(3) Interaction of high energy photons with matter

- Photoelectric Absorption
- (Inverse) Compton Scattering
- Electron-positron pair production
- Application in Detectors
Photoelectric Absorption

Similar to the «Photoelectric Effect», first explained by Einstein: Photons with sufficiently high energies can eject electrons from the atomic «shells». The difference between the photon energy and ionisation energy provides kinetic energy for the freed electron:

\[ E_{\text{kin}} = (\hbar \omega - E_I) \]

P.e. Absorption is the photoelectric effect with electrons from low-lying energy levels. Photons in the X-ray range are needed (~keV):

\[ \hbar \omega \ll m_e c^2 \]

- One of the principal sources of opacity in stellar interiors and stellar atmospheres.
- Absorption of X-rays in interstellar matter gives insight into the composition of interstellar matter (absorption lines).
- Proportional Counters for X-rays: photoelectric absorption in the detector gas (and window material).
Photoelectric Absorption Edges

The energy levels within the atom for which $\hbar \omega = E_1$ are called absorption edges. For the K-edge (1s electrons), the cross-section for photons with $\hbar \omega \gg E_1$ is given by:

$$\sigma_K = \frac{e^{12} m_e^{3/2} Z^5}{192 \sqrt{2} \pi^5 \epsilon_0^6 \hbar^4 c \left( \frac{1}{\hbar \omega} \right)^{7/2}}$$

- This is the cross-section for the removal of the 1s electrons.
- depends very strongly on atomic number
- roughly proportional to $\omega^{-3}$.

=> rare (high Z) elements contribute significantly at high energies.

Figure 4.1. The absorption coefficients for hydrogen, carbon, oxygen and argon atoms as a function of photon energy (or wavelength). (From M. V. Zombeck (1990). *Handbook of space astronomy and astrophysics*, page 295–8, Cambridge: Cambridge University Press.)
The K-edges provide the dominant source of opacity for X-rays traversing interstellar matter. The figure on the right shows the cross-section for standard cosmic abundances of the different elements.

A practical interpolation formula can be used to describe the optical depth $\tau_x$ for X-ray absorption in the interstellar medium:

$$\tau_x(\hbar \omega) = 2 \times 10^{-26} \left( \frac{\hbar \omega}{1 \text{ keV}} \right)^{-8/3} \int N_H \, dl$$

where the optical depth is defined as:

$$\tau_x = \int \sigma_x N_H \, dl$$

$N_H$ is the number density of hydrogen atoms (particles / m³)

**optical density** = fraction of radiation absorbed or scattered on a path $dl$:

$$\frac{I}{I_0} = e^{-\tau}$$

$$\int N_H \, dl$$ is the *column density* (particles / m²) (i.e. "grammage")
The Compton effect is the scattering of high energy photons off electrons, during which the photons transfer energy to the electron. The energy loss of the photons leads to a wavelength shift to a longer wavelength. The electron gains kinetic energy.

(Inverse) Compton scattering is one of the main processes for energy exchange between matter and radiation. It is therefore very important in many aspects of astrophysics.

Compton-Scatter telescopes are used in γ-ray astronomy (see Chapter 5).
Thomson and Compton scattering cross-sections (1)

For photon energies $\hbar \omega \ll m_e c^2$ the classical Thomson scattering cross-section is a good approximation for the scattering off electrons.

An unpolarized light wave is scattered by an electron. The electron is accelerated in the electromagnetic field of the wave ($E_x = E_{x0} \exp(i\omega t)$, $E_y = E_{y0} \exp(i\omega t)$).

$$\ddot{r}_x = \frac{eE_x}{m_e} ; \quad \ddot{r}_y = \frac{eE_y}{m_e}$$
Thomson and Compton scattering cross-sections (2)

The radiation of an accelerated charged particle as a function of the scattering angle is given by:

$$\frac{-dI}{dt} \, d\Omega = \frac{e^2 |\vec{r}|^2}{16\pi^2 \epsilon_0 c^3} \sin^2 \theta \, d\Omega$$

$\theta$ is the angle between the acceleration vector and the direction of emission. The integral over $d\Omega$ is just the Larmor formula.

$$-\left(\frac{dI}{dt}\right)_x \, d\Omega = \frac{e^4 |E_x|^2}{16\pi^2 m_e^2 \epsilon_0 c^3} \cos^2 \alpha \, d\Omega$$

$$-\left(\frac{dI}{dt}\right)_y \, d\Omega = \frac{e^4 |E_y|^2}{16\pi^2 m_e^2 \epsilon_0 c^3} \, d\Omega$$

We replace the electric field components by the Poynting flux (energy / unit area):

$$\vec{S}_x = (\vec{E}_x \times \vec{H}) = c \epsilon_0 E_x^2 \, \vec{i}_z \rightarrow S_x = c \epsilon_0 E_x^2 \quad ; \quad \text{similar: } S_y = c \epsilon_0 E_y^2$$

Here we are actually using time averages: $E_x^2 = \frac{E_{x,0}^2}{2}$

For an unpolarized wave $S_x = S_y = S / 2$, thus...
Thomson and Compton scattering cross-sections (3)

The total scattered radiation into $d\Omega$ is:

$$-\frac{dI}{dt} \, d\Omega = \frac{e^4}{16 \pi^2 m_e^2 \varepsilon_0^2 c^4} \left(1 + \cos^2 \alpha\right) \frac{S}{2} \, d\Omega$$

The **differential cross-section** is the radiation per unit solid angle divided by the incident radiation $S$:

$$\frac{d\sigma_T}{d\Omega} = \frac{e^4}{16 \pi^2 m_e^2 \varepsilon_0^2 c^4} \frac{1 + \cos^2 \alpha}{2}$$

We find the **total cross-section** by integrating over $d\Omega = 2\pi \sin \alpha \, d\alpha$ from 0 to $\pi$:

$$\sigma_T = \frac{e^4}{6\pi \varepsilon_0^2 m_e^2 c^4} \approx 6.653 \times 10^{-29} \text{ m}^2$$

**Thomson scattering:**
- As much radiation is scattered forward as backward.
- $-(dI / dt) = \sigma_T S = \sigma_T c \, u_{\text{rad}}$; $u_{\text{rad}}$ = energy density of radiation at the electron
- Scattered radiation is polarised.
- Thomson scattering does not change the frequency of the radiation
Thomson and Compton scattering cross-sections (4)

Thomson scattering is a good approximation for scattering of photons off electrons as long as $\hbar \omega \ll m_e c^2$ in the centre of momentum frame of reference. If the photon energies are large or the electron is moving ultra-relativistically, the full quantum relativistic cross-section has to be used:

$$\sigma_{KN} = \sigma_T \frac{3}{8} \frac{1}{\varepsilon} \left( 1 - \frac{2(\varepsilon+1)}{\varepsilon^2} \right) \ln(2\varepsilon+1) + \frac{1}{2} + \frac{4}{\varepsilon} - \frac{1}{2(2\varepsilon+1)^2}$$

with: $\varepsilon = \frac{\hbar \omega}{m_e c^2}$

This is the **Klein-Nishina formula**.

$$\varepsilon \ll 1 \Rightarrow \sigma_{KN} \approx \sigma_T$$

(Also for $\gamma \gg 1$ !)

$$\varepsilon \gg 1 \Rightarrow \sigma_{KN} \approx \pi r_e^2 \frac{1}{\varepsilon} (\ln 2\varepsilon + \frac{1}{2})$$

- In the ultra-relativistic limit, the cross-section decreases roughly as $1 / \varepsilon$

- Scattering by nuclei is suppressed roughly by a factor of $(m_e / m_N)^2$, with $m_N = \text{mass of nucleus}$.
What is the change in wavelength of a photon scattering off an electron?

We describe the collision with relativistic 4-vectors:

**Electron:**

\[ p = [γ m_e c, γ m_e \vec{v}] \rightarrow p' = [γ' m_e c, γ' m_e \vec{v}'] \]

**Photon:**

\[ k = \left[ \frac{\hbar \omega}{c}, \frac{\hbar \omega}{c} \vec{i}_k \right] \rightarrow k' = \left[ \frac{\hbar \omega'}{c}, \frac{\hbar \omega'}{c} \vec{i}_{k'} \right] \]

4-momentum conservation yields:

\[ p + k = p' + k' \]

Scalar products of 4-vectors are Lorentz invariant:

\[ p_\mu \cdot p_\mu = γ^2 m_e^2 c^2 - γ^2 m_e^2 v^2 = m_e^2 \frac{c^2 - v^2}{1 - \frac{v^2}{c^2}} = m_e^2 c^2 \]

In the same way:

\[ p' \cdot p' = m_e^2 c^2 \quad ; \quad k \cdot k = k' \cdot k' = 0 \]

Thus:

\[ (p + k)^2 = (p' + k')^2 \]

\[ p \cdot p + 2 p \cdot k + k \cdot k = p' \cdot p' + 2 p' \cdot k' + k' \cdot k' \]

\[ p \cdot k = p' \cdot k' \]
Compton scattering - energy transfer (2)

We multiply both sides of the conservation equation by $k'$:

$$\mathbf{p} \cdot k' + k \cdot k' = \mathbf{p}' \cdot k' + k' \cdot k'$$
$$\mathbf{p} \cdot k' + k \cdot k' = \mathbf{p} \cdot k$$

This can be evaluated:

$$\frac{\omega'}{\omega} = \frac{1 - (\frac{\nu}{c})\cos \theta}{\left[ 1 - (\frac{\nu}{c})\cos \theta + (\frac{\hbar \omega}{\gamma m_e c^2})(1 - \cos \alpha) \right]}$$

with:

$$\cos \alpha = \mathbf{i}_k \cdot \mathbf{i}_k' ; \quad \cos \theta = \mathbf{i}_k \cdot \frac{\mathbf{V}}{v} ; \quad \cos \theta' = \mathbf{i}_k' \cdot \frac{\mathbf{V}}{v}$$

$\alpha$ = photon scattering angle,
$\theta$ = angle between incoming photon and electron,
$\theta'$ = angle between outgoing photon and incoming electron

For a stationary electron ( $\nu = 0$ , $\gamma = 1$ ) :

$$\frac{\omega'}{\omega} = \frac{1}{\left[ 1 + (\frac{\hbar \omega}{m_e c^2})(1 - \cos \alpha) \right]}$$

$$\frac{\Delta \lambda}{\lambda} = \frac{\lambda' - \lambda}{\lambda} = \frac{\hbar \omega}{m_e c^2} (1 - \cos \alpha)$$
Thus, in the case of a stationary electron, the wavelength of the photon becomes longer, i.e. it looses energy.

If however the electron is more energetic than the photon (\( \gamma m_e c^2 >> \hbar \omega \)), we get the following:

\[
\frac{\omega' - \omega}{\omega} \approx \frac{v}{c} \frac{\cos \theta' - \cos \theta}{1 - \frac{v}{c} \cos \theta'}
\]

- energy transfer possible in both directions
- frequency change \( \sim \frac{v}{c} \)
- for random scattering angles, no net increase in the photon energy to first order, but there is a net gain to second order (i.e. \( \sim \frac{v^2}{c^2} \)) \( \rightarrow \) **Inverse Compton Scattering**
Inverse Compton Scattering is the process by which a low-energy photon scatters off a high energy electron and thereby gains energy, thus reaching a higher frequency.

- Inverse Compton Scattering is an important source of X-ray and γ-ray radiation.
- Inverse Compton Scattering of Cosmic Microwave Background photons in regions of hot ionised gas leads to spectral distortions (Sunyaev-Zeldovich effect).
- Important energy loss mechanism for high energy electrons.
Inverse Compton Scattering - some formulas

**Energy loss rate of high energy electrons:**

\[
\frac{dE}{dt} = \frac{4}{3} \sigma_T c u_{\text{rad}} \left( \frac{v^2}{c^2} \right) \gamma^2
\]

- \( u_{\text{rad}} \) is the energy density of the radiation; the flux density is \( N \hbar \omega = c u_{\text{rad}} \).
- This formula is exact for \( \gamma \hbar \omega \ll m_e c^2 \) ("Thomson regime").

**Spectral Emissivity (Blumenthal and Gould):**

\[
I(\nu) \, d\nu = \frac{3 \sigma_T c}{16 \gamma^4} \frac{N(\nu)}{\nu_0^2} \nu \left[ 2 \nu \ln \left( \frac{\nu}{4 \gamma^2 \nu_0} \right) + \nu + 4 \gamma^2 \nu_0 - \frac{\nu^2}{2 \gamma^2 \nu_0} \right] d\nu
\]

- radiation field is assumed monochromatic (\( \nu_0 \))
- \( N(\nu_0) \) is the number density of photons
- at low frequencies \( I(\nu) \) is proportional to \( \nu \)
Inverse Compton Scattering – energy gain

**Maximum energy gain for photons:**

\[ \hbar \omega_{\text{max}} \approx 4 \gamma^2 \hbar \omega_0 \]

exact for \( \gamma \hbar \omega \ll m_e c^2 \)

**Average energy gain for photons:**

\[ \hbar \bar{\omega} = \frac{4}{3} \gamma^2 \left( \frac{v}{c} \right)^2 \hbar \omega_0 \approx \frac{4}{3} \gamma^2 \hbar \omega_0 \]

Electrons with Lorentz factors of \(~1000\) can thus convert radio- into UV-photons, IR-photons into X-rays and optical photons into \( \gamma \)-rays!

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Figure 4.8. The emission spectrum of inverse Compton scattering; \( v_0 \) is the frequency of the unscattered radiation. (From G. R. Blumenthal and R. J. Gould (1970). *Rev. Mod. Phys.*, **42**, 237.)
Electron-Positron Pair Production

- High-energy photons can be converted into electron-positron pairs.
- This process is not possible in free space, but only in the presence of an electromagnetic field (field of a nucleus, collision of two photons, magnetic field of the Earth...).
- Important energy loss mechanism at the highest photon energies.
- Basis of the electromagnetic cascade caused by $\gamma$-rays in the atmosphere (see Chapter 5).
Electron-Positron Pair Production is impossible in free space.

This is because of the required conservation of energy and momentum. Pair production is not possible in free space, not even in the case where the electron-positron pair moves in the direction of the original photon:

I. energy conservation: \[ \hbar \omega = 2 \gamma m_e c^2 \]

=> momentum of the pair: \[ p = 2 \gamma m_e v = \frac{\hbar \omega}{c^2} v \]

II. momentum conservation: \[ \frac{\hbar \omega}{c} \neq p \]

Thus, some of the energy and momentum of the photon must be absorbed by a third body, or in an electromagnetic field. One possibility we will not discuss here in detail is for example the interaction of high energy photons with the Earth's magnetic field, which results in an electromagnetic cascade initiated by e+e- pair production.
Pair Production of other particle-antiparticle pairs

Pair production of other particle-antiparticle pairs is possible, if the photon energy is sufficiently high.

For electron-positron pair production, the photon needs an energy \( > 2 \times 0.511 \text{ MeV} \sim 1 \text{ MeV} \).

For pair production of the next heavier particle-antiparticle pair, the muon and its antiparticle, an energy \( > 2 \times 105 \text{ MeV} = 210 \text{ MeV} \) is needed.

Thus, production of electron-positron pairs is the most common process.
Electron-Positron Pair Production in the field of a nucleus (1)

Cross-section for intermediate photon energies:

\[
\sigma_{\text{pair}} = \alpha \sigma_T \frac{Z^2}{8\pi} \left[ \frac{28}{9} \ln \left( \frac{2\hbar \omega}{m_e c^2} \right) - \frac{218}{27} \right] \text{ m}^2 \text{ atom}^{-1}
\]

No screening is assumed. This is the approximation for photons with:

\[1 \ll \frac{\hbar \omega}{m_e c^2} \ll \frac{1}{\alpha Z^{1/3}}\]

Cross-section in the ultra-relativistic limit:

\[
\sigma_{\text{pair}} = \alpha \sigma_T \frac{Z^2}{8\pi} \left[ \frac{28}{9} \ln \left( \frac{183}{Z^{1/3}} \right) - \frac{2}{27} \right] \text{ m}^2 \text{ atom}^{-1}
\]

Complete screening is assumed. This is the valid approximation for photons with:

\[\frac{\hbar \omega}{m_e c^2} \gg \frac{1}{\alpha Z^{1/3}}\]

The cross-section for pair production in the field of an electron is very much smaller.
The Screening Effect in $e^+ e^-$ pair production

In interactions between particles or photons with the field of a nucleus, the influence of the atomic electrons is not always negligible. They can screen a fraction of the nuclear charge, if the distance of the high energy particle is larger than the distance of the electrons from the nucleus.

This leads to an adjustment of the nuclear potential:

Coulomb potential:

$$U(r) = \frac{zZe^2}{r}$$

Fermi-Thomas potential: $U(r) = \frac{zZe^2}{r} \exp\left(-\frac{r}{a}\right)$

with the atomic radius $a = 1.4 a_0 Z^{-1/3}$

The screening effect is small as long as the particle trajectory is within the atom $dx < a$. This is true as long as the momentum transfer is sufficiently large: $dp > \hbar/a$ (Heisenberg !)

Exact calculations show that in the non-relativistic case, the momentum transfer is almost always large and screening is negligible. In the relativistic case, however, it can be small, so that the screening effect has to be taken into account.
**Conversion length for pair production:**

\[ \xi_{\text{pair}} = \frac{\rho}{N_N \sigma_{\text{pair}}} = \frac{M_A}{N_0 \sigma_{\text{pair}}} \]

\( N_N \) is the number density of nuclei and \( M_A \) is the atomic mass and \( N_0 \) is Avogadro's constant.

\[ I(\xi) = I_0 \exp\left(-\frac{\xi}{\xi_{\text{pair}}}\right) \]

The radiation/conversion lengths for pair production and bremsstrahlung at ultra-relativistic energies are roughly the same:

\[ \xi_{\text{pair}} \approx \xi_{\text{brems}} \]

The similarity between the two processes can also be seen in their Feynman diagrams. (left: pair production, middle: bremsstrahlung, right: annihilation)
a little excursion: Feynman diagrams

Introduction to Feynman diagrams:

http://www2.slac.stanford.edu/vvc/theory/feynman.html

Compton scattering calculation:

http://www.phys.ualberta.ca/~gingrich/phys512/latex2html/node102.html
Another important mechanism for $e^+e^-$ pair production occurs when a photon of very high energy interacts with an ambient photon (extragal. background light, starlight, CMB...).

**What is the threshold energy required for this process?**

We assume that two photons collide and produce a particle-antiparticle pair at rest:

$$k_1 = [\frac{\varepsilon_1}{c}, \frac{\varepsilon_1}{c}i_1] ; \quad k_2 = [\frac{\varepsilon_2}{c}, \frac{\varepsilon_2}{c}i_2] ; \quad p_1 = [mc, 0] ; \quad p_2 = [mc, 0]$$

We use 4-momentum conservation and the following scalar identities:

$$k_1 \cdot k_1 = k_2 \cdot k_2 = 0$$
$$p_1 \cdot p_1 = p_2 \cdot p_2 = p_1 \cdot p_2 = m^2 c^2$$

Thus:

$$k_1 + k_2 = p_1 + p_2$$
$$(k_1 + k_2)^2 = (p_1 + p_2)^2$$
$$k_1 \cdot k_1 + 2k_1 \cdot k_2 + k_2 \cdot k_2 = p_1 \cdot p_1 + 2p_1 \cdot p_2 + p_2 \cdot p_2$$
Pair Production in photon-photon collisions (2)

\[ 2 \left( \frac{\varepsilon_1 \varepsilon_2}{c^2} - \frac{\varepsilon_1 \varepsilon_2}{c^2} \cos \theta \right) = 4 m_e^2 c^2 \]

\[ \varepsilon_2 = \frac{2 m_e^2 c^4}{\varepsilon_1 (1 - \cos \theta)} \]

The threshold occurs when the angle between the two photons \( \theta = \pi \), hence follows for \( e^+ e^- \) pair production:

\[ \varepsilon_2 \geq \frac{m_e^2 c^4}{\varepsilon_1} = \frac{0.26 \times 10^{12}}{\varepsilon_1} \text{ eV} \]

This means for example that a photon of energy > 400 TeV will undergo pair production even with the low energy photons (~6 x 10^{-4} eV) of the CMB.
What is the cross-section of pair production in photon-photon collision?

1. Cross-section in the classical regime

$$\sigma = \sigma_T \frac{3}{8} \left( 1 - \frac{m_e^2 c^4}{\omega^2} \right)^{\frac{1}{2}} ; \quad \omega = \sqrt{\varepsilon_1 \varepsilon_2}$$

valid for: \( \omega \approx m_e c^2 \)

2. Cross-section in the ultra-relativistic limit

$$\sigma = \sigma_T \frac{3}{8} \frac{m_e^2 c^4}{\omega^2} \left[ 2 \ln \left( \frac{2 \omega}{m_e c^2} \right) - 1 \right]$$

valid for: \( \omega \gg m_e c^2 \)

With the help of these cross-sections, one can determine the opacity of the interstellar and intergalactic medium for high energy photons and determine the flux of generated positrons.
Comparison of photon cross-sections

This figure shows the different contributions to photon absorption in lead:

- **Photoelectric absorption** is only important at low energies (\(< \sim 2\) MeV)
- **Compton scattering** leads to significant energy loss at intermediate energies
- **Pair production** becomes important for energies \(> 2\) MeV and is dominant above 5 MeV and up to the highest energies.

The relative contributions change somewhat for interactions with other materials (change in Z !)

Figure 4.16. The total mass absorption coefficient for high energy photons in lead, indicating the contributions associated with the photoelectric absorption, Compton scattering and electron–positron pair production. (From H. A. Enge (1966). *Introduction to nuclear physics*, page 193, London: Addison-Wesley Publishing Co.)
Comparison of photon cross-sections for different Z

Contributions to Photon Cross Section in Carbon and Lead

Carbon ($Z = 6$)
- experimental $\sigma_{\text{tot}}$
- $\sigma_{\text{coh}}$
- $\sigma_{\text{nuc}}$
- $\sigma_{\text{incoh}}$

Lead ($Z = 82$)
- experimental $\sigma_{\text{tot}}$
- $\sigma_{\text{coh}}$
- $\sigma_{\text{nuc}}$
- $\sigma_{\text{incoh}}$
Excitation of Resonances - the GZK effect (1)

Resonances are excited hadronic states of a very short lifetime.

In astrophysics the $\Delta^+ (1232)$ - resonance, an excited proton state of mass 1232 MeV, plays an important role for the propagation of cosmic rays through the CMB. This resonance has a lifetime of the order of $10^{-23}$ s.

In the rest frame of ultra-high energy cosmic ray protons, the CMB photons can reach sufficiently high energies to excite the resonance:

$$p^+ + \gamma_{\text{CMB}} \rightarrow \Delta^+$$

The resonance then decays quickly, following mostly two principal channels:

$$\Delta^+ \rightarrow p^+ + \pi^0 \rightarrow p^+ + 2\gamma$$

$$\Delta^+ \rightarrow n + \pi^+ \rightarrow n + \mu^+ + \nu_\mu \rightarrow p^+ + e^- + \bar{\nu}_e + \mu^+ + \nu_\mu$$
This interaction makes the CMB effectively opaque for ultra-high energy protons with energies above \( \sim 6 \times 10^{19} \) eV, which travel farther than \( \sim 50 \) Mpc.

The graph shows the effect on the energy of extragalactic particles as a function of the distance from the source. Details of the curve depend on the assumptions on the magnetic fields in the intergalactic medium.

It can be seen that one expects a certain maximum energy at a distance that is far enough from the source. This would lead to an effective cut-off of the spectrum of ultra-high energy cosmic rays.

This effect has been named after the theorists who found it (independently): Greisen, Zatsepin and Kuzmin. First evidence for its existence at ultra-high energies comes from the High-Resolution Fly's Eye Experiment (see Chapter 6).
Some Detector Types in High Energy (Astro)physics

Gas-filled detectors
- proportional and Geiger counters
- wire chambers, drift chambers
- time projection chamber
- spark chambers

Solid state detectors
- semiconductor devices (e.g. CCD)
- scintillation detectors
- crystal detectors
- Cherenkov detectors (see Chap. 2)
- transition detectors (see Chap. 2)

“I wish you’d spend at least half as much time on our domestic spark chamber in the open fireplace!”
Proportional Counters & Geiger Counters (1)

Proportional Counters and Geiger-Müller Counters are based on the design of the ionisation chamber. The voltage applied to an Ionization Chamber is very low and serves just to collect the electron-ion pairs at the anode and cathode.

The voltage applied to a Proportional Counter is sufficiently high that the electron-ion pairs induced by the ionising particle or radiation generate secondary pairs. An avalanche of particles builds up. Its charge is proportional to the applied voltage; the proportional counter works as a charge amplifier. The total energy of the particle, X-ray or gamma-ray can be measured. Because of the short path length in gas, they are used mainly to detect X-rays with $0.1 \text{ keV} < E < 20 \text{ keV}$. 

Ionization Chambers, Proportional Counters and Geiger Counter detect charged particles by ionization and photons by photoabsorption.
If the voltage is raised above a certain limit, the device saturates and works now as a Geiger-Müller-Counter. A single electron-ion pair is now sufficient to ionize all the fill gas in the neighbourhood of the pair.

A primary avalanche builds up and excited gas atoms also give off UV photons to trigger secondary avalanches.

Depending on the design, X- and Gamma-rays are detected in interactions with the fill gas or indirectly by freeing electrons from the walls of the counter.

The fill gas is usually argon, neon or another inert gas of large Z. Additionally, a quenching gas in the Geiger counter (halogen or an organic gas) stops the flow of electrical current after a few microseconds. Ions collide with quench gas molecules and give up their energy by causing them to dissociate. Geiger counters are also used to count cosmic rays and radioactive emissions.
The generation of secondary ionizing particles (as in the proportional counter) is also seen in other ionization detectors. Electrons that are freed from their atoms by the primary particle and are energetic enough to ionize other particles are called \textit{delta rays} or \textit{knock-on electrons}.

The generation of delta rays in nuclear emulsions or solid-state ionization detectors make the determination of $dE/dx$ more difficult. The energy that goes into these electrons has to be taken properly into account.

Shown on the left is a "Picture from CERN 2-metre hydrogen bubble chamber exposed to a beam of negative kaons with energy 4.2 GeV. This piece corresponds to about 70 cm in the bubble chamber." (http://teachers.web.cern.ch) Several delta rays are created along the tracks of the kaons. The large spiral comes from a particularly energetic knock-on electron.
Wire Chambers and Drift Chambers replace today Bubble Chambers in High Energy Physics, due to their fast electronic read-out.

**Wire Chamber**
A chamber, similar to a Geiger-Müller tube, with many parallel wires arranged in a grid and connected to high voltage. The metal casing is on ground potential. Ionising particles generate electron-ion pairs in their trail, with the electrons moving to the nearest wires. This provides spatial resolution of the particle track.

**Multi Wire Proportional Chamber (MWPC)**
Improvement to the Wire Chamber: it is operated as a proportional counter and thus yields also information on the particle's energy. Applying a strong magnetic field allows to determine also the charge of the particle.

**Drift Chamber**
Additionally measures precisely the timing of the pulses from electrons and ions arriving at the wires. The distance at which the particle passed the wire can thus be inferred, which yields a greater accuracy of the particle track.
Mass spectrometers are used to measure the ratio of charge over mass of charged particles. In the example above, a mixture of different ions is accelerated to the same energy. The ion beam traverses then a magnetic field, where heavier ions are deflected more than lighter ions (with the same charge). A detector can then register ions of a certain mass (more exactly: a certain q/m).

Other mass spectrometers use electric instead of magnetic fields. There are many different designs.
The time of flight, i.e. the travel time of a particle can be used to measure its velocity and – if its energy is known – to measure its mass.

Different detector designs can be used. A very simple example is shown in the upper figure.

The design in the lower figure uses a reflector, made of electric fields. This way, the distance the particles travel can be increased while keeping the detector size compact. In addition, neutral particles will be filtered out of the beam.

Time of Flight detectors are often used in connection with other detectors, in particle physics and cosmic ray experiments.
The most sophisticated particle detector of the Wire Chamber type is a Time Projection Chamber. It provides track reconstruction and particle identification.

Ionising particles collide with gas atoms in the chamber and generate electron-ion pairs. The electrons drift to the two ends of the chamber following a strong electric field. The ions drift towards the central cathode.

A solenoidal magnetic field reduces diffusion of the electrons. The momentum of the primary particle is measured by deflection in the magnetic field.

At both ends of the chamber, two orthogonal MWPCs measure the position and energy of the electrons. The dE/dx of the primary particle can be measured with good precision and is used for particle identification.

A precise timing measurement of the electron/ion drift times together with the information from the MWPCs provides a 3D track reconstruction.
Historically, the Spark Chamber was used to visualise the path of cosmic rays:

- The chamber consists of a stack of metal (Al) plates and is filled with a gas. Ionising particles traverse the detector and generate electron-ion pairs in their path.

- Two scintillators at the top and bottom of the chamber, connected to photomultiplier tubes, register traversing particles. If they measure a coincidence, a high voltage is applied to the metal plates, which then discharge along the ionised path of the particle. A track of sparks (conducting plasma of ions and electrons) becomes visible.
Today, arrays of small "Spark Chambers" are used to detect the paths of $\gamma$-rays. Here, the "Spark Chambers" are just very small Geiger counter cells, often filled with neon gas. They are arranged in arrays and the arrays in layers. Incoming $\gamma$-rays are converted into electron-positron pairs, e.g. within a layer of tungsten. The electron and positron leave a track of triggered cells, where each triggered cell emits a spark that can be recorded.
When atoms in scintillators are excited by high energy particles, a part of the excitation energy is emitted as low energy (e.g. visible) photons. These photons can be measured to determine the energy deposited into the scintillator.

Primary cosmic rays can excite atoms directly, X-rays or gamma-rays interact via photoionisation, Compton effect or pair production in the scintillator, producing high energy electrons. These produce photons in the scintillator that can be detected with photomultiplier tubes.

Materials used are NaI or CsI, organic materials (also liquid!) or plastics.

Scintillators are often used in cosmic ray detectors, because they can be made compact and resistant. They are also used for X-ray detection at energies > 20 keV.
Semiconductors as Solid State Detectors

In semiconductors, the ionizing particles produce electron-hole pairs. The energy needed to produce these is much smaller than for electron-ion pairs in a gas (Si: 3.5 eV, Ge: 2.94 eV, gas: ~ 20 eV). Thus, about 10 times more pairs are produced in a solid detector by a particle of a certain energy => higher statistics => better resolution in dE/dx.

from www.tpub.com
Semiconductors are solids similar to insulators, but with smaller bandgaps and with less impurities. Their conductivity can be influenced with the application of electric fields or changes in temperature. Semiconductor devices, electronic components made of semiconductor materials, are essential in modern electrical devices, from computers to cellular phones to digital audio players.

"Semiconductors' intrinsic electrical properties are very often permanently modified by introducing impurities, in a process known as doping. Usually it is reasonable to approximate that each impurity atom adds one electron or one "hole" that may flow freely. Upon the addition of a sufficiently large proportion of dopants, semiconductors conduct electricity nearly as well as metals.

Depending on the kind of the impurity, a region of semiconductor can have more electrons or holes, and then it is called N-type or P-type semiconductor, respectively. " (wikipedia)
Semiconductors (2) – pn-junctions

Forward biasing the p-n junction drives holes to the junction from the p-type material and electrons to the junction from the n-type material. At the junction the electrons and holes combine so that a continuous current can be maintained.

The application of a reverse voltage to the p-n junction will cause a transient current to flow as both electrons and holes are pulled away from the junction. When the potential formed by the widened depletion layer equals the applied voltage, the current will cease except for the small thermal current.

(from http://hyperphysics.phy-astr.gsu.edu)
Reverse-biased pn-junctions of semiconductors can be used as photodiodes and particle detectors:

Semiconductors can be doped with impurities that cause either an increase of free electrons (n-type) or a decrease (= increase in free holes, p-type). The Fermi level is shifted towards the conduction level or the valence level.

When a p- and n-type semiconductor are joined, electrons can flow, if an electric field is applied from p to n, but not in the reverse case.

In reverse-bias, electrons and holes at the connection recombine and a depletion region is built up of positive and negative ions. No current flows.

Only if a photon or ionizing particle generates an electron-hole pair in the depletion region, a current can flow (electron flows in n direction, hole in p-direction). Thus an incident photon or particle can be detected.

Use in cosmic ray telescopes, CCDs…
Charge Coupled Devices (CCD) (1)

CCDs are widely used imaging detectors for photons with wavelength < 1.1 µm (Silicon bandgap 1.12 eV).

Recording with a three-phase CCD:

CCD chips are integrated circuits on silicon wavers

Each channel (pixel) carries 3 read-out electrodes. The central electrode has a positive voltage relative to the others.

Photons excite electrons into the conduction band. The electrons accumulate under the positive electrode (potential well), while the holes are swept into the substrate.
Read-out of a three-phase CCD:

At the end of the integration time, the accumulated charge is being read out.

By sequentially shifting the positive voltage from electrode to electrode, the charge of each channel is moved to an amplifier and read out.

**Advantages:**

High quantum efficiency and large dynamic range.

**Background:**

- « Dark current », i.e. thermal excitation of electrons into the conduction band. -> Cooling of CCDs helps (~ -100°)
- Electronic noise during read-out from the amplifier.
- Cosmic rays.

more info (in French):