Element production on the sun
Spectral lines of hydrogen

absorption spectrum

Light source

hydrogen gas

Slit

Prism

Red

Violet

Photographic film
Hydrogen emission spectrum

wave length nm
Spectral analysis

Kirchhoff und Bunsen:
Every element has a characteristic emission band

Max Planck
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 $\gamma$-rays

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

$\sim 8$ MeV

Nuclear Resonance Fluorescence (NRF)
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**Diagram:**

- Two Phonon State $[2^+ \otimes 3^-]_1^-$
- PDR
- GDR

**Axes:**

- E1 - Strength
- Energy (MeV)

**Labels:**

- $S_n$
- 5, 10, 15

**Key Points:**

- Pygmy dipole resonance
- Giant dipole resonance
- Neutron skin nuclei

Hans-Jürgen Wollersheim - 2020
Low energy photon scattering at S-DALINAC

- "white" photon spectrum
- wide energy region examined

Diagram:
- E<sub>γ</sub> < 10 MeV
- radiator target
- electrons and bremsstrahlung intensity vs. energy
- copper (Cu) target
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 $\gamma$-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 $\gamma$-ray spectrum provided by S-DALINAC

multipole order from angular distribution
Spin and Parity determination using monoenergetic photons

(a) E1
(b) M1
(c) E2

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

linearly polarized photon beam

E1 transition
M1 transition
E1 transition

Counts / 2 keV

vertical
out-of-plane

E1
E1

backward

horizontal

E2

$E_\gamma$ (MeV)

6.6 6.7 6.8 6.9 7.0 7.1
Spin and Parity determination using monoenergetic photons

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

linearly polarized photon beam

M1 transition
E1 transition

Counts / 2 keV

vertical
backward
in-plane
horizontal

M1
M1
M1

E_\gamma (MeV)

7.9  8.0  8.1  8.2  8.3
Absorption processes

Absorption lines only a few eV wide!

- atomic attenuation
  - several processes
  - contributes at each energy
  - independent of $\Omega_0$

- resonant absorption
  - only at resonance energies
  - depends on $\Omega_0$

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

Hans-Jürgen Wollersheim - 2020
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

\[ R(G_0) = \frac{N_{\text{woA}} - f \cdot N_{\text{wA}}}{N_{\text{woA}}} \]

\[ f = \frac{N_{\text{std wA}}}{N_{\text{std wA}}} \]
First $\gamma\gamma$-coincidences in a $\gamma$-beam

First $\gamma\gamma$-coincidences in a $\gamma$-beam

First $\gamma\gamma$-coincidences in a $\gamma$-beam

Total power received by Earth from the Sun

174 Peta (10^{15}) Watt

89 PW absorbed by land and oceans

extreme light infrastructure, Europe
Compton scattering and inverse Compton scattering

Compton scattering:
- Elastic scattering of a high-energy $\gamma$-ray on a free electron.
- A fraction of the $\gamma$-ray energy is transferred to the electron.
- The wave length of the scattered $\gamma$-ray is increased: $\lambda' > \lambda$.

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

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

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

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 $\gamma$-ray is decreased: $\lambda' < \lambda$.

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

\[
E'_\gamma = \gamma \cdot E_\gamma \left(1 - \frac{v}{c} \cos \theta_{e-\gamma}\right)
\]

Lorentz factor: \(\gamma = (1 - \beta^2)^{-1/2} = 1 + \frac{T_{e\text{MeV}}}{931.5 - 0.00055}\)

Doppler shift

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

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 $E_\gamma \ll m_e c^2$

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

\[
E'_\gamma \approx 4\gamma^2 \cdot E_\gamma
\]

electron and $\gamma$ interaction $\theta_{e-\gamma} \sim 180^0$  $\gamma'$ emission relative to electron $\theta_{e-\gamma'} \sim 0^0$
Laser Compton backscattering

Energy – momentum conservation yields $\sim 4\gamma^2$ Doppler upshift
Thomson scattering cross section is very small ($6 \cdot 10^{-25} \text{ cm}^2$)

High photon density and electron density are required
Gamma rays resulting after inverse Compton scattering

Photon scattering on relativistic electrons ($\gamma >> 1$)

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

$$T_{e}^{\text{lab}} = 720 \text{ MeV} \Rightarrow \gamma_{e} = 1 + \frac{T_{e}^{\text{lab}}[\text{MeV}]}{931.5 \cdot A_{e}[u]} = 1410$$

$$E_{\gamma} = 2\gamma_{e}^{2} \frac{1 + \cos \theta_{L}}{1 + (\gamma_{e}\theta_{\gamma})^{2} + a_{0}^{2} + \frac{4\gamma_{e}E_{L}}{mc^{2}}} \cdot E_{L}$$

$$\frac{4\gamma_{e}E_{L}}{mc^{2}} = \text{recoil parameter}$$

$$a_{L} = \frac{eE}{m\omega_{L}c} = \text{normalized potential vector of the laser field}$$

$$E = \text{laser electric field strength} \ E_{L} = \hbar \omega_{L}$$

$$\gamma_{e} = \frac{E_{e}}{mc^{2}} = \frac{1}{\sqrt{1 - \beta^{2}}} = \text{Lorentz factor}$$

**maximum frequency amplification:**

head-on collision ($\theta_{L} = 0^\circ$) & backscattering ($\theta_{\gamma} = 0^\circ$)

$$E_{\gamma} \sim 4\gamma_{e}^{2} \cdot E_{L} \approx 18.3 \text{ MeV}$$
Scattered photons in collision

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

\[ \rightarrow N_e = 6.25 \times 10^9 \quad \rightarrow N_L = 1.3 \times 10^{18} \]

Luminosity:

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

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

(full spectrum)

Yb: Yag J-class laser

10 Peta (10^{15}) Watt

repetition rate:

\[ f = 3.2 \text{ kHz} \]
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

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

classical electron radius

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

\[ E_\gamma = 2\gamma_e^2 \frac{1 + \cos \theta_L}{1 + (\gamma_e \theta_L)^2 + a_0^2 + \frac{4\gamma_e E_L}{mc^2}} \cdot E_L \]

- **Energy spectrum**
  - \( \theta = \pi \)
  - \( \sin \theta = 1/\gamma \)

- **Gammas energy vs angles**
  - Compton edge
  - Initial
  - After collimator 1
  - After collimator 2

- **Photon extraction line**
  - Collimator 1: \( d=11 \text{ m} \), \( r=0.3 \text{ cm} \), \( t=5 \text{ cm} \) (W)
  - Collimator 2: \( d=15 \text{ m} \), \( r=0.1 \text{ cm} \), \( t=5 \text{ cm} \) (W)
Inverse Compton scattering of laser light
- Widths of particle-bound states: $\Gamma \leq 10eV$

- 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: $\sigma_0 \approx 200 \, [b]$ (for $\Gamma_0 = \Gamma$, 5 MeV)

- Example: 10 mg, A~200 \rightarrow N_{\text{target}} = 3 \cdot 10^{19}, N_\gamma = 100, \text{ event rate} = 0.6 \, [s^{-1}]$
Count rate estimate
- $10^4 \gamma/(s \text{ eV})$ in 100 macro pulses
- 100 $\gamma/(s \text{ eV})$ per macro pulse
- example: 10 mg, A ~ 200 target
- resonance width $\Gamma = 1 \text{ eV}$
- 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 $127^0$
$\varepsilon_{rel}(\text{HPGe}) = 100\%$
solid angle $\sim 1\%$
photopeak $\varepsilon_{pp} \sim 3\%$
Nuclear Resonance Fluorescence

- narrow bandwidth allows selective excitation and detection of decay channels
Decay to intrinsic excitations