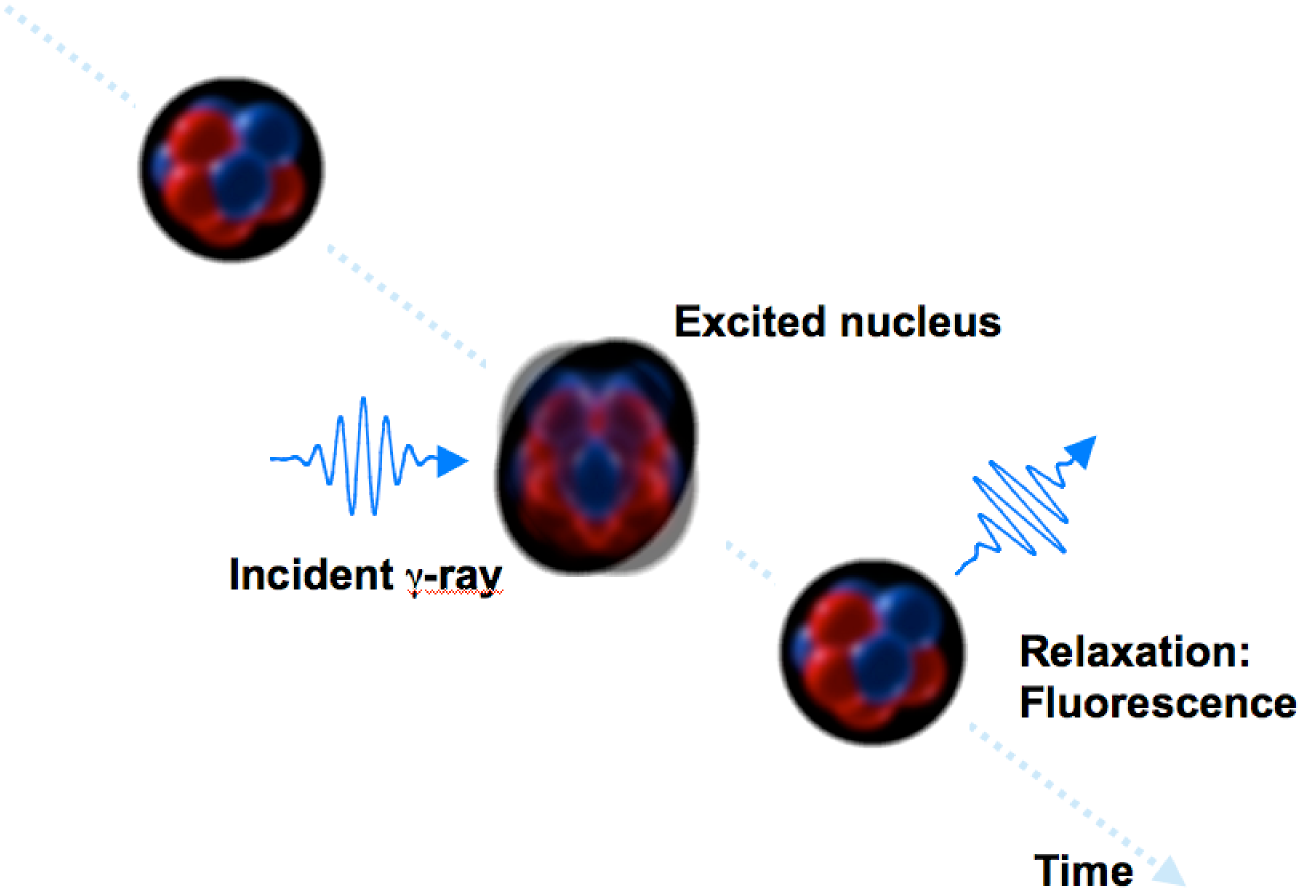
Spectral analysis
Kirchhoff und Bunsen:
Every element has a characteristic emission band





Max Planck

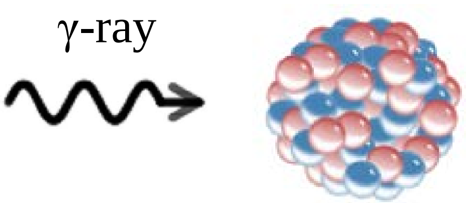
Nuclear Resonance Fluorescence

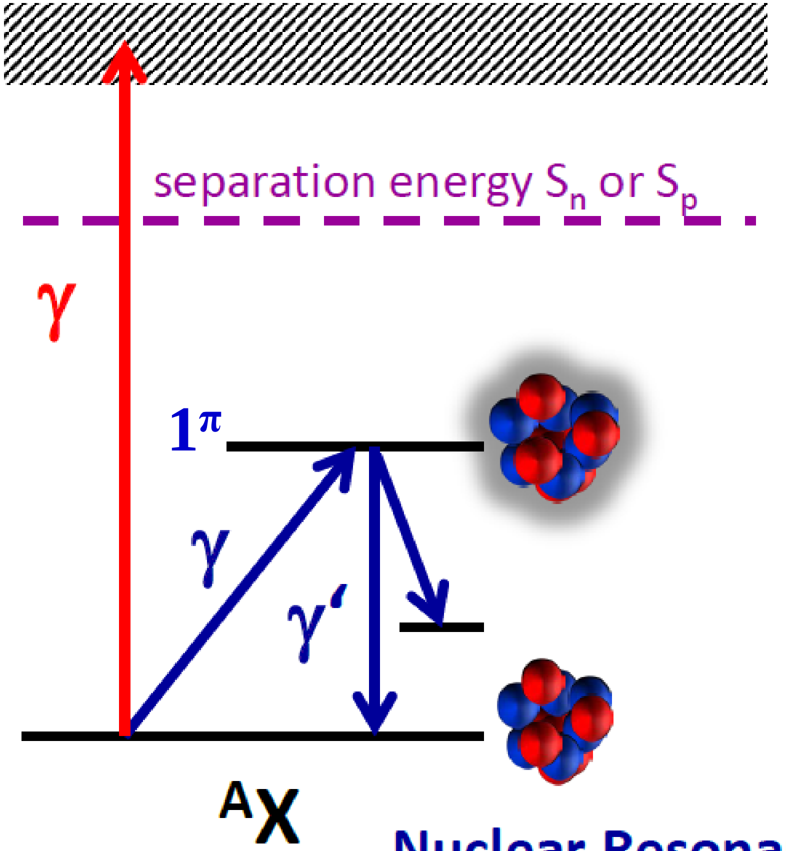


Nuclear Resonance Fluorescence (NRF) is analogous to atomic resonance fluorescence but depends upon the number of protons AND the number of neutrons in the nucleus

Photon-nuclear reactions with MeV γ-rays

- pure electromagnetic interaction
- spin selectivity (mainly **E1, M1, E2** transitions)



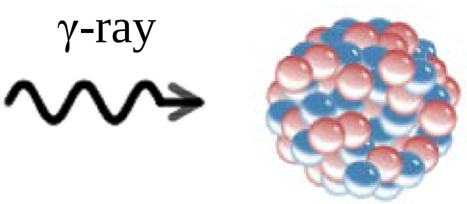


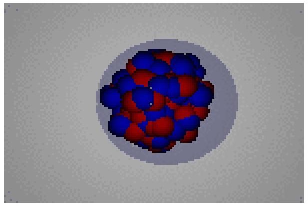
~ 8 MeV

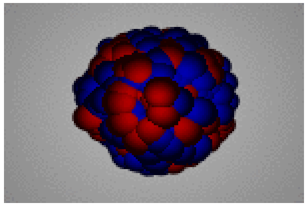
Nuclear Resonance Fluorescence (NRF)

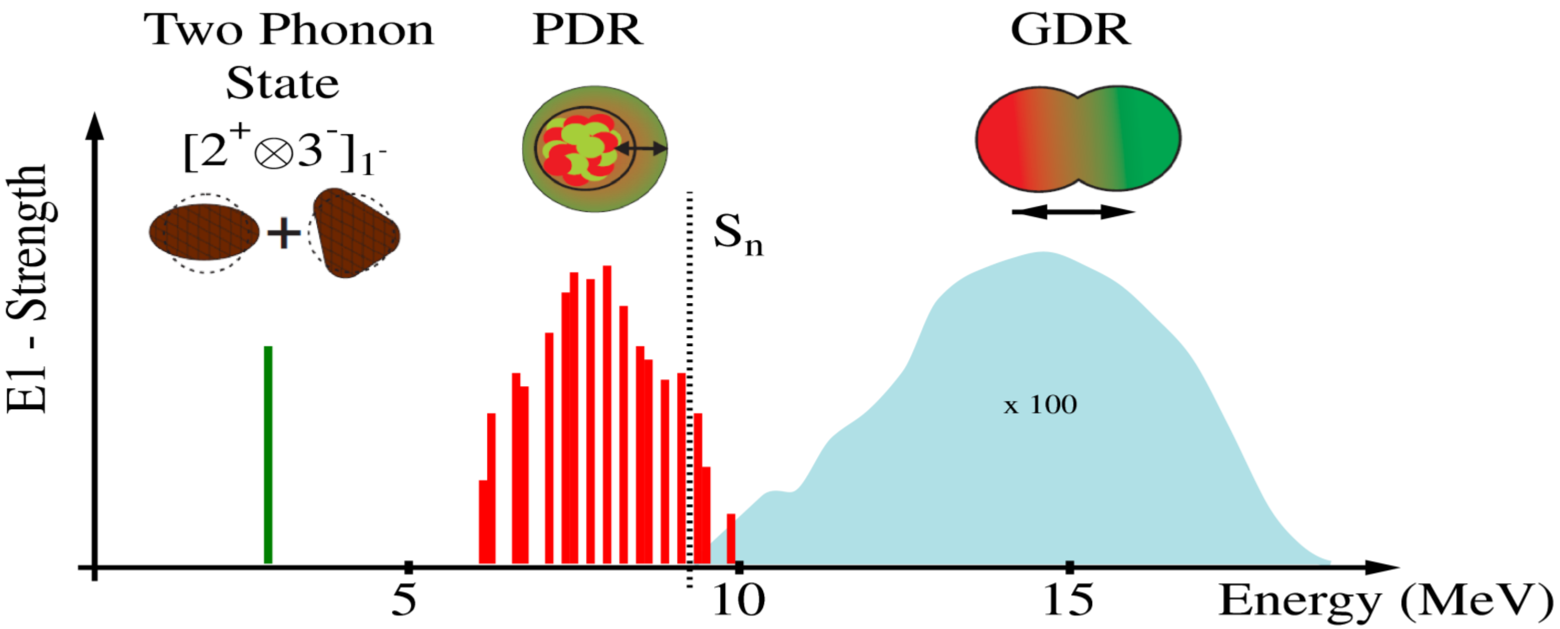
Photon-nuclear reactions with MeV γ-rays

- pure electromagnetic interaction
- spin selectivity (mainly **E1, M1, E2** transitions)





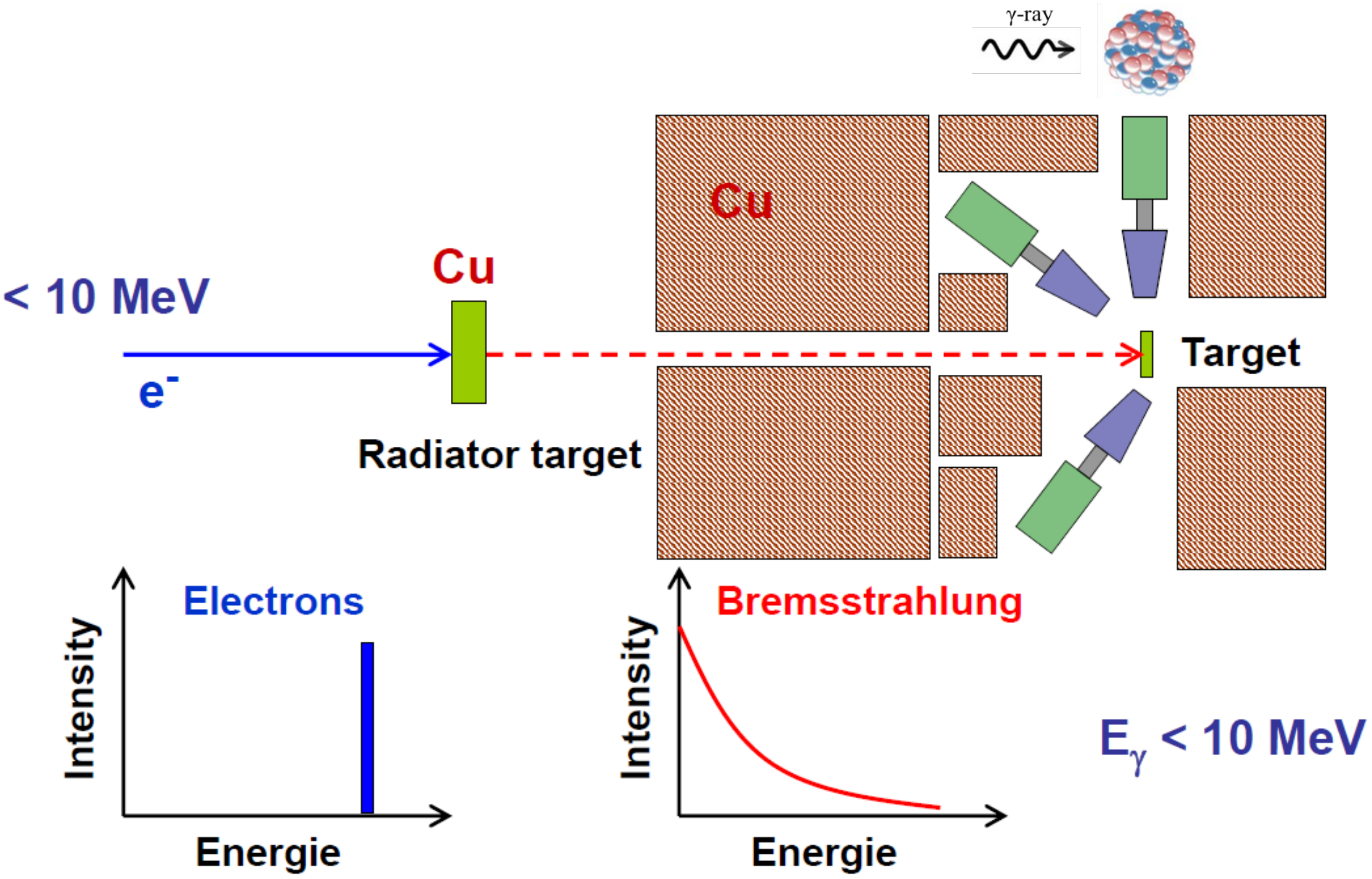




pygmy dipole resonance
neutron skin nuclei

giant dipole resonance

Low energy photon scattering at S-DALINAC



- “white“ photon spectrum
- wide energy region examined

S-DALINAC at TU Darmstadt

Recirculating superconducting LINAC

Niobium cavities

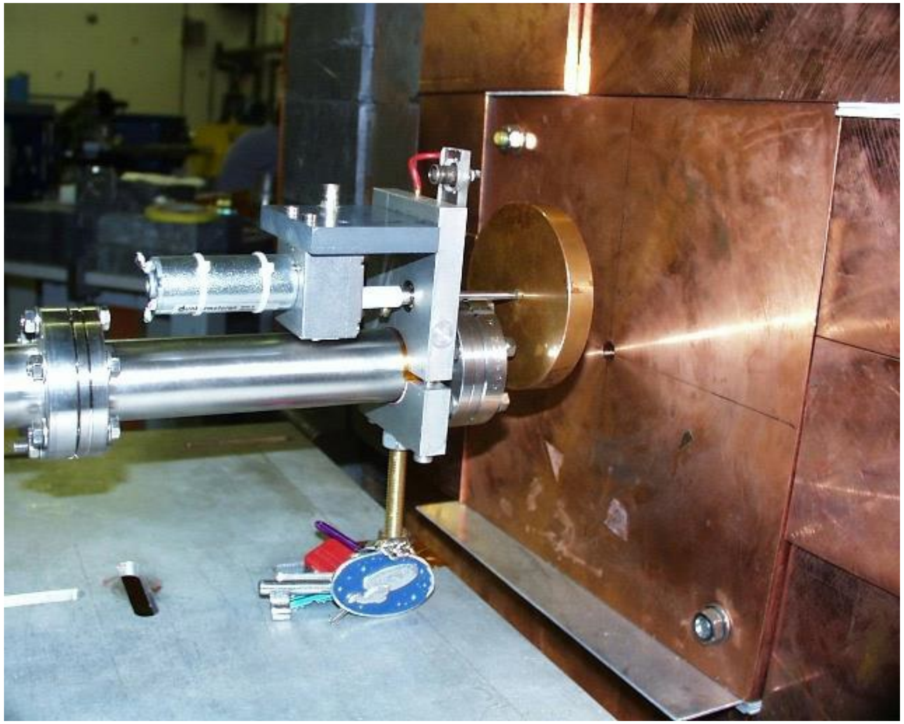
liquid He cooled @ 2 K

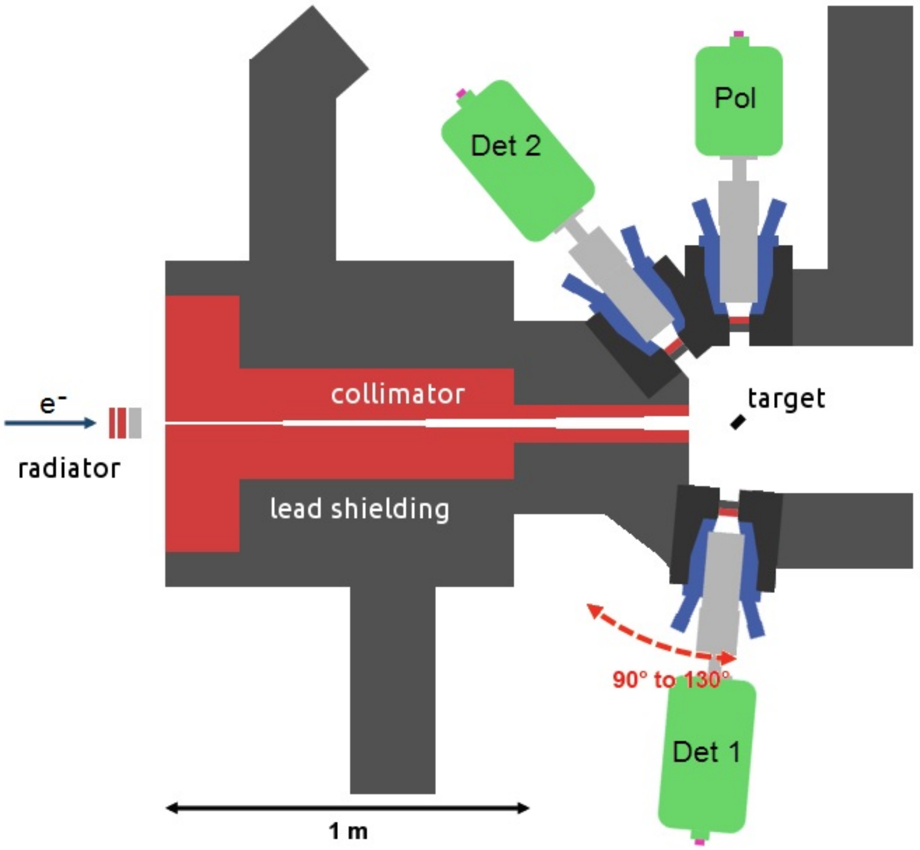
3 GHz cw e-beams

<130 MeV, ≤60 μA

Darmstadt high intensity photon set-up

Bremsstrahlung γ-ray spectrum
provided by S-DALINAC



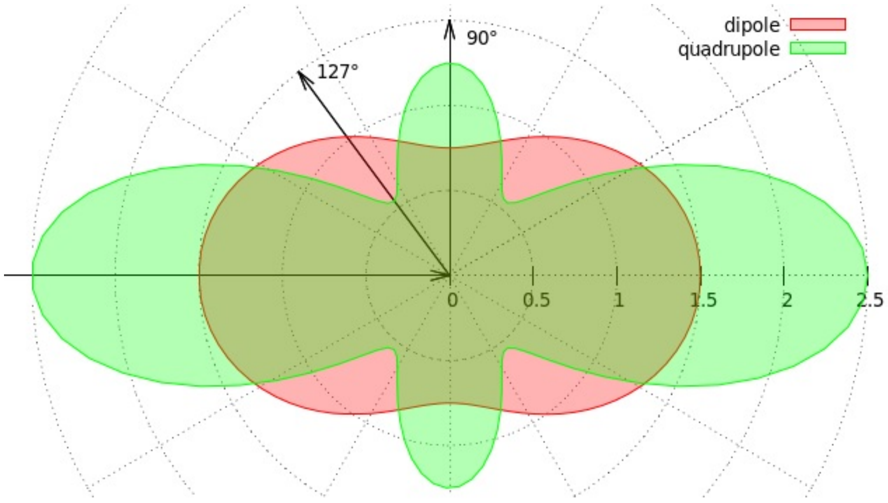


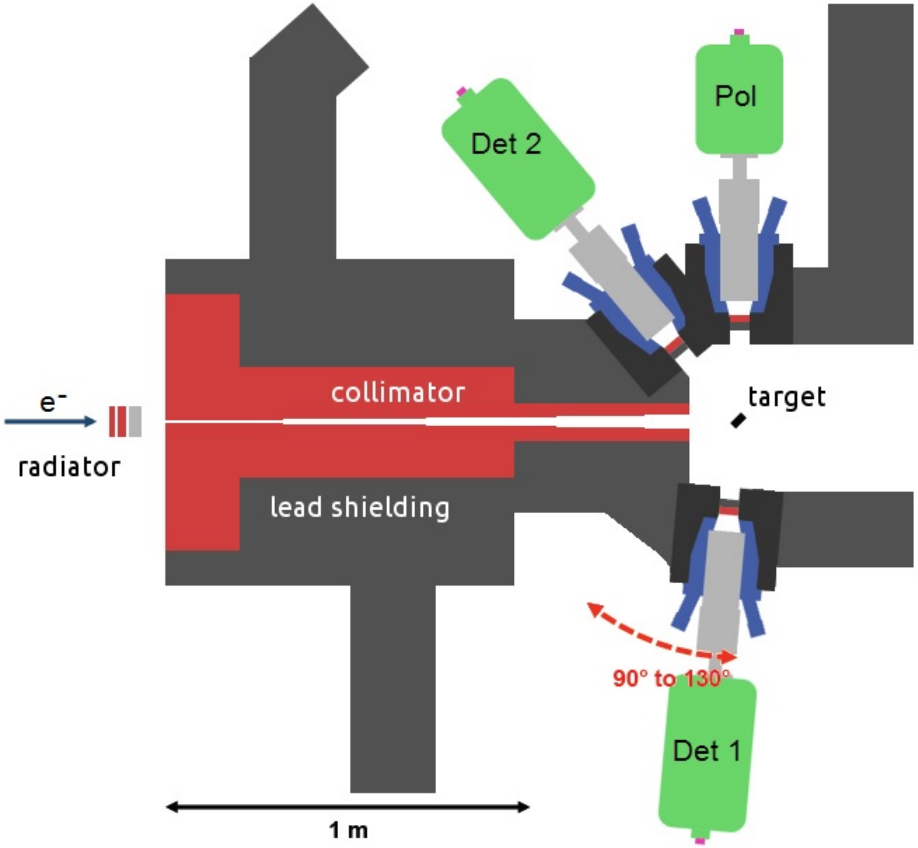
photon energies up
to 11 MeV available

multipole order from
angular distribution

Darmstadt high intensity photon set-up

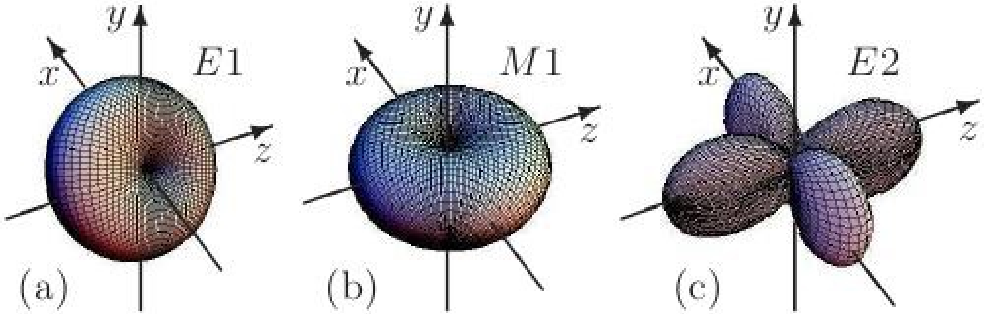
Bremsstrahlung γ-ray spectrum
provided by S-DALINAC



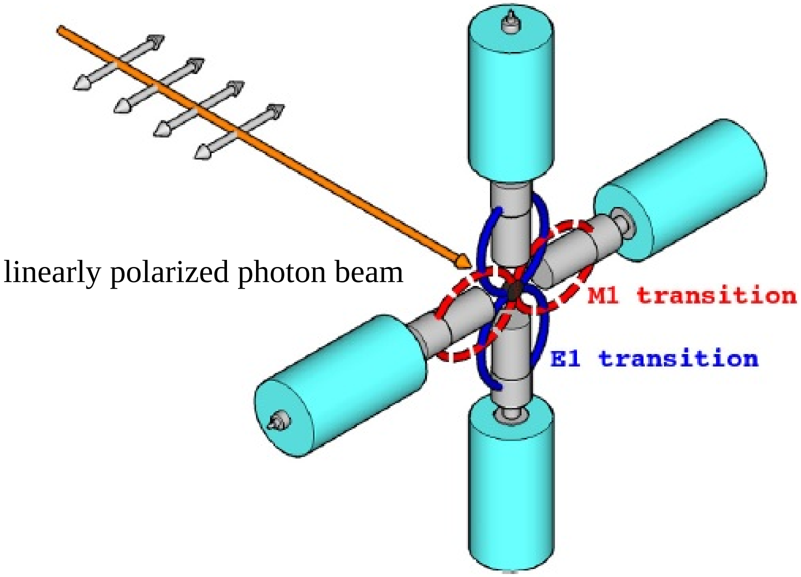


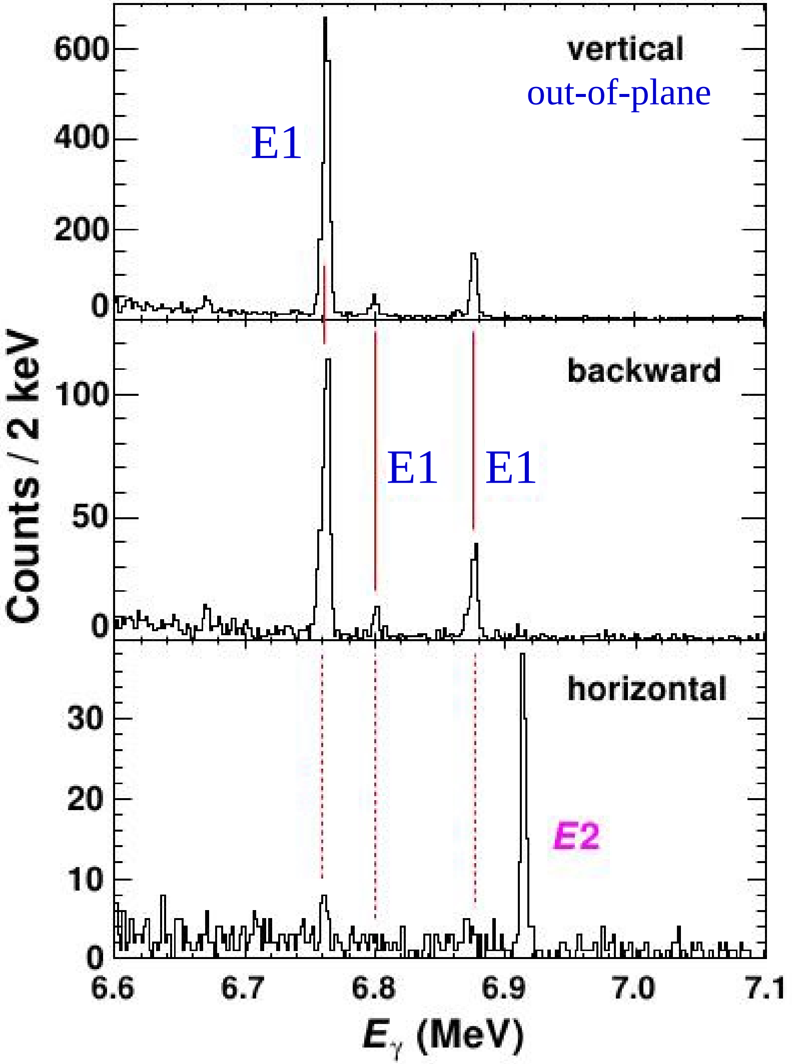
multipole order from
angular distribution

Spin and Parity determination using monoenergetic photons

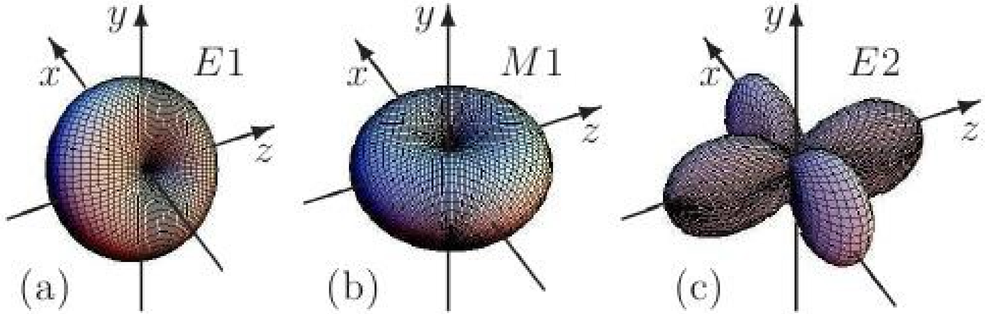


z axis: beam direction; x axis: vector of polarization





Spin and Parity determination using monoenergetic photons



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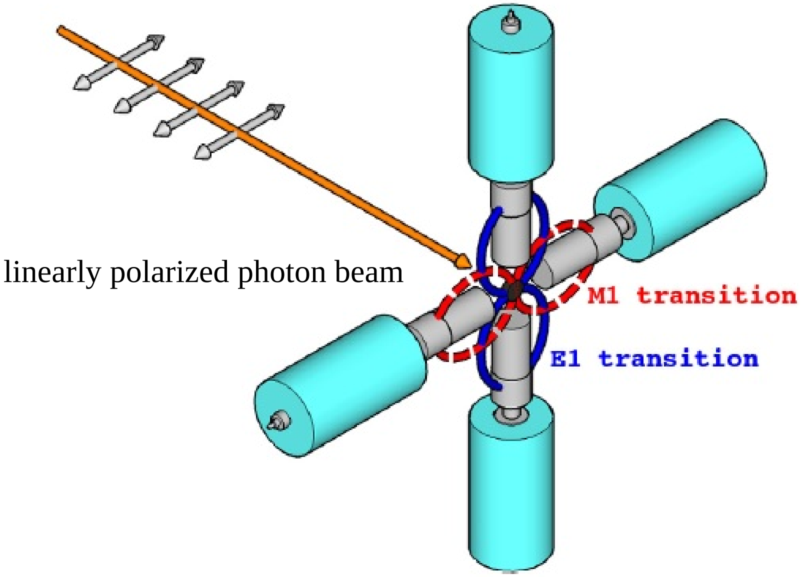
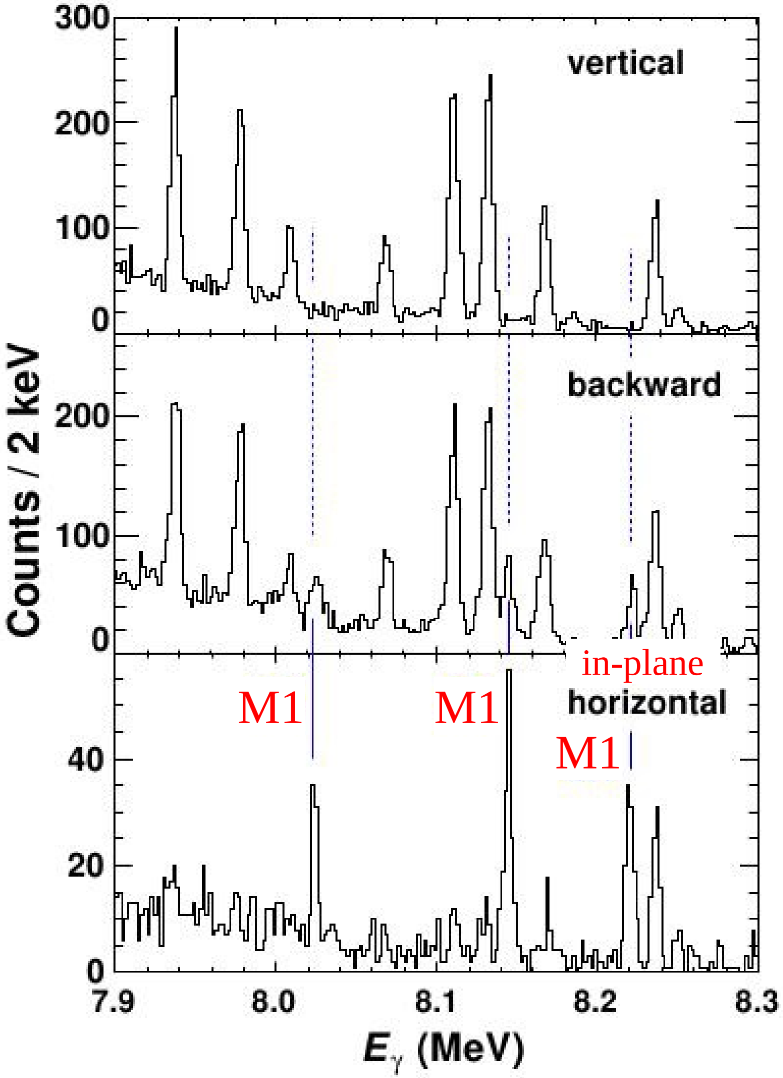
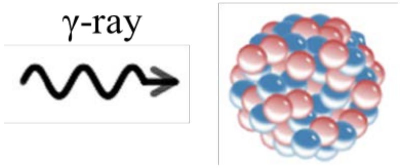
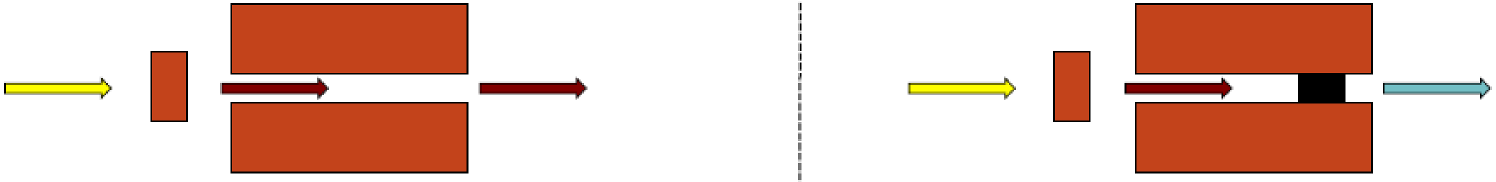


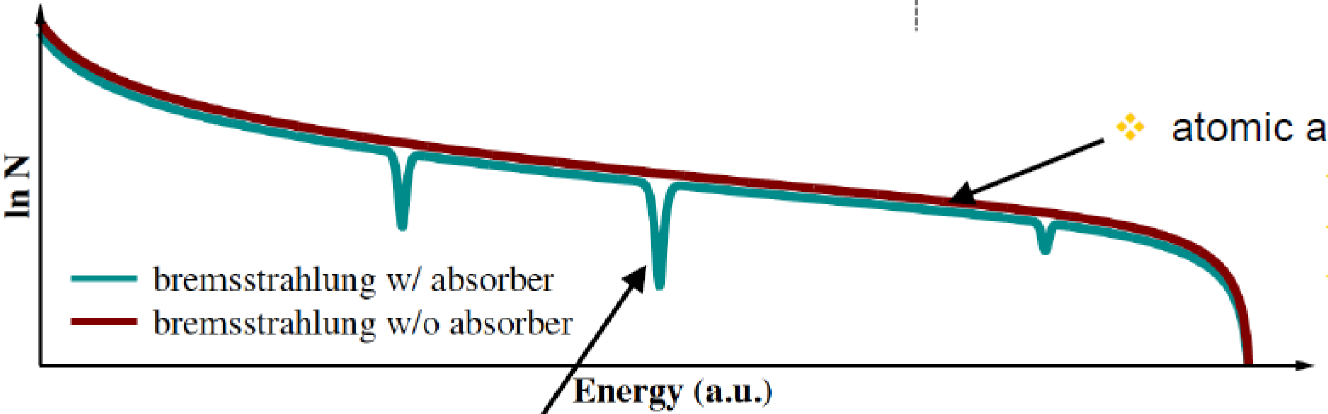


Absorption processes

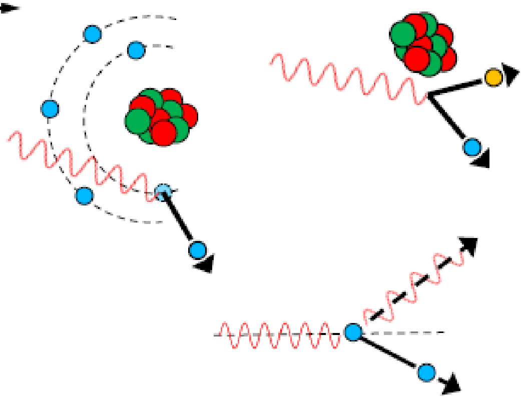


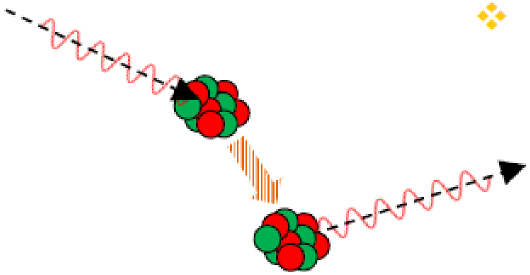
Absorption lines only a few eV wide!





- atomic attenuation
  - several processes
  - contributes at each energy
  - independent of Γ_0

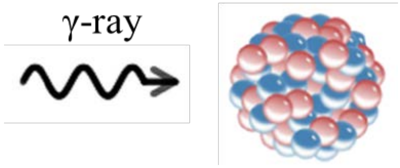




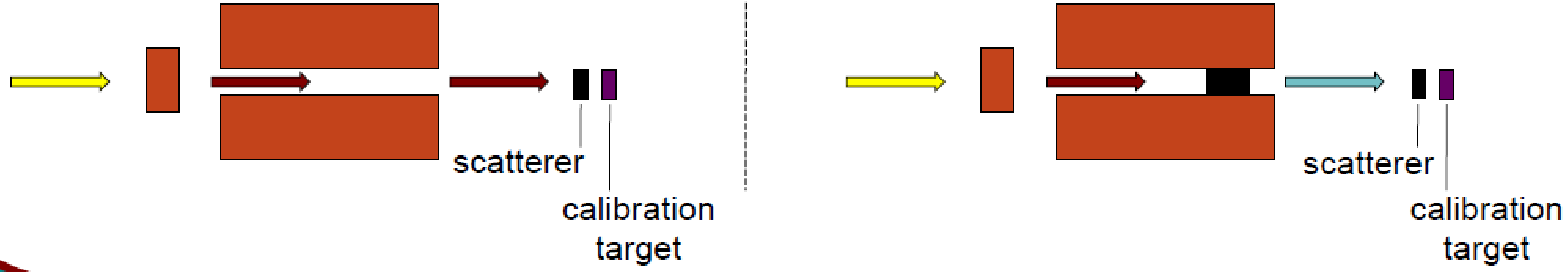
- resonant absorption
  - only at resonance energies
  - depends on Γ_0

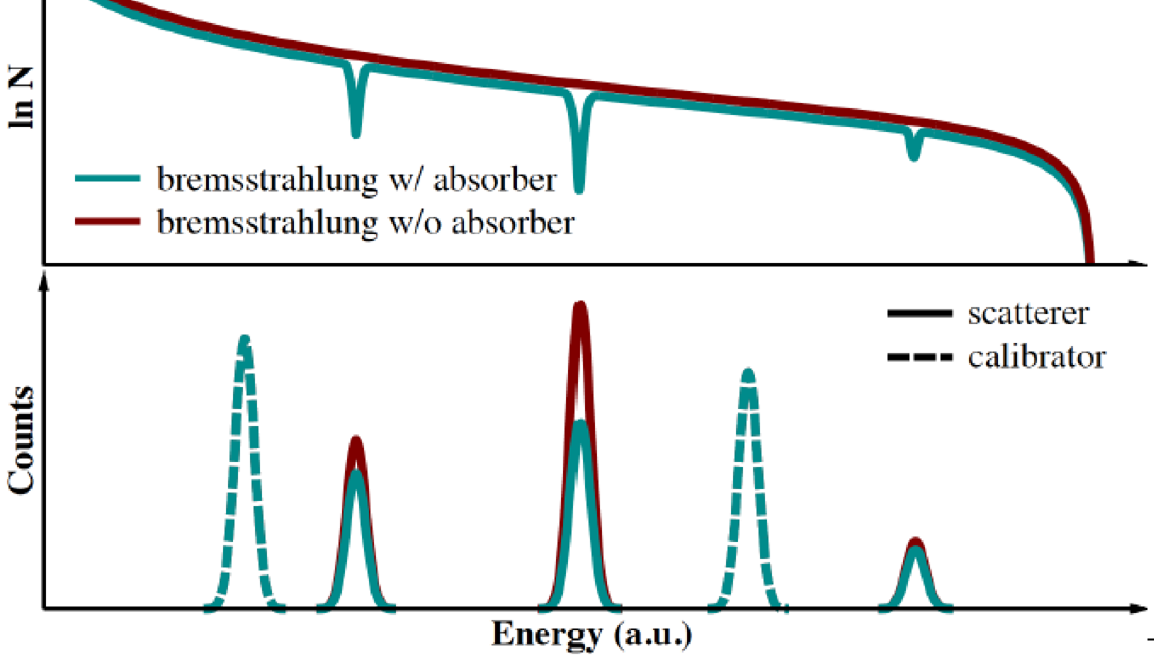
$$\sigma_a \propto \Gamma_0 \cdot e^{-\left(\frac{E-E_r}{\Delta}\right)^2}$$

Principle of measurement and self absorption



Use scatterer made of absorber material as „high-resolution detector“.



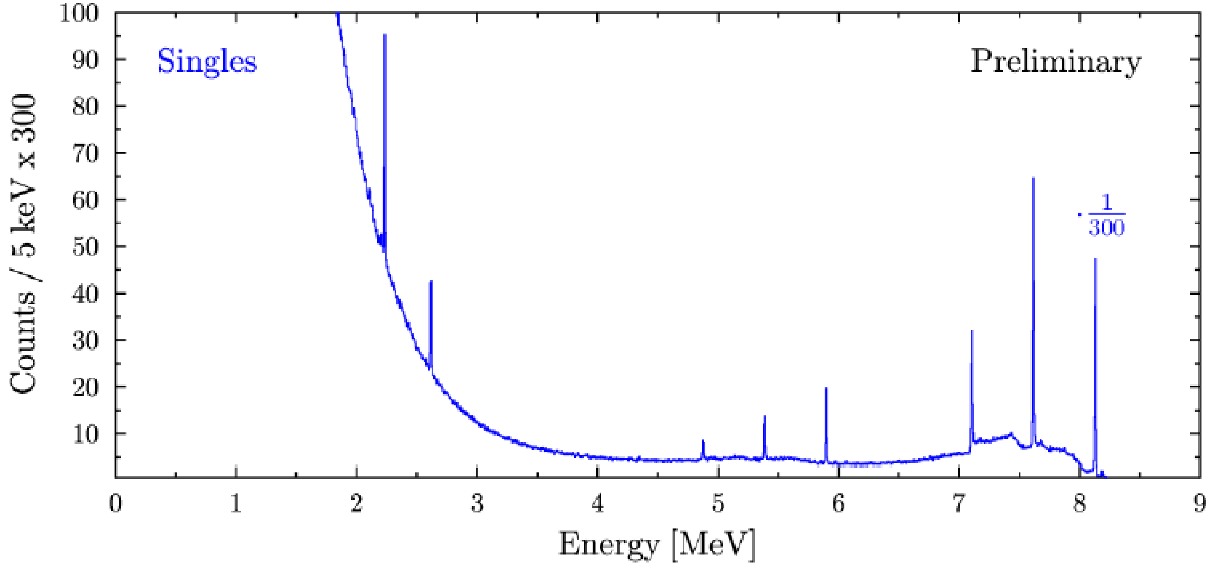


Self Absorption:
Decrease of Scattered Photons
because of Resonant Absorption

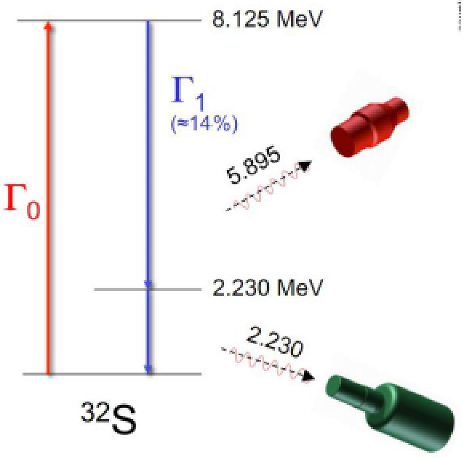
$$R(\Gamma_0) = \frac{N_{\mathrm{woA}} - f \cdot N_{\mathrm{wA}}}{N_{\mathrm{woA}}}$$

$$f = \frac{N^{\mathrm{std}}_{\mathrm{woA}}}{N^{\mathrm{std}}_{\mathrm{wA}}}$$

First γγ-coincidences in a γ-beam



B. Löher et al., Nucl. Instruments Methods Phys. Res. Sect. A **723**, 136–142 (2013).



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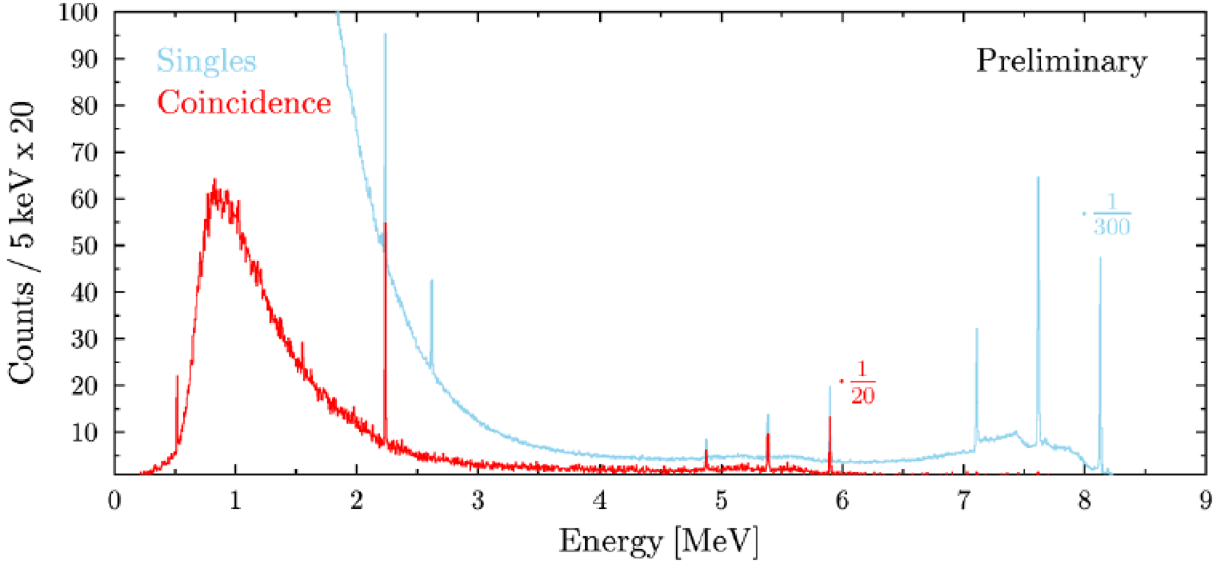

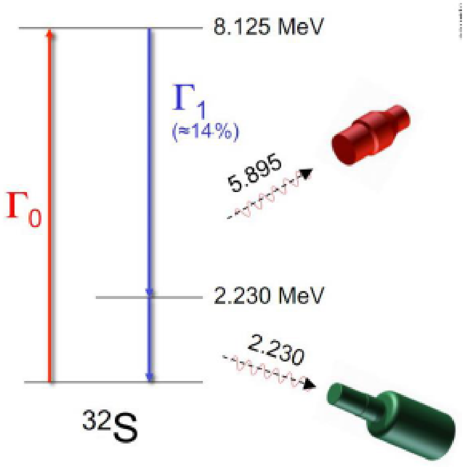

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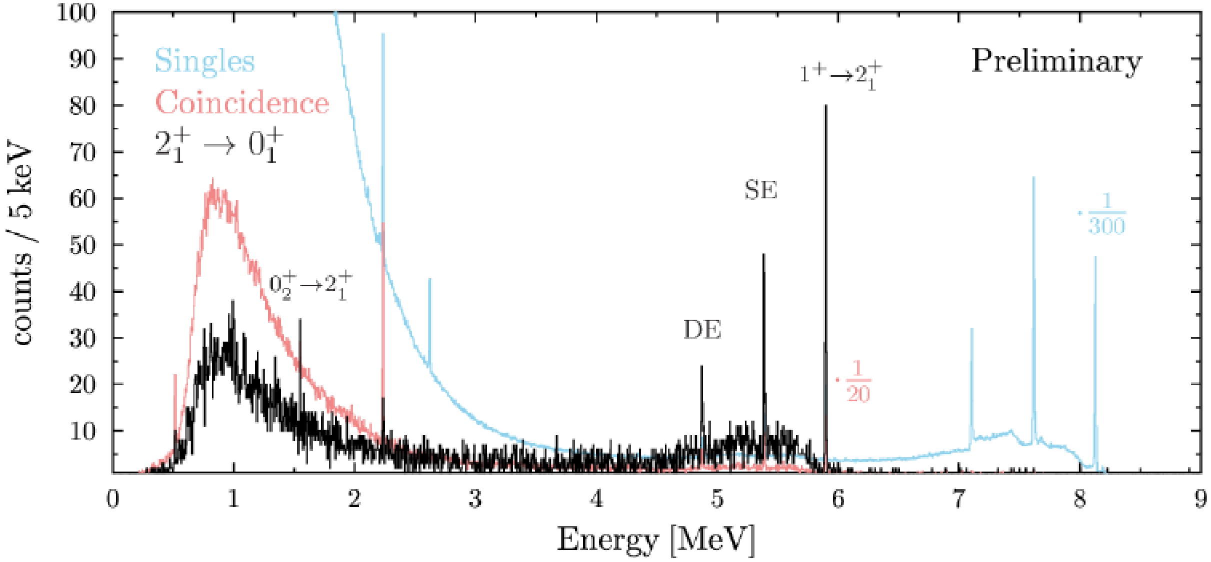
First γγ-coincidences in a γ-beam



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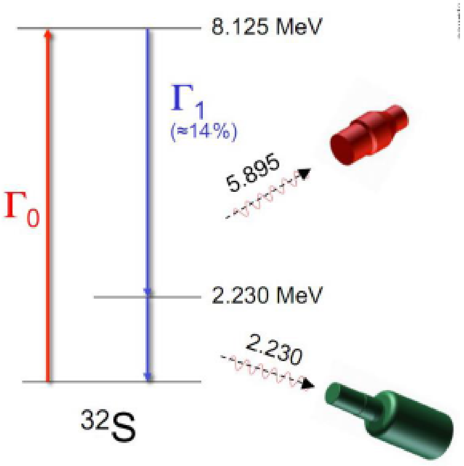
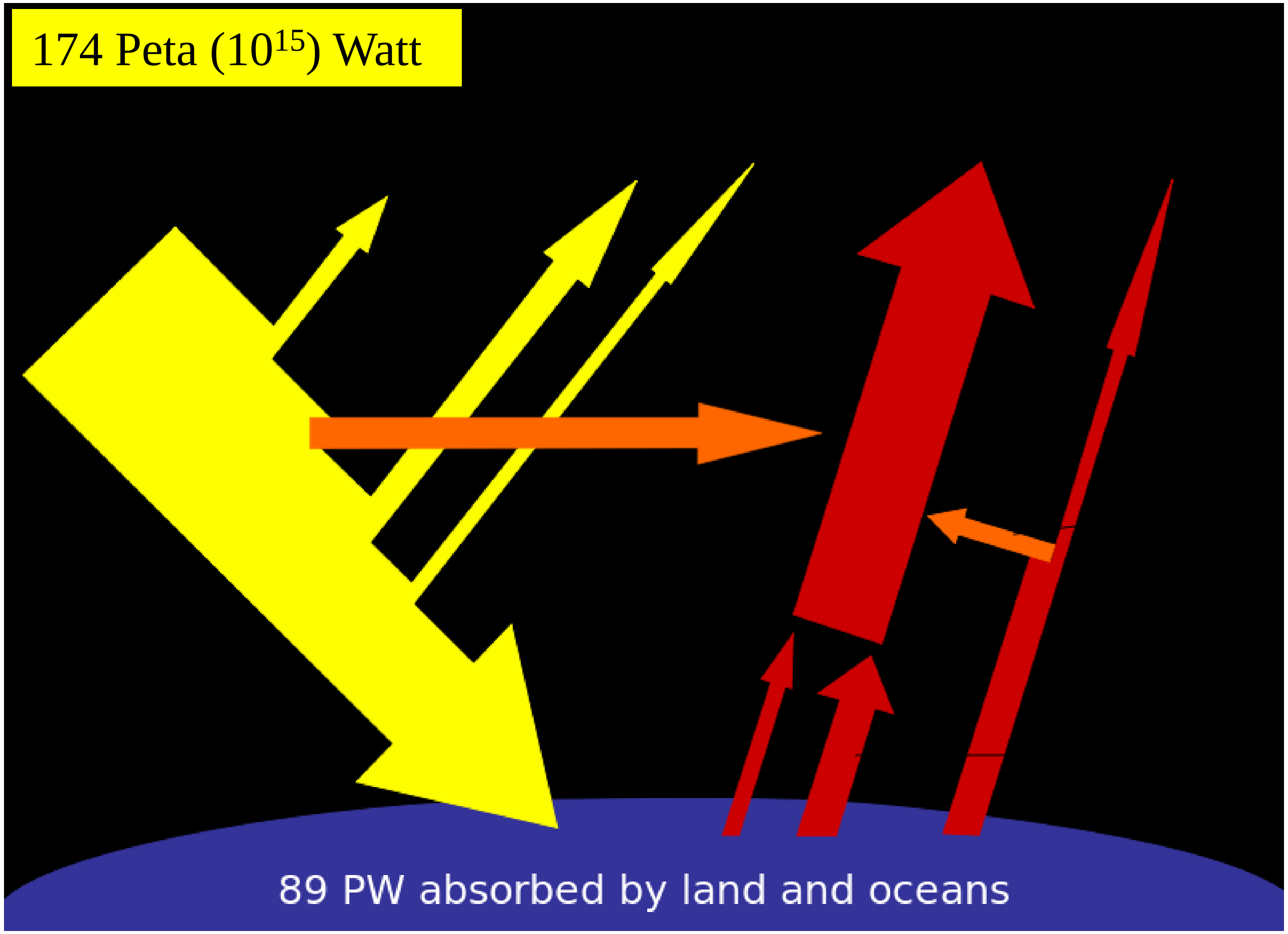
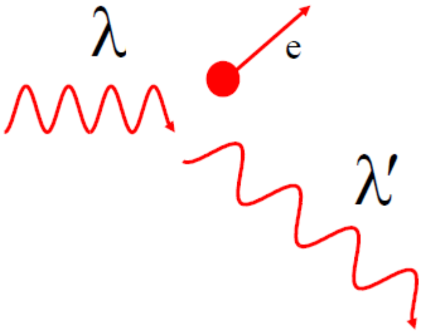


Total power received by Earth from the Sun



@ eli Nuclear Physics **e**xtreme **l**ight **i**nfrastructure, Europe

Compton scattering and inverse Compton scattering



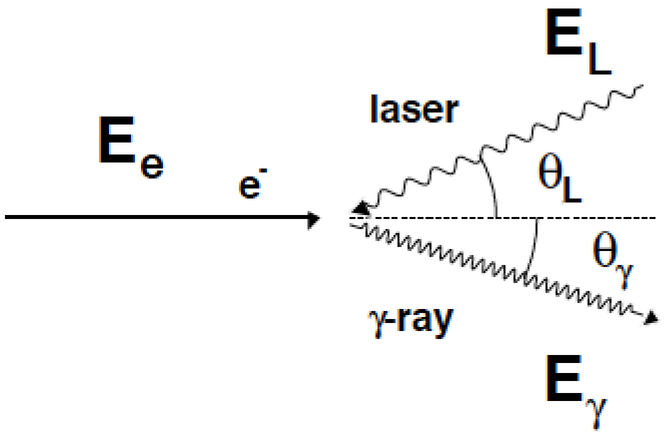
Compton scattering:

- Elastic scattering of a high-energy γ-ray on a free electron.
- **A fraction of the γ-ray energy is transferred to the electron.**
- The wave length of the scattered γ-ray is increased: λ‘ > λ.

$$h\nu \geq m_e c^2$$

$$\lambda' - \lambda = \frac{h}{m_e c} \cdot \left(1 - cos\theta_\gamma\right)$$

$$\boxed{E'_\gamma = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_e c^2} \cdot (1 - cos\theta)}}$$



Inverse Compton scattering:

- Scattering of low energy photons on ultra-relativistic electrons.
- **Kinetic energy is transferred from the electron to the photon.**
- The wave length of the scattered γ-ray is decreased: λ‘ < λ.

$$\lambda' \approx \lambda \cdot \frac{1 - \beta \cdot cos\theta_\gamma}{1 + \beta \cdot cos\theta_L}$$

Inverse Compton scattering

- Electron is moving at relativistic velocity
- Transformation from **laboratory frame** to **reference frame of e$^-$** (rest frame):
  in order to repeat the derivation for Compton scattering

$$E_\gamma = \gamma \cdot E_\gamma \underbrace{\left(1 - \frac{v}{c} cos\theta_{e^-\gamma}\right)}_{\text{Doppler shift}}$$

Lorentz factor: $\gamma = (1-\beta^2)^{-1/2} = 1 + \frac{T_e^{MeV}}{931.5\cdot 0.00055}$

$$\boxed{E'_\gamma = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_e c^2}\cdot(1 - cos\phi)}}$$

Compton scattering in rest frame

$$E'_\gamma = \gamma \cdot E'_\gamma \left(1 + \frac{v}{c} cos\theta_{e^-\gamma'}\right)$$

transformation into the laboratory frame

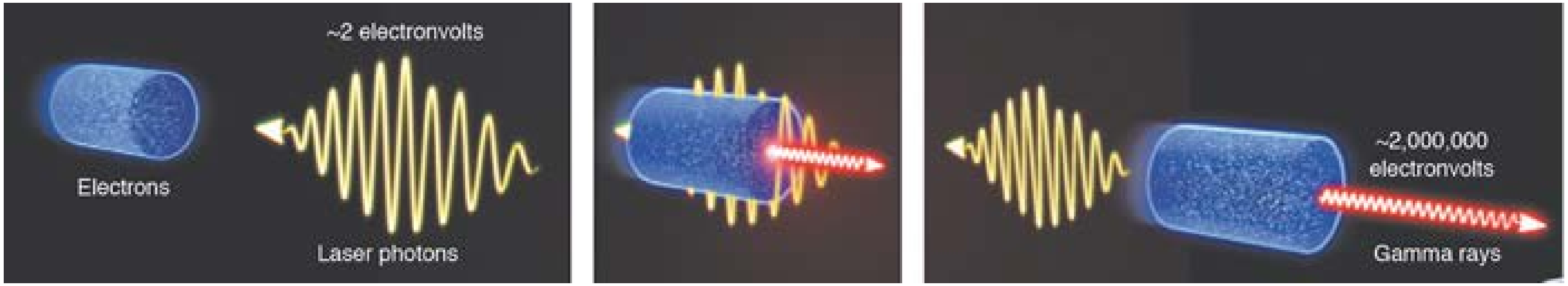
- Limit $E_\gamma \ll m_e c^2$

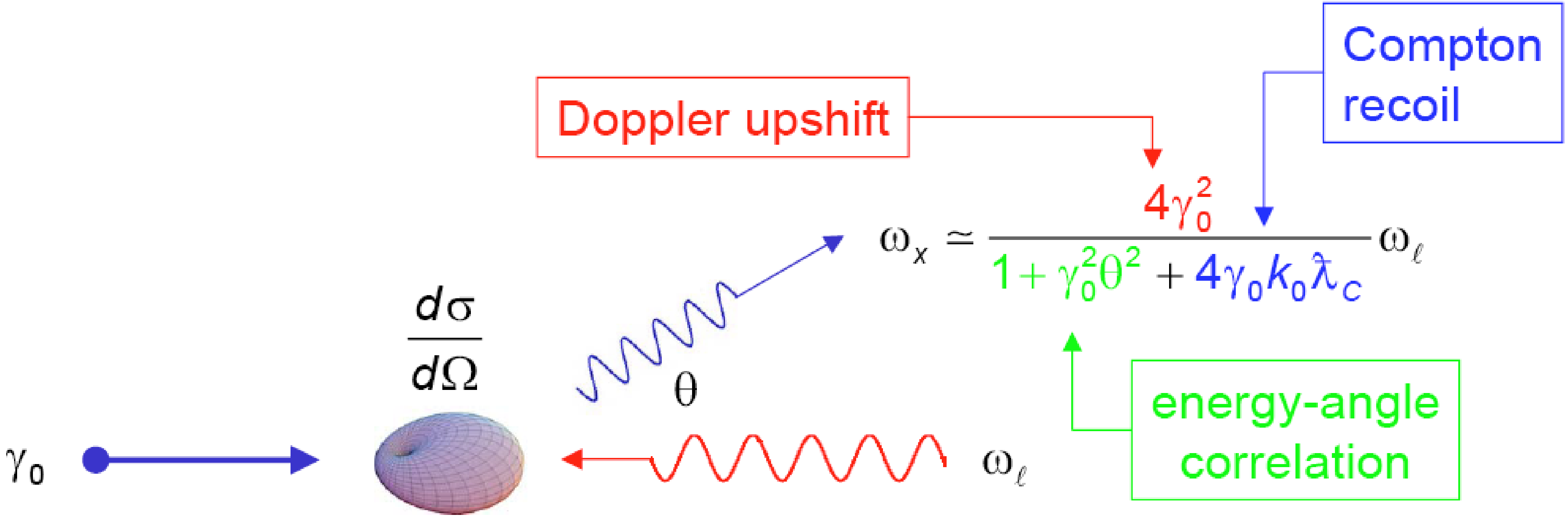
$$E'_\gamma \approx \gamma^2 \cdot E_\gamma \left(1 - \frac{v}{c} cos\theta_{e^-\gamma}\right)\left(1 + \frac{v}{c} cos\theta_{e^-\gamma'}\right)$$

$$\boxed{E'_\gamma \approx 4\gamma^2 \cdot E_\gamma}$$

electron and γ interaction $\theta_{e^-\gamma}\sim 180^0$ γ‘ emission relative to electron $\theta_{e^-\gamma'}\sim 0^0$

Laser Compton backscattering





Doppler upshift

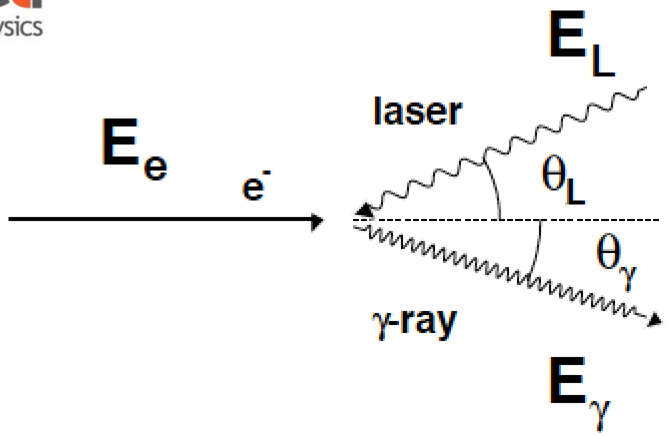
Compton recoil

$$\omega_x \simeq \frac{4\gamma_0^2}{1+\gamma_0^2\theta^2+4\gamma_0 k_0 \bar{\lambda}_c}\,\omega_\ell$$

energy-angle correlation

Energy – momentum conservation yields $\sim 4\gamma^2$ Doppler upshift
Thomsons scattering cross section is very small ($6\cdot 10^{-25}$ cm^2)
⇨ High photon density and electron density are required

Gamma rays resulting after inverse Compton scattering



photon scattering on relativistic electrons (γ >> 1)

$$h\nu = 2.3\ \text{eV} \quad (\equiv 515\ nm)$$

$$T_e^{lab} = 720\ MeV \quad \rightarrow \quad \gamma_e = 1 + \frac{T_e^{lab}[MeV]}{931.5 \cdot A_e[u]} = 1410$$

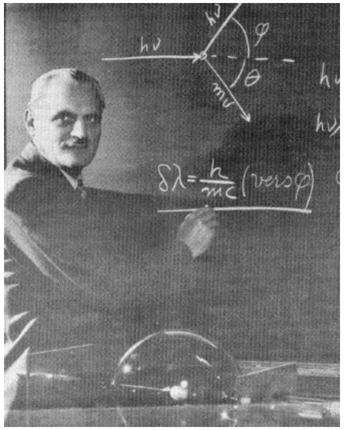
$$\boxed{E_\gamma = 2\gamma_e^2 \frac{1 + cos\theta_L}{1 + \left(\gamma_e\theta_\gamma\right)^2 + a_0^2 + \frac{4\gamma_e E_L}{mc^2}} \cdot E_L}$$

$\frac{4\gamma_e E_L}{mc^2}$ = recoil parameter

$a_L = \frac{eE}{m\omega_L c}$ = normalized potential vector of the laser field

E = laser electric field strength $E_L = \hbar\omega_L$

$\gamma_e = \frac{E_e}{mc^2} = \frac{1}{\sqrt{1-\beta^2}}$ = Lorentz factor



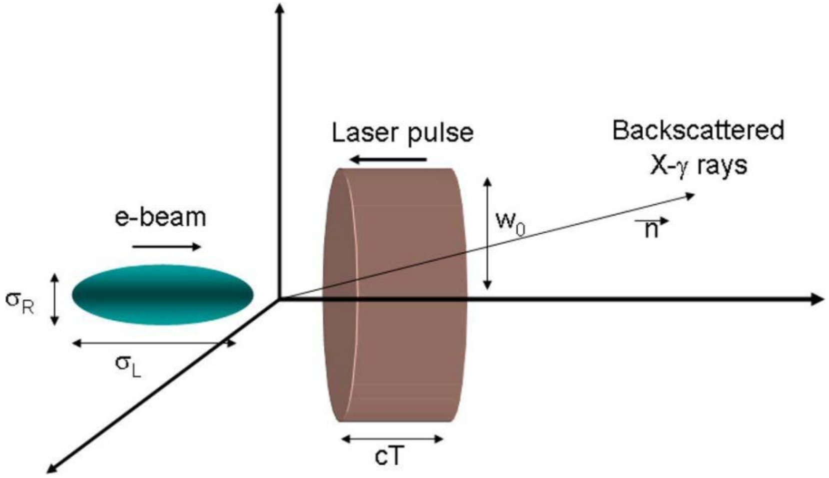
A. H. Compton
Nobel Prize 1927

maximum frequency amplification:

head-on collision ($\theta_L = 0^0$) & backscattering ($\theta_\gamma = 0^0$)

$$\boxed{E_\gamma \sim 4\gamma_e^2 \cdot E_L} \qquad \cong 18.3\ MeV$$

Scattered photons in collision



Yb: Yag J-class laser

10 Peta (10^{15}) Watt

$Q = 1[nC]$ $\quad$ $U_L = 0.5[J]$ $\quad h\nu_L = 2.4[eV] = 3.86 \cdot 10^{-19}[J] \equiv 515[nm]$

$\rightarrow N_e = 6.25 \cdot 10^9$ $\quad$ $\rightarrow N_L = 1.3 \cdot 10^{18}$

$\boxed{\text{Luminosity:} \quad L = \frac{N_L \cdot N_e}{4\pi \cdot \sigma_R^2} \cdot f} \cong 2.9 \cdot 10^{32} \cdot f\ [cm^{-2}s^{-1}]$ $\quad \sigma_R = 15[\mu m]$

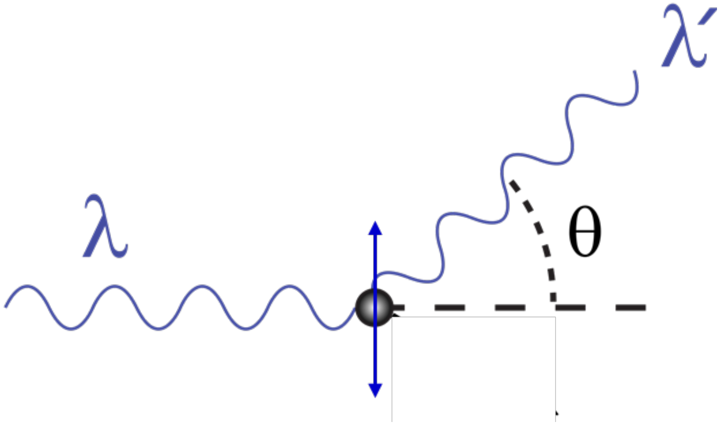
$\boxed{\gamma\text{-ray rate:} \quad N_\gamma = L \cdot \sigma_{Thomson}} \cong 2 \cdot 10^8 \cdot f\ [s^{-1}]$ $\quad \sigma_T = 0.67 \cdot 10^{-24}[cm^2]$

(full spectrum)

repetition rate:
$f = 3.2\ kHz$

Thomson scattering

J. J. Thomson
Nobel prize 1906

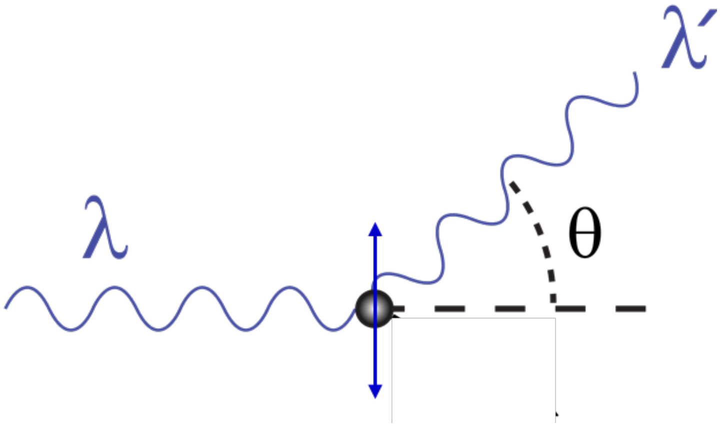


Thomson scattering = elastic scattering of electromagnetic radiation by an electron at rest

- the electric and magnetic components of the incident wave act on the electron
- the electron acceleration is mainly due to the electric field
  - → the electron will move in the direction of the oscillating electric field
  - → the moving electron will radiate electromagnetic dipole radiation
  - → the radiation is emitted mostly in a direction perpendicular to the motion of the electron
  - → the radiation will be polarized in a direction along the electron motion

Thomson scattering

J. J. Thomson
Nobel prize 1906



$$\frac{d\sigma_T(\theta)}{d\Omega} = \frac{1}{2} r_0^2 \cdot (1 + cos^2\theta)$$

differential cross section

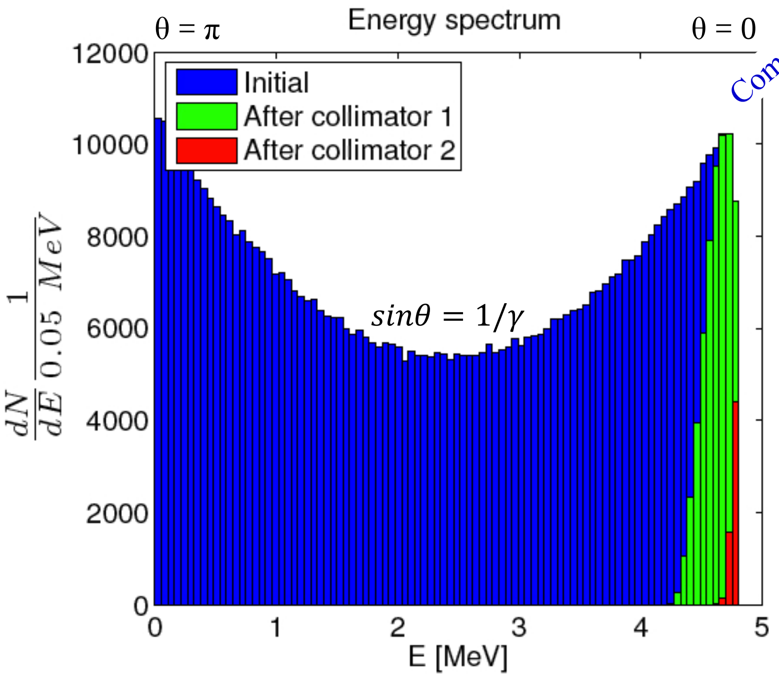
$$r_0 = \frac{e^2}{4\pi\varepsilon_0 m_e c^2} = 2.818 \cdot 10^{-15}\ [m]$$

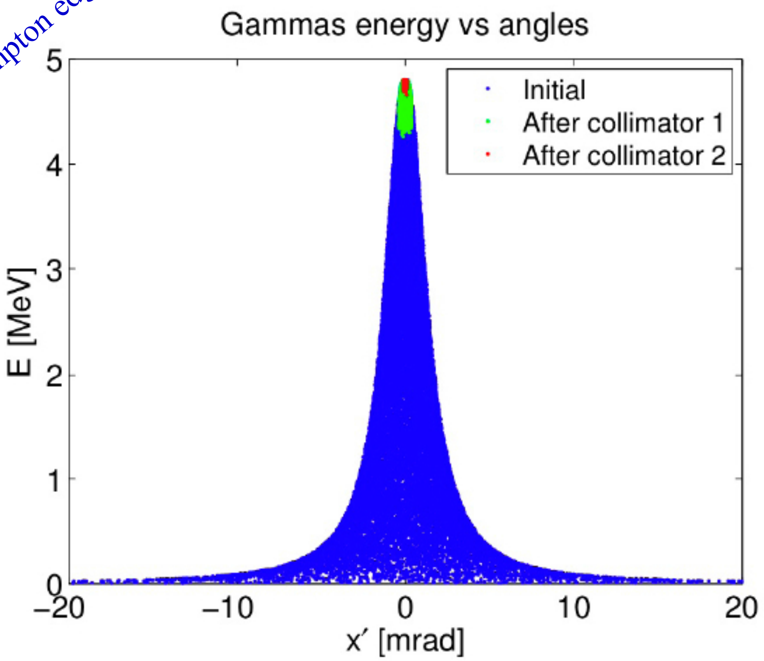
classical electron radius

$$\sigma_T = \int \frac{d\sigma_T(\theta)}{d\Omega} d\Omega = \frac{2\pi r_0^2}{2} \int_0^\pi (1 + cos^2\theta) d\theta = \frac{8\pi}{3} r_0^2 = 6.65 \cdot 10^{-29}\ [m^2] = 0.665\ [b]$$

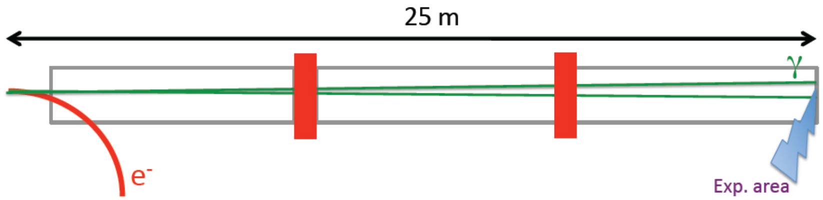
Scattered photons in collision

$$E_\gamma = 2\gamma_e^2 \frac{1+\cos\theta_L}{1+\left(\gamma_e\theta_\gamma\right)^2 + a_0^2 + \frac{4\gamma_e E_L}{mc^2}} \cdot E_L$$



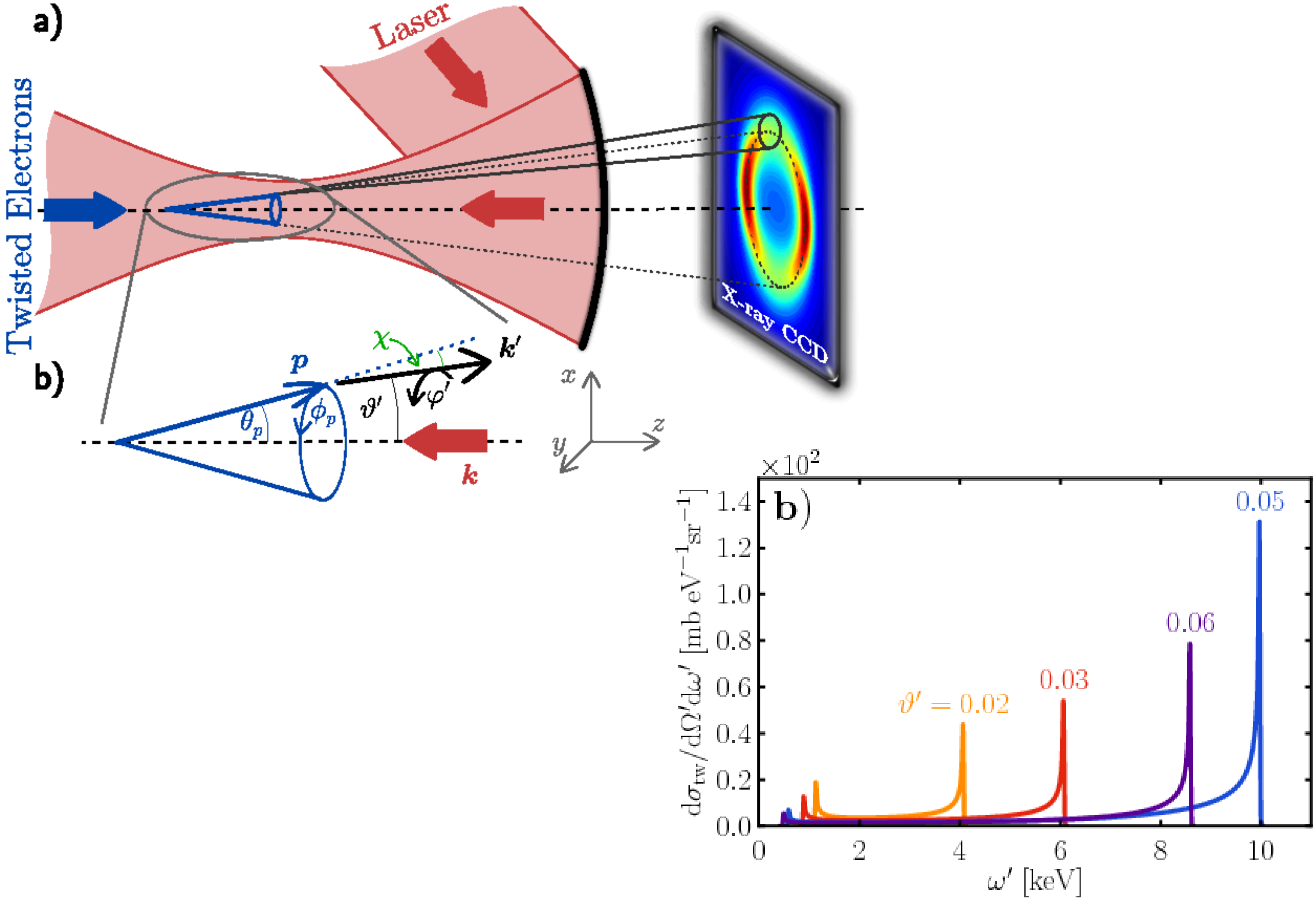


Photon extraction line

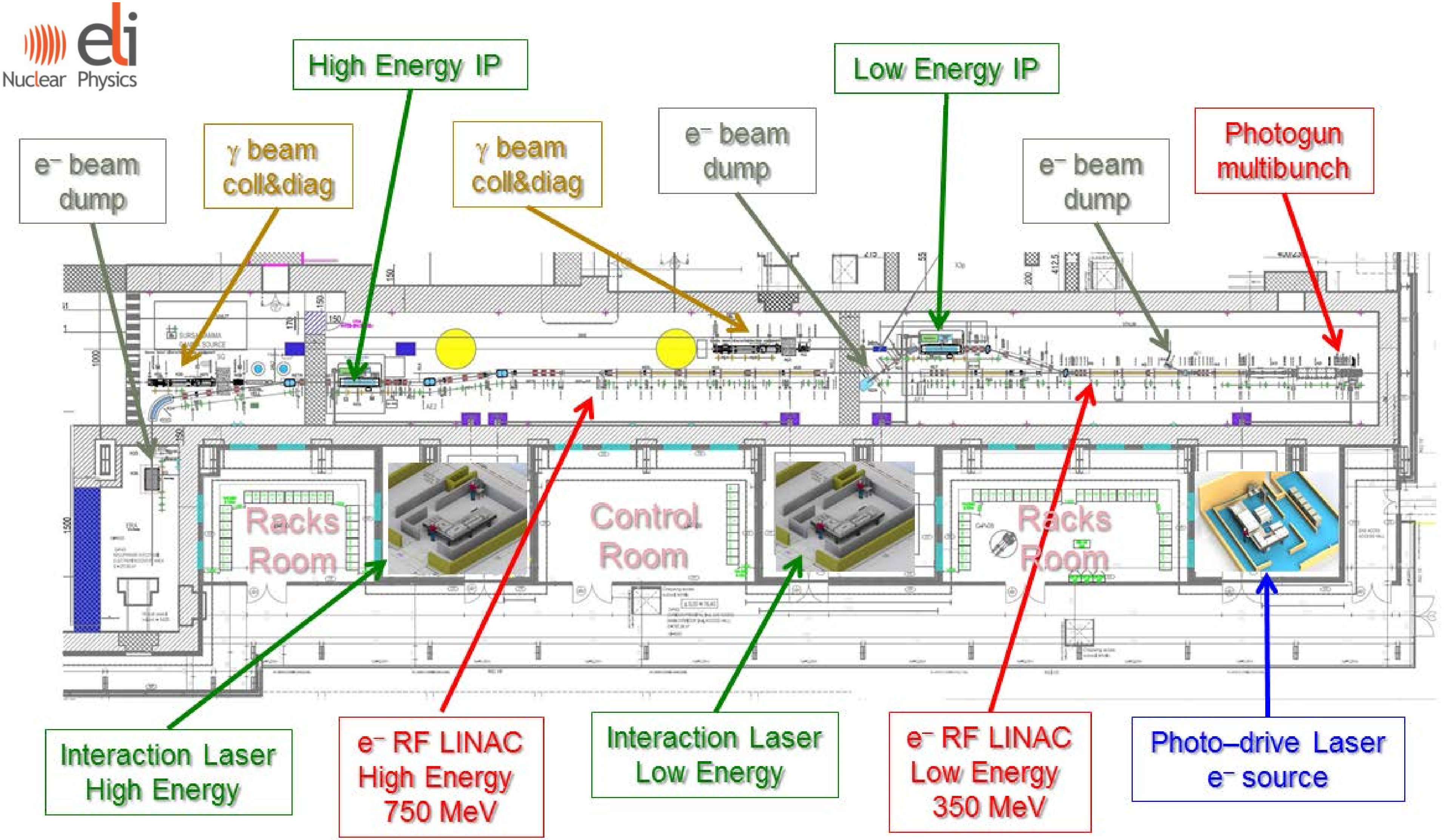


- Collimator 1 : d=11 m r= 0.3 cm , t= 5 cm (W)
- Collimator 2 : d=15 m r= 0.1 cm, t= 5 cm (W)

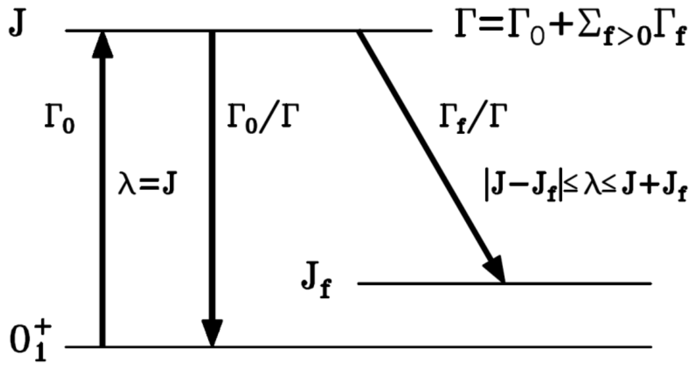
Inverse Compton scattering of laser light



Extreme Light Infrastructure – Nuclear Physics



Nuclear Resonance Fluorescence



- Widths of particle-bound states: $\Gamma \lesssim 10eV$

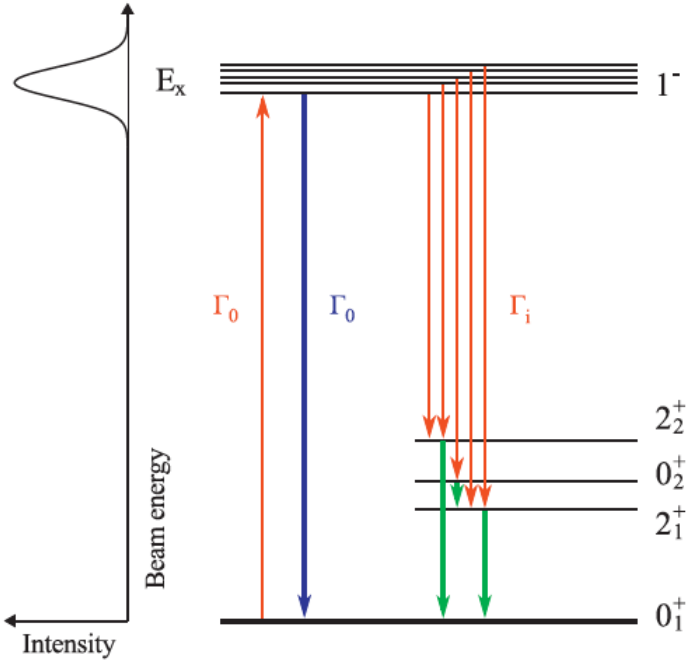
- Breit-Wigner absorption resonance curve for isolated resonance:

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

- Resonance cross section can be very large: $\sigma_0 \cong 200\ [b]$ (for $\Gamma_0 = \Gamma$, 5 MeV)

- Example: 10 mg, A~200 → $N_{target} = 3\cdot10^{19}$, $N_\gamma = 100$, event rate = 0.6 [s^{-1}]

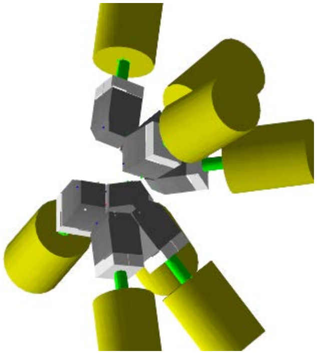
Nuclear Resonance Fluorescence



Count rate estimate

- 10^4 γ/(s eV) in 100 macro pulses
- 100 γ/(s eV) per macro pulse
- example: 10 mg, A ~ 200 target
- resonance width Γ = 1 eV
- 2 excitations per macro pulse
- 0.6 photons per macro pulse in detector
- pp-count rate 6 Hz
- 1000 counts per 3 min

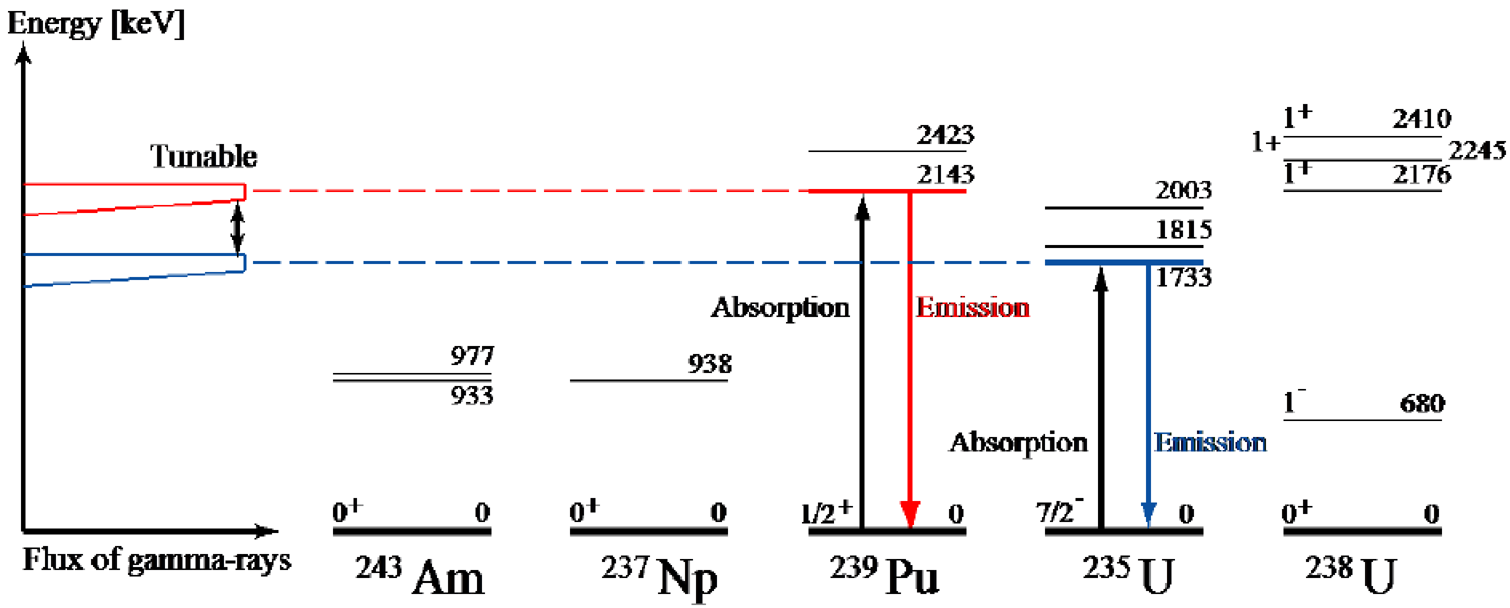
❖ narrow band width 0.5%



8 HPGe detectors
2 rings at 90^0 and 127^0
ε_{rel}(HPGe) = 100%
solid angle ~ 1%
photopeak ε_{pp} ~ 3%

Nuclear Resonance Fluorescence

❖ narrow bandwidth allows selective excitation and detection of decay channels



Deformation and scissors mode

- **Decay to intrinsic excitations**