Ramsauer approach to the aerosol phase function in the Pierre Auger Observatory

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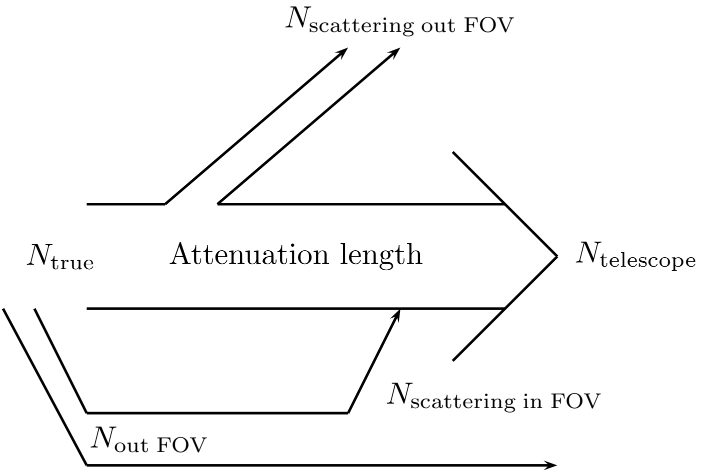
Multiple scattering and shower energy estimation



$$N_{\text{true}} = N_{\text{telescope}} + N_{\text{scattering out FOV}} - N_{\text{scattering in FOV}}$$

Outline

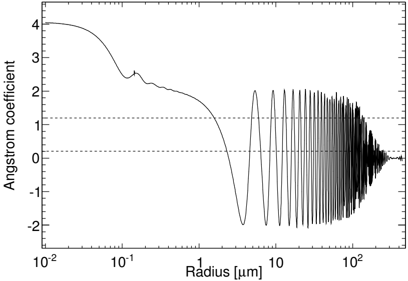
1. An atmospheric phase function based on the Ramsauer approach
   - Light scattering by particles
   - Solution from the Ramsauer effect
2. Application to the Pierre Auger Observatory
   - Parametrization of the aerosol phase function
   - On a possible problem at small scattering angles
3. Conclusions

Light scattering by (spherical) particles

Rayleigh scattering: $R \ll \lambda$

$\Rightarrow$ Molecular

- total cross section: $\sigma_{\rm tot} \propto \lambda^{-4}$,
- phase function: $P_{\rm Ray}(\theta) \propto 1 + \cos^2\theta$.



Mie scattering: $R \geq \lambda$

$\Rightarrow$ Aerosols (for instance, sand during a sandstorm)

- total cross section: $\sigma_{\rm tot} \propto \lambda^{-\gamma}$, with $\gamma = 0.7 \pm 0.5$,
- phase function $P_{\rm Mie}(\theta)$ from typical parametrizations or tabulated.

Mie framework

σ_{tot} depends on (wavelength λ, radius R, relative refractive index n)

$$\frac{\sigma_{\mathrm{tot}}}{\pi R^2} \simeq \frac{2}{x^2} \sum_{\ell=1}^{N} (2\ell + 1)\, \mathrm{Re}(a_\ell + b_\ell)$$

where $x = kR$ and $y = nx$

$$a_\ell = \frac{x\psi_\ell(x)\psi'_\ell(y) - y\psi'_\ell(x)\psi_\ell(y)}{x\zeta_\ell(x)\zeta'_\ell(y) - y\zeta'_\ell(x)\zeta_\ell(y)} \qquad b_\ell = \frac{y\psi_\ell(x)\psi'_\ell(y) - x\psi'_\ell(x)\psi_\ell(y)}{y\zeta_\ell(x)\zeta'_\ell(y) - x\zeta'_\ell(x)\zeta_\ell(y)}$$

$$\psi_\ell(z) = z j_\ell(z) \qquad \zeta_\ell(z) = z j_\ell(z) - \mathrm{i} z y_\ell(z)$$

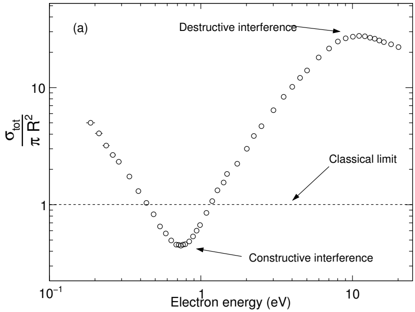
Bohren criterion: $N = x + 4x^{1/3} + 2$

$(\lambda = 0.4\ \mu m,\ R = 50\ \mu m) \longrightarrow N = 824$

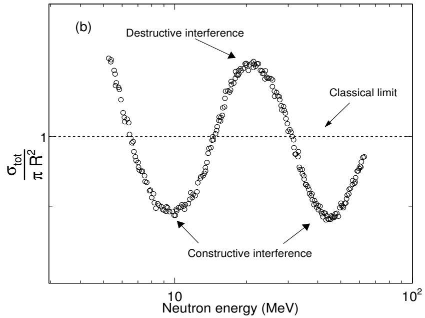
The Ramsauer effect

- discovered in 1921 while studying scattering of electron over Argon atoms,
- several years before the Bohr's idea.

Electron on Krypton atom

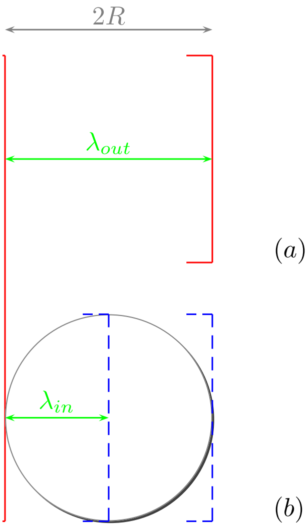


Neutron on Lead nucleus



Description of the Ramsauer effect

- Idea: one part of the wave goes through the target and another does not,
- recombination behind the target
  $\rightarrow$ interference.



Ramsauer solutions

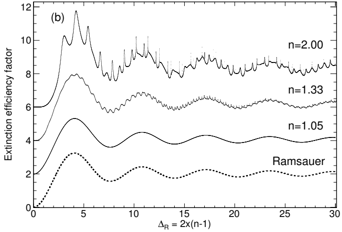
- total cross section

$$\sigma_{\rm tot} = 2\pi R^2 \left[1 - 2\,\frac{\sin[2(n-1)kR]}{2(n-1)kR} + \left(\frac{\sin[(n-1)kR]}{(n-1)kR}\right)^2\right]$$

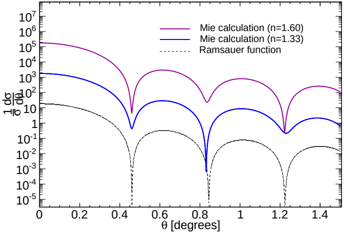
- phase function

$$P_{\rm Ramsauer}(\theta) = \frac{1}{\sigma}\frac{d\sigma}{d\theta} = \frac{1}{4\pi}\left[kR\,\frac{1+\cos\theta}{2}\,\frac{2J_1(kR\sin\theta)}{kR\sin\theta}\right]^2$$

Total cross section



Independent of the refractive index

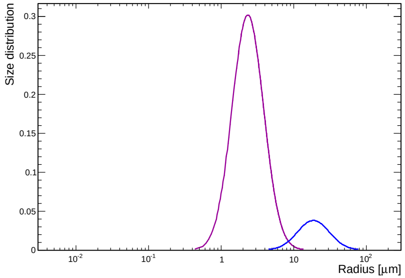


K Louedec, S Dagoret and M Urban, Phys. Scr. **80** *(2009) 035403*

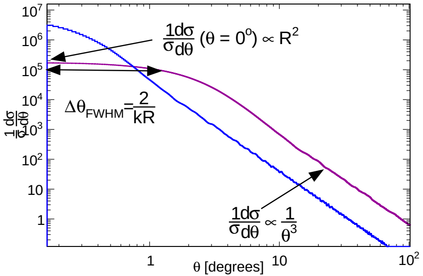
Aerosol size distribution

$$n(R \mid \bar{R}, \sigma) = \frac{\mathrm{d}N(R)}{\mathrm{d}R} = \frac{N}{\sqrt{2\pi}\,\log\sigma}\,\frac{1}{R}\exp\left(-\frac{\log^2(R/\bar{R})}{2\,\log^2\sigma}\right)$$

Aerosol size distributions

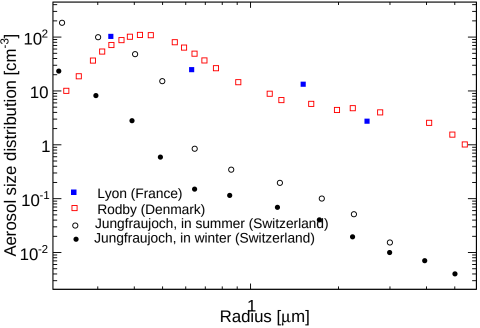


Ramsauer phase functions



Typical radius $\bar{R} \nearrow \Longrightarrow$ forward scattering $\nearrow$

Different kinds of aerosols in the atmosphere



Measurements at different locations

- depends on the location,
- depends on the season.

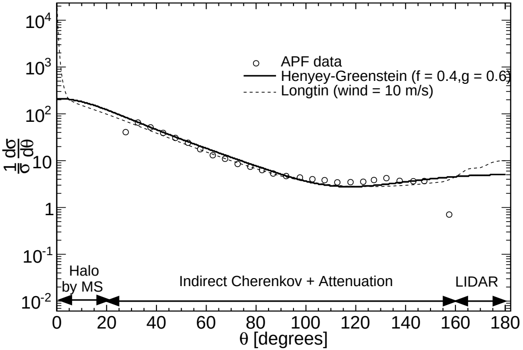
Usually, 3 kinds of aerosols

- $0.01\ \mu m \leq R \leq 0.1\ \mu m$: the "aitken" mode,
- $0.1\ \mu m \leq R \leq 1.0\ \mu m$: the "accumulation" mode,
- $R \geq 1.0\ \mu m$: the "coarse" mode (lifetime hours to days).

Outline

Measurements by the APF in Auger

- the Henyey-Greenstein parametrization: $P_{\mathrm{HG}}(\theta \mid g = \langle \cos\theta \rangle, f)$
  Auger $\rightarrow$ ($f = 0.4$, $g = 0.6$)
- the Longtin's desert model (tabulated phase function)
  Auger $\rightarrow$ wind $= 10\ m/s$



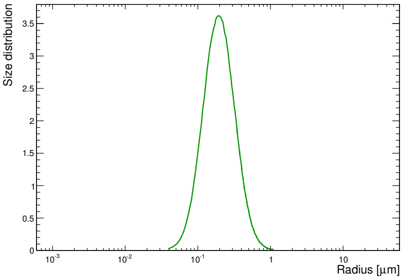
APF measurements uniquely between 24^{o} and 150^{o}

Uncertainty at small and large scattering angles

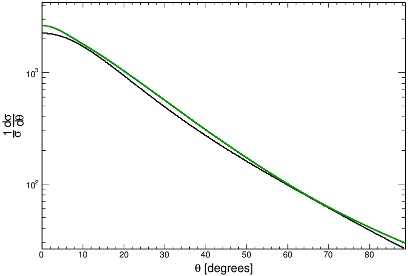
S Benzvi et al, Astroparticle Physics **28** *(2007) 312-320*

The Henyey-Greenstein phase function

Aerosol size distribution



Ramsauer phase function

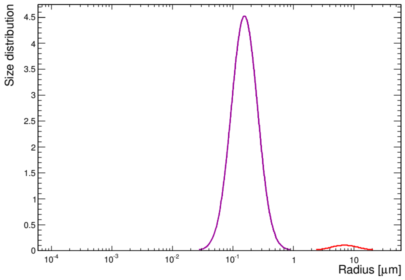


One aerosol population

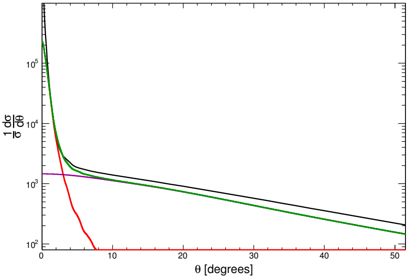
$$(\bar{R}_1 = 0.25\ \mu m, \log\sigma_1 = 1/2)$$

The Longtin phase function

Aerosol size distributions



Ramsauer phase functions



Two aerosol populations

$(\bar{R}_1 = 0.25\ \mu m, \log\sigma_1 = 1/2)$, at 85%

$(\bar{R}_2 = 9\ \mu m, \log\sigma_2 = 1/2)$, at 15%

Outline

Summary

- the Ramsauer approach is a powerful tool to describe scattering phenomena,
- the aerosol size distribution in Auger is not known *yet*.

Measurements of aerosol size on-site in Malargüe are made since the last year