

Basics of Gaseous Detectors

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MC-PAD 16 - 18 March 2011

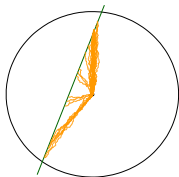
Overview

The detectors discussed in today's workshop rely essentially on the same principles:

- a charged particle (or a photon) ionizes gas atoms/molecules along its track,
- an electric field transports electrons (and ions) towards electrodes,
- electrons are multiplied in a strong electric field,
- the motion of electrons and ions induces a current on the readout electrodes.

Overview

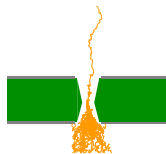
- drift tube



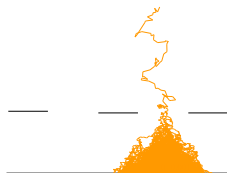
- RPC



- GEM



- Micromegas/InGrid



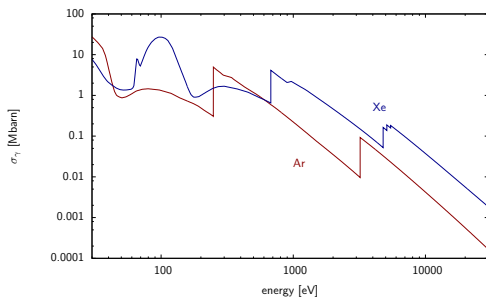
Aside: Gas Choice

- The examples on the following slides focus on argon, which is a commonly used detection gas.
- Why?
 - third most common gas in the atmosphere (0.93%), cheap
 - inert, not toxic
 - more detailed motivation → later
- Typically, a "quenching gas" (e. g. CH_4 or CO_2) is added for stability.



Photo-Ionization

The (photo-electric) interaction of a photon with a gas molecule is described by the photoabsorption cross-section σ_γ .



Example: 5.9 keV γ in Ar

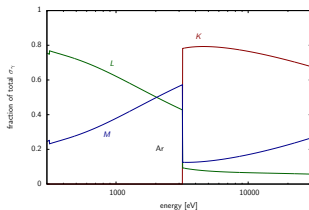
- $\sigma_\gamma \approx 0.019$ Mbarn
- attenuation length at RT, $p = 1$ atm:
 $\lambda \approx 2$ cm

B. L. Henke et al.,

At. Data Nucl. Data Tables **54** (1993), 181-342

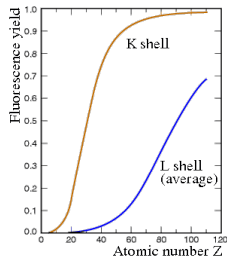
Photo-Ionization

Ionization of core shells is followed by atomic relaxation processes.

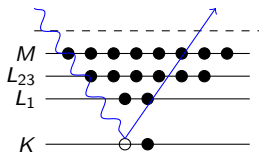


D. A. Verner et al.,

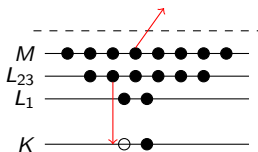
At. Data Nucl. Data Tables 55 (1993), 233-280



● K shell ionization



● Auger effect



● fluorescence

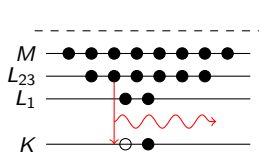
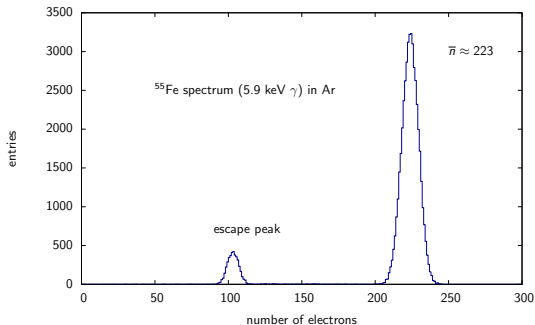


Photo-Ionization

The emerging δ electrons (i. e. photoelectrons and Auger electrons) ionize and excite gas atoms along their path \rightarrow secondary electrons



Calculation: Heed + Magboltz

W Value and Fano Factor

- mean number of electrons

$$\bar{n} = \frac{E_\gamma}{W}$$

- variance

$$\sigma^2 = F\bar{n}$$

W value and Fano factor F are determined by the partitioning of ionizing collisions vs. excitations in the photoelectron degradation process.

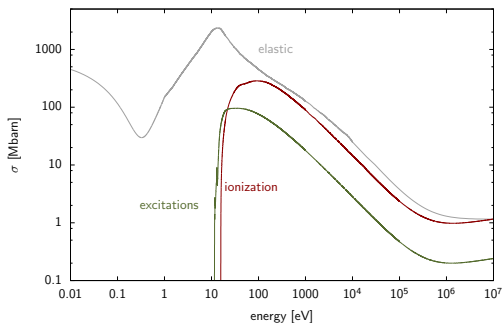
- photons/electrons at \gtrsim keV energies:

Gas	W [eV]	F
Ne	35.4	0.13 - 0.17
Ar	26.4	0.16
Xe	22.1	0.17
CO ₂	33.0	0.32
CH ₄	27.3	0.26 - 0.29

ICRU Technical Report 31 (1979)
IAEA TECDOC 799 (1995)

Aside: Excitation and Ionization

- cross-sections for scattering of electrons by Ar atoms (from Magboltz)



Ionization by Charged Particles

Charged particle interaction with the gas is described by the differential cross-section $d\sigma/dE$, where E is the energy transfer in a collision.

- average number of collisions per cm (cluster density)

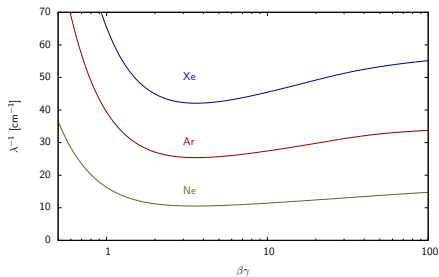
$$\lambda^{-1} = N \int_0^{E_{\max}} dE \frac{d\sigma}{dE}$$

- average energy loss per cm (stopping power)

$$\frac{dE}{dx} = N \int_0^{E_{\max}} dE \frac{d\sigma}{dE} E$$

Cluster Density

- cluster density at $T = 20^\circ \text{C}$,
 $p = 1 \text{ atm}$:



Calculation: Heed

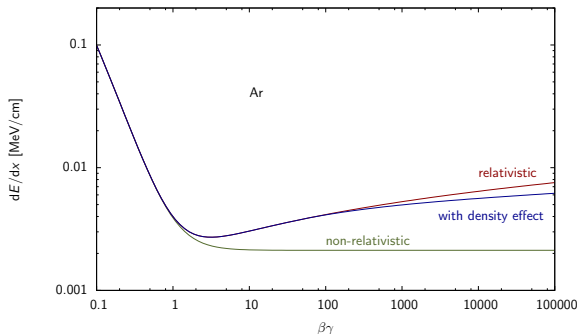
- minimum ionizing electrons:

Gas	$\lambda^{-1} [\text{cm}^{-1}]$
Ne	11
Ar	23
Xe	43
CO ₂	34
CH ₄	25

F. Rieke and W. Prepejchal,
Phys. Rev. A **6** (1972), 1507-1519

Stopping Power

- Bethe-Bloch formula

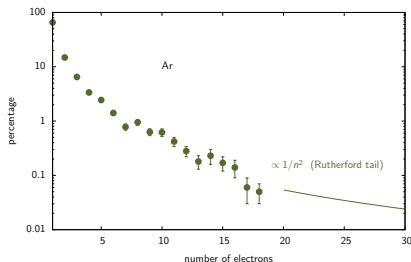


$$\frac{dE}{dx} = -\frac{4\pi z^2 e^4}{mc^2} NZ \frac{1}{\beta^2} \left[\ln \frac{2mc^2 \beta^2 \gamma^2}{I} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right].$$

Energy Loss Fluctuations

Fluctuations in the ionization process:

- number of collisions over a distance \rightarrow Poisson distribution,
- number of electrons produced in a single collision \rightarrow cluster size distribution



H. Fischle et al.

Nucl. Instr. Meth. A **301** (1991), 202-214

Dielectric Theory of Energy Loss

Classical approach:

- moving charged particle (velocity βc) polarizes the medium (characterized by complex dielectric function ϵ)
- the resulting electric field \mathbf{E} slows down the particle

$$\frac{dE}{dx} = q\mathbf{E} \cdot \frac{\beta}{\beta}$$

- Fourier transform

$$\frac{dE}{dx} = -\frac{2q^2}{\beta^2\pi} \int d\omega \int dk \left[\omega k \left(\beta^2 - \frac{\omega^2}{k^2 c^2} \right) \operatorname{Im} \left(\frac{1}{-k^2 c^2 + \epsilon(k, \omega) \omega^2} \right) + \frac{\omega}{kc^2} \operatorname{Im} \left(\frac{-1}{\epsilon(k, \omega)} \right) \right]$$

Reinterpretation in quantum picture:

collisions with energy transfer $E = \hbar\omega$ and momentum transfer $\hbar k \rightarrow$ exchange of virtual photons

Photoabsorption-Ionization Model

Model for $\varepsilon(k, \omega)$

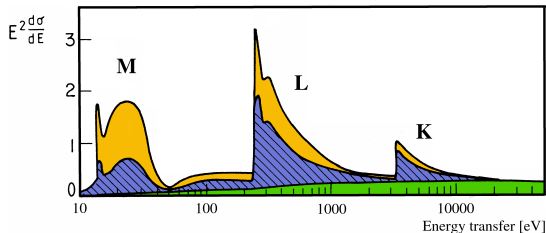
- small momentum transfer: use optical data, $\varepsilon'' \approx (N\hbar c/E) \sigma_\gamma$
- large k : scattering by free electrons

$$\begin{aligned} \frac{\beta^2 \pi \hbar c}{z^2 \alpha_f} N \frac{d\sigma}{dE} &= \text{Im} \left(\frac{-1}{\varepsilon(E)} \right) \ln \frac{2m\beta^2 c^2}{E} \\ &+ \text{Im} \left(\frac{-1}{\varepsilon(E)} \right) \ln \frac{1}{|1 - \beta^2 \varepsilon(E)|} \\ &+ \left(\beta^2 - \frac{\varepsilon'(E)}{|\varepsilon(E)|^2} \right) \left(\frac{\pi}{2} - \arctan \frac{1 - \beta^2 \varepsilon'(E)}{\beta^2 \varepsilon''(E)} \right) \\ &+ \frac{1}{E^2} \int_0^E dE' \text{Im} \left(\frac{-1}{\varepsilon(E')} \right) E' \end{aligned}$$

W. W. M. Allison and J. H. Cobb,
Ann. Rev. Nucl. Part. Sci. **30** (1980), 253-293

Photoabsorption-Ionization Model

$$\begin{aligned}
 \frac{\beta^2 \pi \hbar c}{z^2 \alpha_f} N \frac{d\sigma}{dE} &= \text{Im} \left(\frac{-1}{\varepsilon(E)} \right) \ln \frac{2m\beta^2 c^2}{E} \\
 &+ \text{Im} \left(\frac{-1}{\varepsilon(E)} \right) \ln \frac{1}{|1 - \beta^2 \varepsilon(E)|} \\
 &+ \left(\beta^2 - \frac{\varepsilon'(E)}{|\varepsilon(E)|^2} \right) \left(\frac{\pi}{2} - \arctan \frac{1 - \beta^2 \varepsilon'(E)}{\beta^2 \varepsilon''(E)} \right) \\
 &+ \frac{1}{E^2} \int_0^E dE' \text{Im} \left(\frac{-1}{\varepsilon(E')} \right) E'
 \end{aligned}$$



Implementations:

- Heed
- G4PAIModel

Energy Loss Fluctuations

- Number of ionization electrons over 1 cm Ar

