Atmospheric fluorescence

Fernando Arqueros
Universidad Complutense de Madrid

Outline

- Introduction
  - Features of air-fluorescence radiation
  - The fluorescence technique for the detection of UHECR
- The atmospheric fluorescence
  - Molecular excitation by electron impact
  - Radiative and collisional de-excitation
  - Dependence on atmospheric parameters
- The fluorescence yield
  - Definitions
  - The effect of secondary electrons
- Experimental techniques and results
- In Summary ..

Introduction

Cosmic Rays – Atmospheric Fluorescence
What do they have to do?

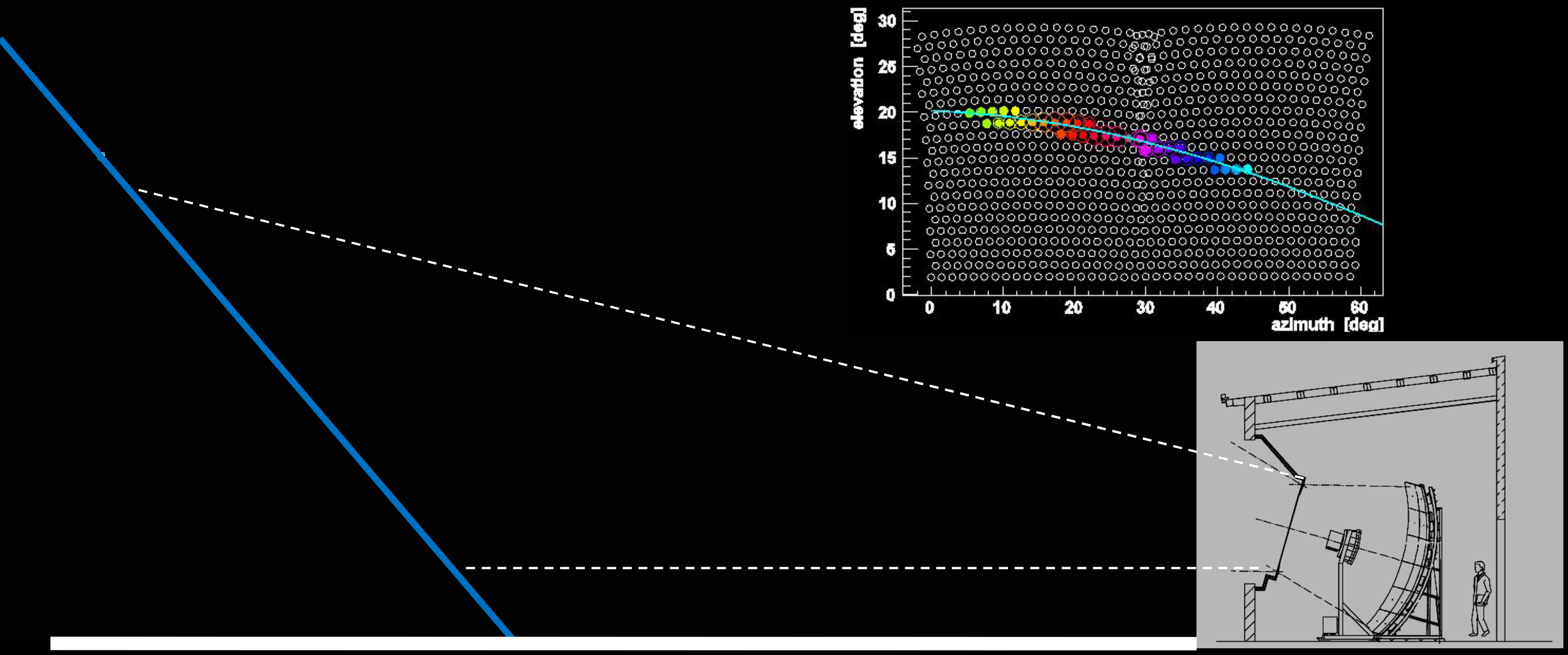
- An ultra-high energy cosmic ray ($>10^{18}$eV) generates a shower in the atmosphere containing a large number of charged particles, mainly electrons.
- Electrons lose energy by collision with atmospheric molecules. A very small fraction of these collisions excite/ionize nitrogen molecules to some specific levels which de-excite giving rise to UV light.
- Appropriate telescopes can detect this fluorescence light.

HiRes, Auger, TA, ASHRA, JEM-EUSO, OWL

Features of the air-fluorescence radiation

- Near UV (300 – 400 nm).
- Emitted isotropically.
- Illustratively a 10^{20} eV shower $\equiv$ a 100 W light bulb moving at the speed of light.

Detection of air showers using the fluorescence technique



Fluorescence telescopes “see” the UV light emitted by N_2 molecules excited by shower electrons

Measure of the EM energy of an air-shower using the fluorescence technique

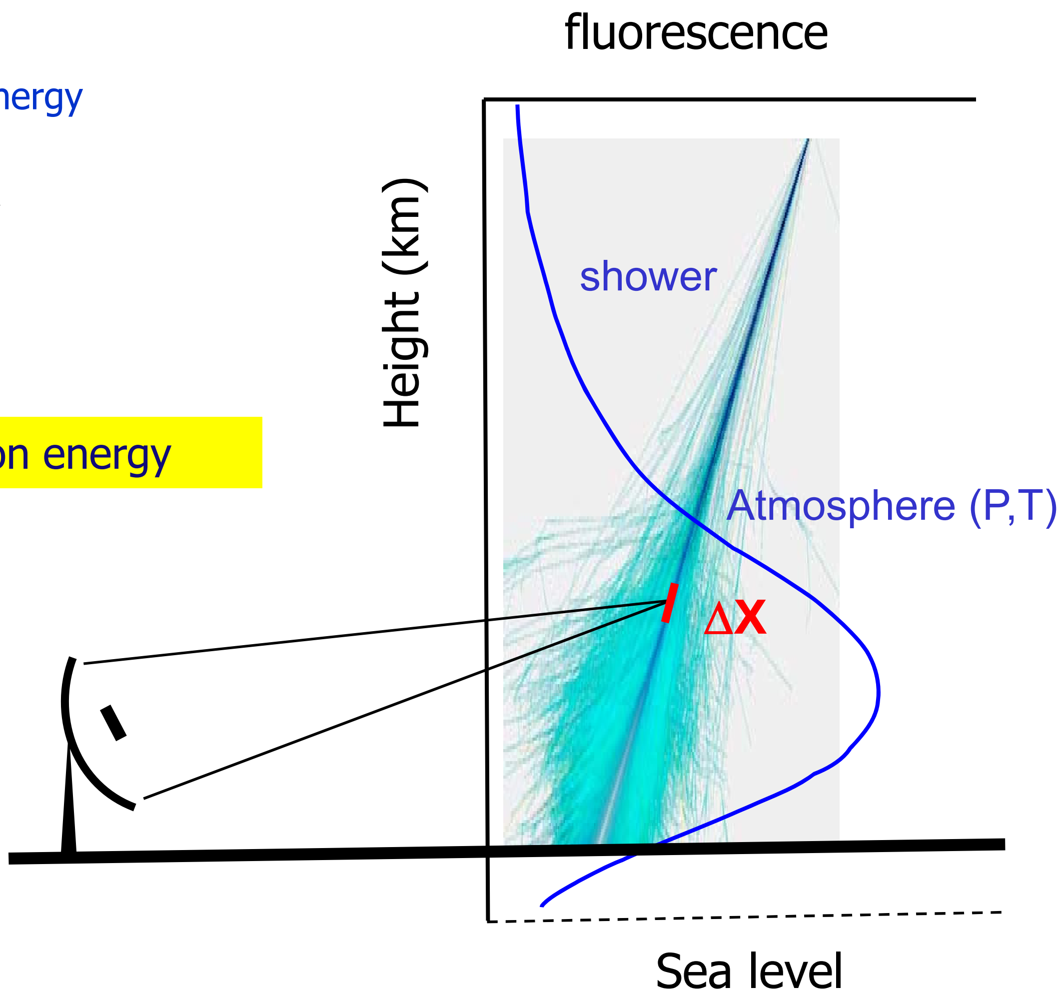
Fluorescence photons — Deposited energy

$$\frac{dN_\gamma}{dX} = Y(P,T,h)\ \frac{dE_{dep}}{dX}$$

Fluorescence yield (photons / MeV)

Assumption: FY independent on electron energy

$$E_{dep} = \int dX \frac{1}{Y(P,T,h)} \frac{dN_\gamma}{dX}$$



$Y(P, T, h)$ is measured in lab experiments

International effort to increase the accuracy of the fluorescence yield

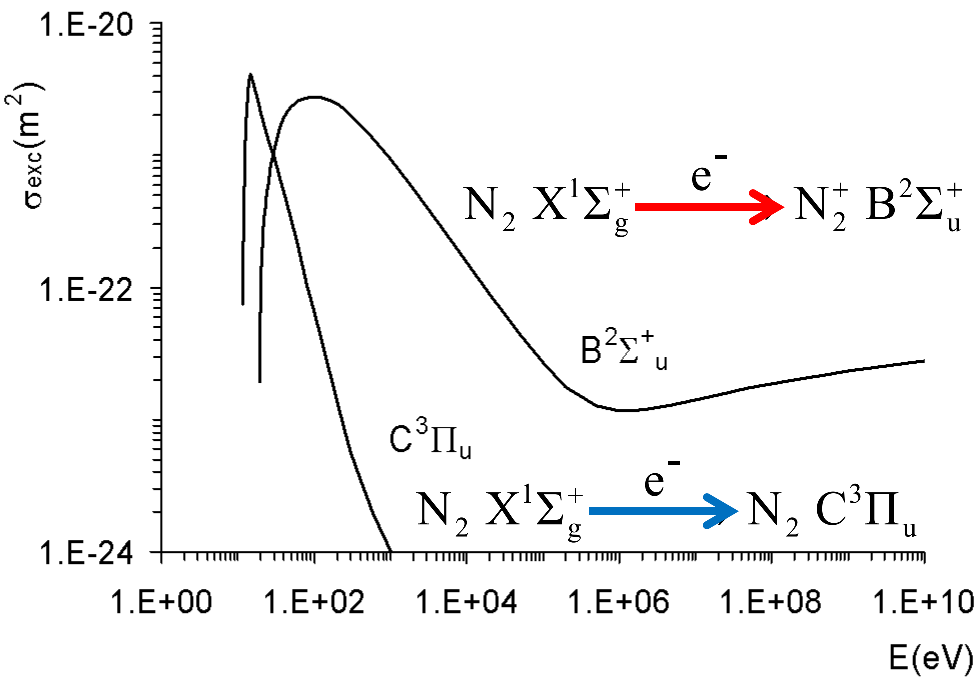
5th Fluorescence Workshop, El Escorial, Madrid – September 2007

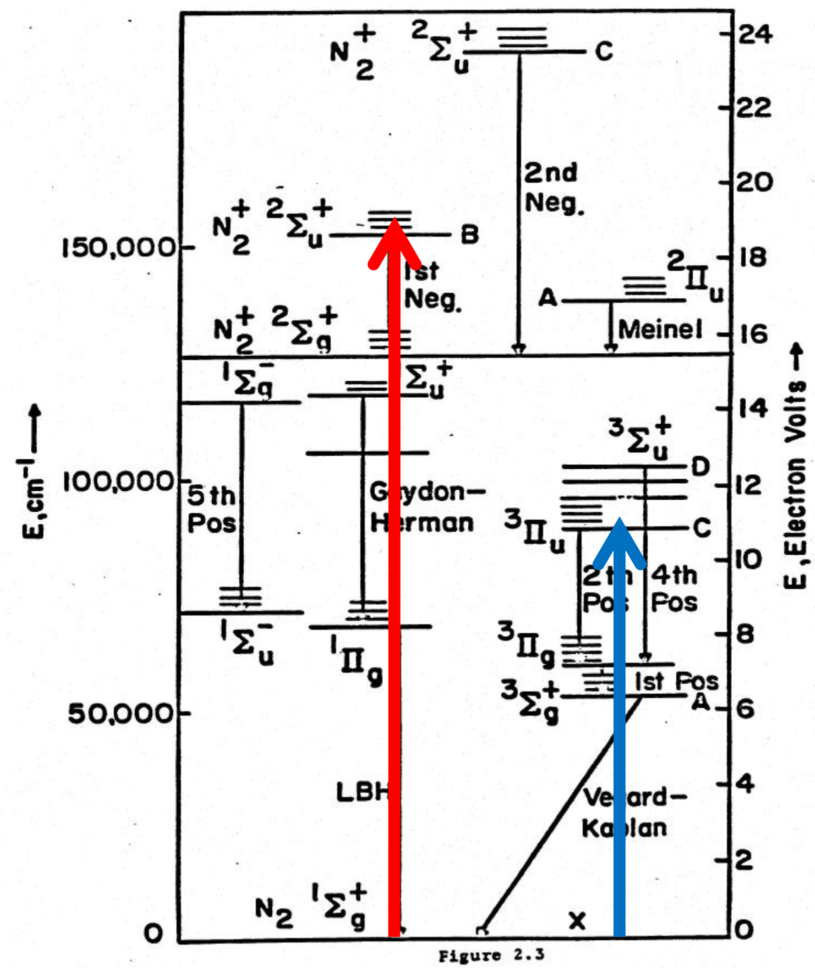
http://top.gae.ucm.es/5th_FW/

- Proceedings to be appear in Nucl. Instr. Methods A
- A summary of the workshop is already available at arXiv:0807.3844

Generation of air-fluorescence

Molecular excitation by electron impact



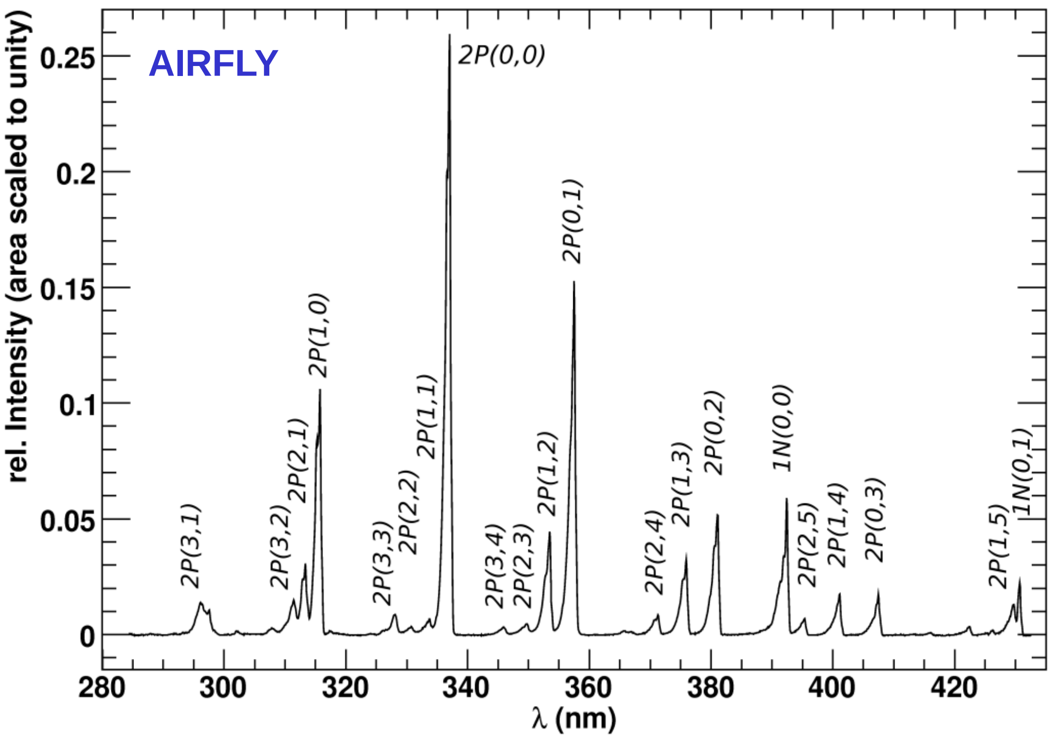


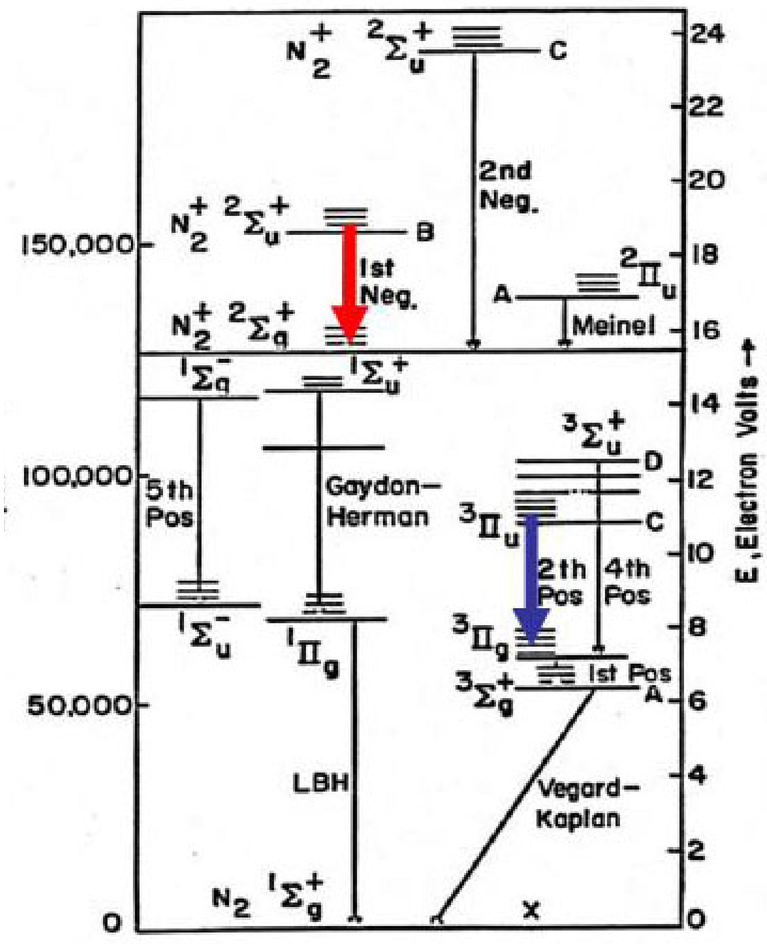
Excitation of $C^3\Pi_u$ molecular state is mainly performed by electron with very low energy

Radiative de-excitation

First Negative System (1N) $N_2^+\left(B^2\Sigma_u^+ \rightarrow X^2\Sigma_g^+\right)$

Second Positive System (2P) $N_2\left(C^3\Pi_u \rightarrow B^3\Pi_g\right)$





Radiative de-excitation

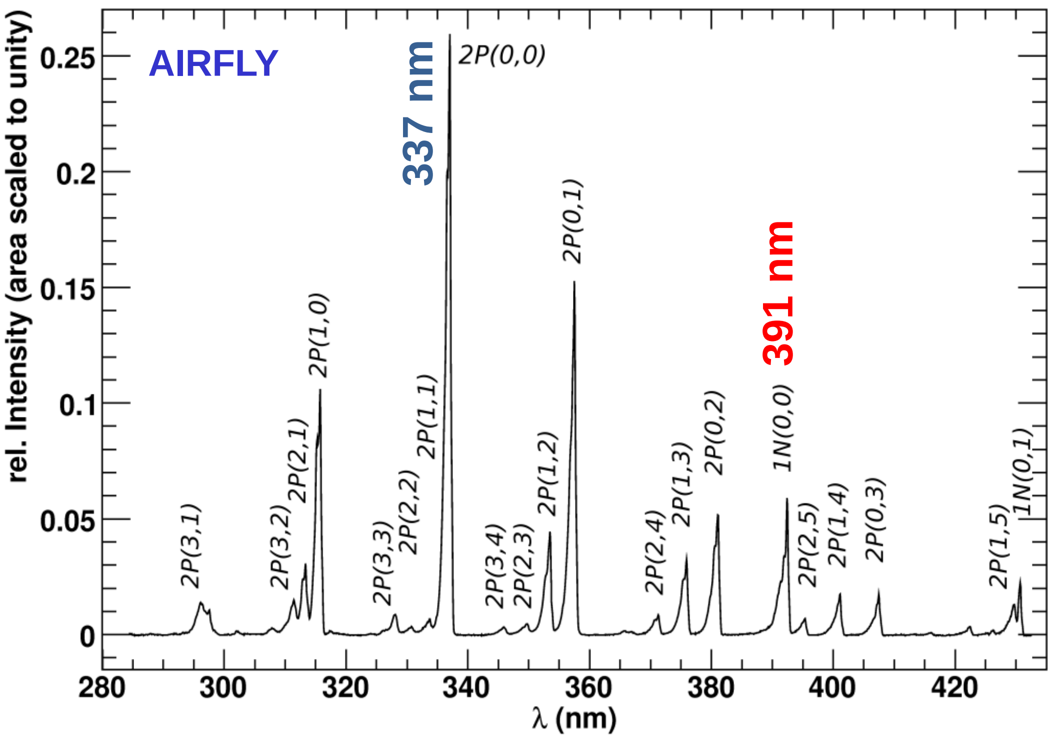
First Negative System (1N) $N_2^+\left(B^2\Sigma_u^+ \rightarrow X^2\Sigma_g^+\right)$

Second Positive System (2P) $N_2\left(C^3\Pi_u \rightarrow B^3\Pi_g\right)$

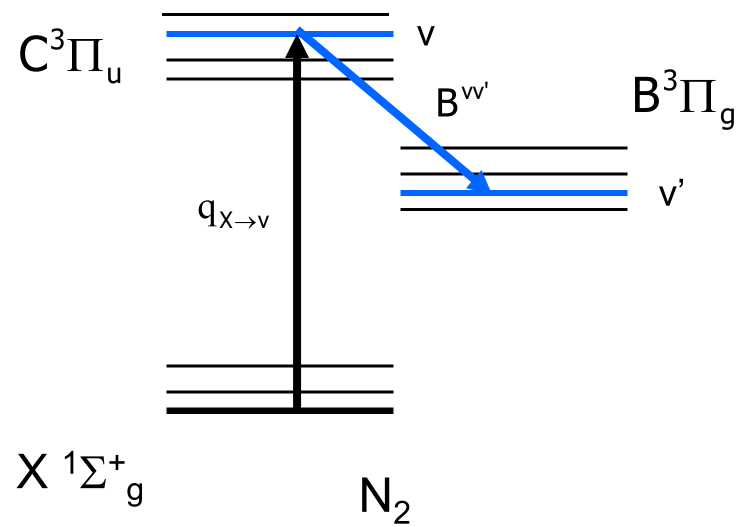
Relative intensities / Transition probabilities

$$\frac{I_{vv'}}{I_{v0}} = \frac{q_{X\rightarrow v}}{q_{X\rightarrow 0}} \frac{B^{vv'}}{B^{00}}$$

Franck-Condon factors



Band v-v' of the 2P system



Dependence on atmospheric parameters

Pressure dependence - Collisional de-excitation (quenching)

Excited nitrogen molecules may de-excite by collision with other molecules in the environment.

P' characteristic pressure

P = P' $\Rightarrow$ collisional rate = radiative rate

$$I_{vv'}(P) \propto \frac{P}{1+\frac{P}{P'_v}}$$

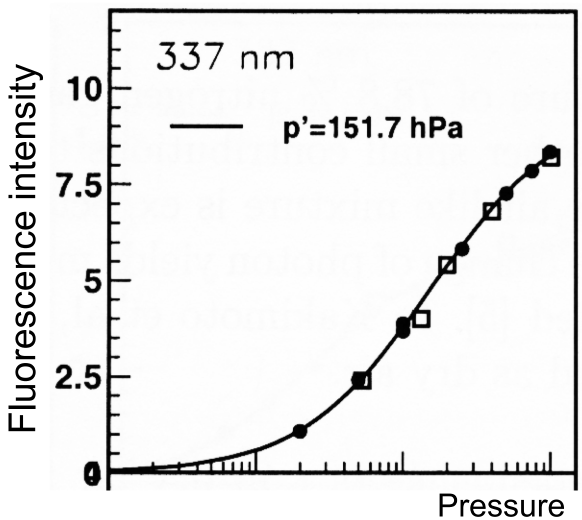
$$\frac{1}{P'} = \sum_i \frac{f_i}{P'_i}; \quad P'_i = \frac{kT}{\tau_r}\frac{1}{\sigma_{Ni}\bar{v}_{Ni}}$$

Air components N_2, O_2, H_2O, Ar..

lifetime

Collisional cross section

Relative velocity



Nagano et al. (2004)

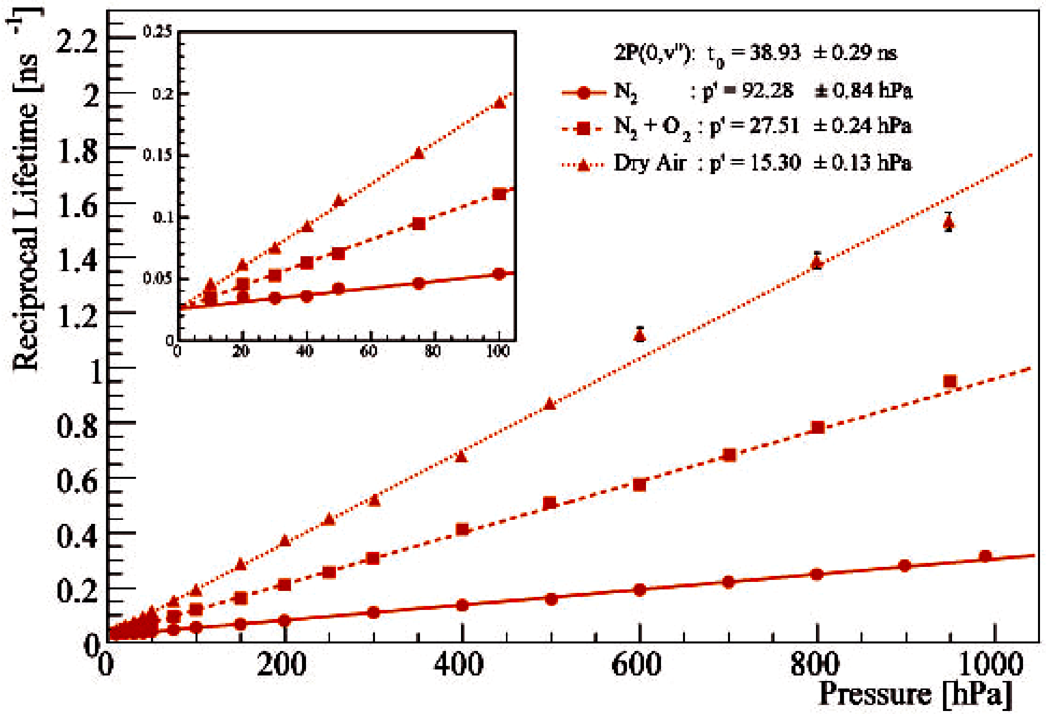
At high pressure P >> P' fluorescence intensity is nearly P independent

Fluorescence Intensity vs pressure provides a measure of P'

Apparent Lifetime

AIRLIGHT (5th FW, El Escorial 2007)

$$\frac{1}{\tau(P)} = \frac{1}{\tau_r}\left(1 + \frac{P}{P'}\right)$$



radiative lifetime $\tau_r \approx$
40 ns (2P)
60 ns (1N)

Lifetime of the population decreases with pressure
P' can be measured from $1/\tau$ versus P

Temperature dependence

$$\frac{1}{P'} = \sum_i \frac{f_i}{P'_i}; \quad P_i' = \frac{kT}{\tau_r} \frac{1}{\sigma_{Ni} \bar{v}_{Ni}}$$

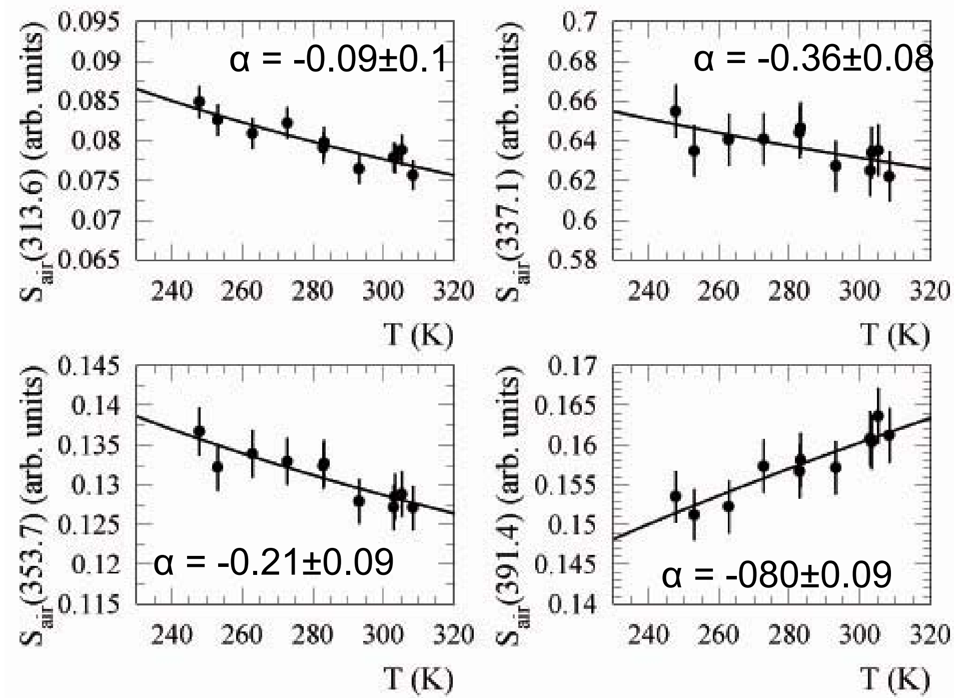
$$\bar{v}_{Ni} = \sqrt{\frac{8kT}{\pi\mu}}$$

Relative velocity grows with √T

$$\sigma_{Ni} \propto T^{\alpha}$$

Quenching cross section depends on the velocity of the colliders

AIRFLY (5th FW, El Escorial 2007)



$$\frac{1}{I} \propto 1 + b' T^{\alpha + \frac{1}{2}}$$ at constant density

Effect of humidity

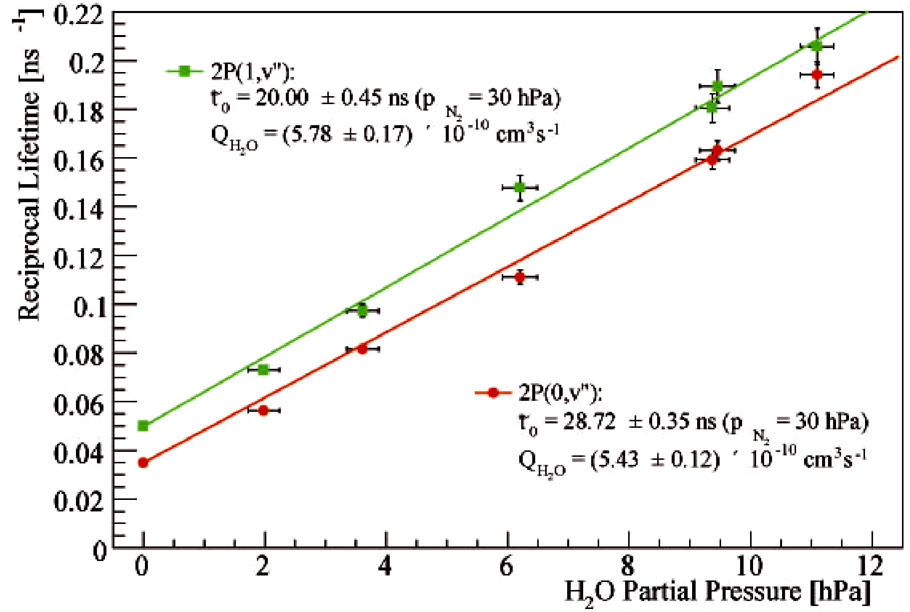
$$\frac{1}{P'} = \sum_i \frac{f_i}{P'_i};$$

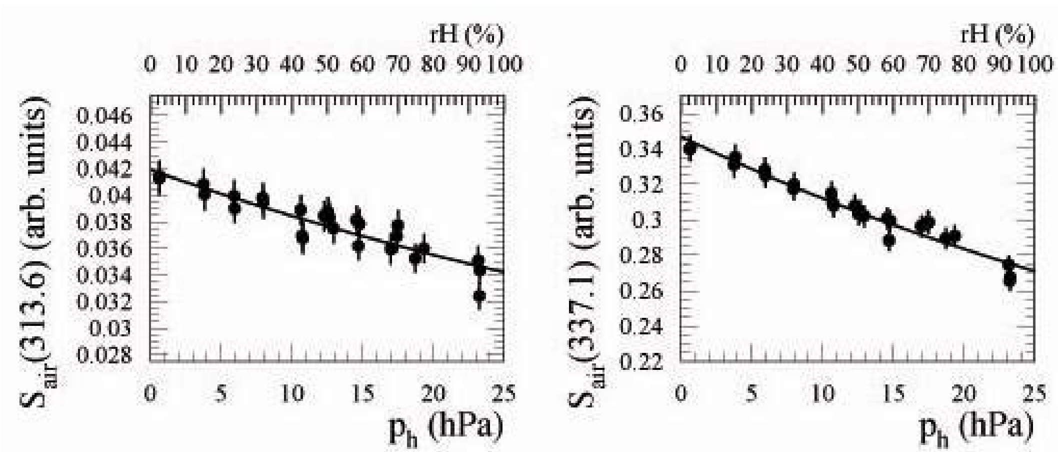
Air components
N_2, O_2, **H_2O**, Ar..

Partial pressure of H_2O

$$\frac{1}{P'_{hum}} = \frac{1}{P'_{dry}}\left(1 - \frac{P_w}{P}\right) + \frac{P_w}{P}\frac{1}{P'_w}$$

AIRLIGHT (5th FW, El Escorial 2007)





AIRFLY (5th FW, El Escorial 2007)

The fluorescence yield

The fluorescence yield - Definitions

$\varepsilon_{vv'}$ [m^{-1}] Number of photons per unit electron path legth.

$$\frac{\varepsilon_{vv'}}{\rho} = \frac{A_{vv'}}{1 + P / P'_v}$$

Number of photons per unit column density (i.e. per gcm^{-2})

$A_{vv'} = \varepsilon_{vv'}/\rho$ in the absence of collisional quenching

Both $\varepsilon_{vv'}$ and $Y_{vv'}$ are measured in the laboratory

$Y_{vv'}$ [Mev^{-1}] Number of photons per unit deposited energy.

More useful for calorimetric applications

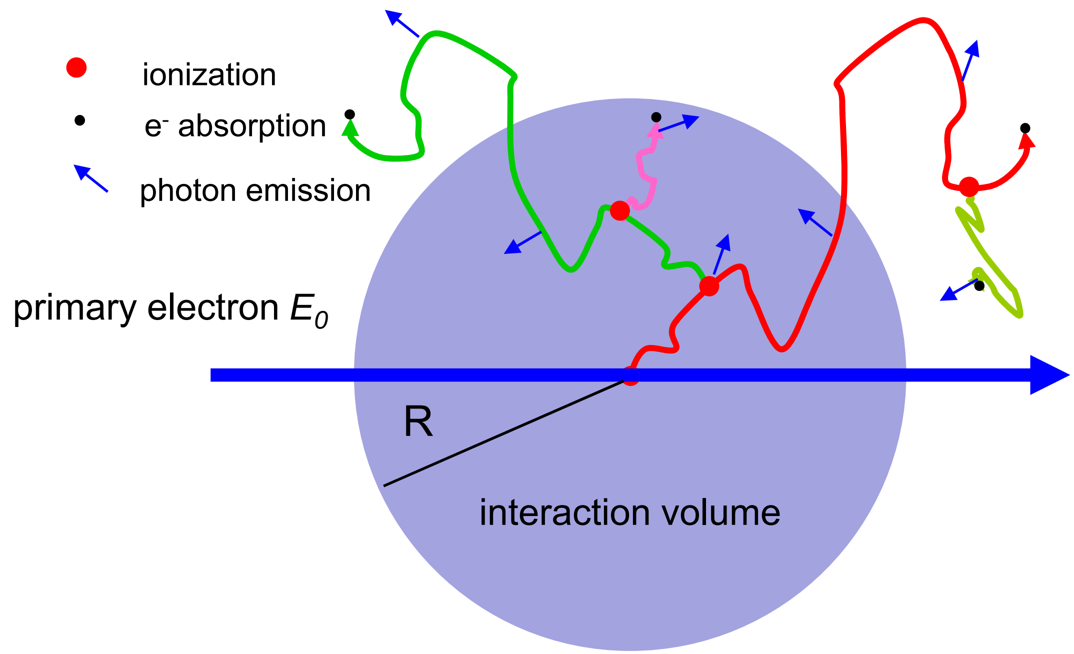
$$\frac{\mathrm{d}N_{ph}}{\mathrm{d}X} = Y(P,T,h)\frac{\mathrm{d}E_{dep}}{\mathrm{d}X}$$

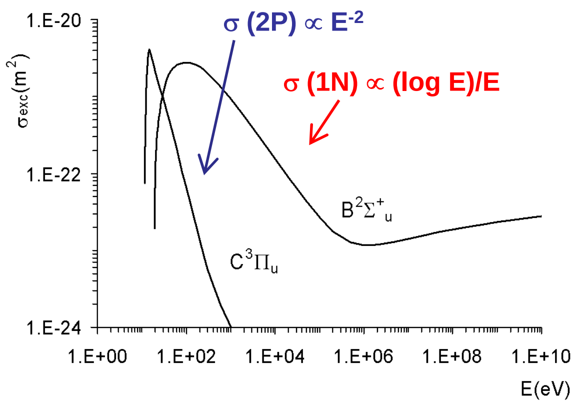
$$Y_{vv'} = \frac{Y^0_{vv'}}{1 + P / P'_v}$$

Relationship between $Y_{vv'}$ and $\varepsilon_{vv'}$

$$Y_{vv'} = \frac{\varepsilon_{vv}}{(\mathrm{d}E / \mathrm{d}x)_{\mathrm{dep}}}$$

Secondary electrons





Fluorescence is mainly produced by secondary electrons ejected in ionization processes

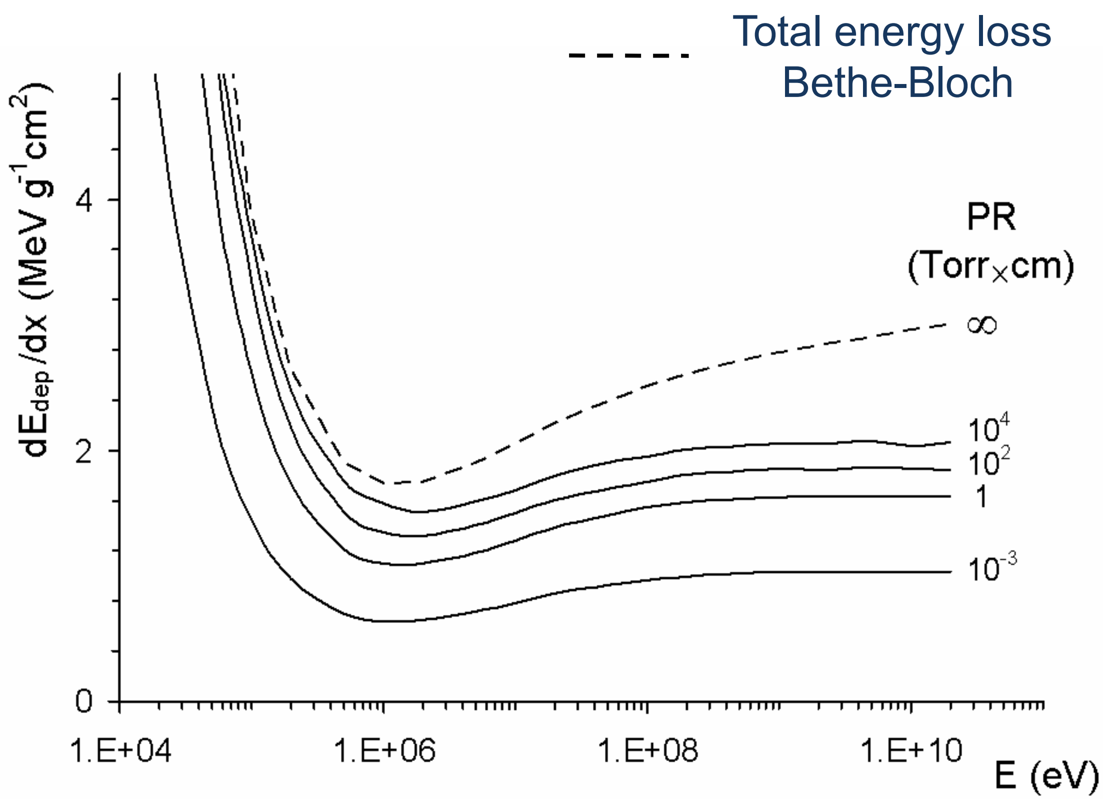
Both fluorescence and deposited energy must be measured/computed in the same volume

Very important in lab experiments. Fluorescence from small volumes

ε [photons/m] vs. Y [photons/MeV]

$$Y_{vv'} = \frac{\varepsilon_{vv}}{\left(\frac{dE}{dx}\right)_{dep}}$$

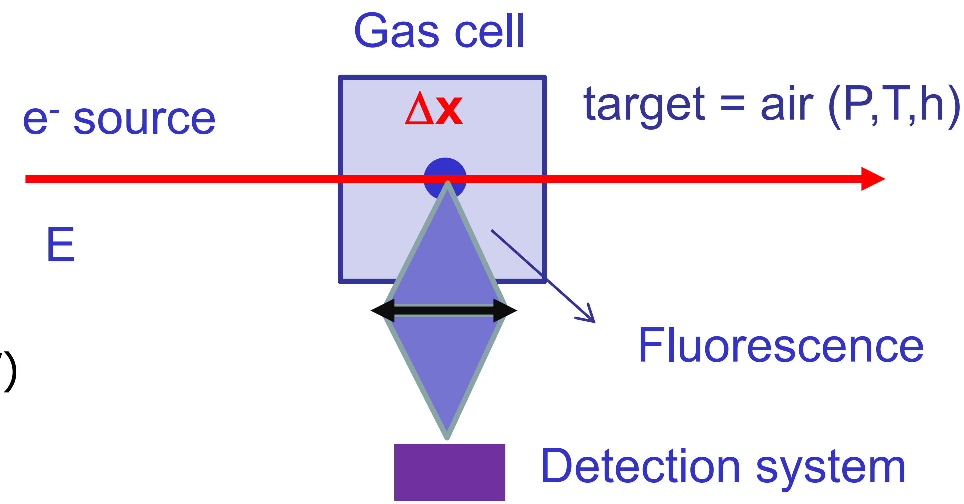
Energy deposited per unit path length



Deposited energy is not equal to the energy loss for small volumes

Experimental techniques and some results

Experimental techniques



- Electron beam
  - accelerators (keV – GeV)
  - radioactive sources ^{90}Sr (MeV)
  - low energy beams (keV)

- Fluorescence measurement
  - Monochromators, filters
  - Photon counting: PMTs, HPDs

Relationship between $Y_{vv'}$ and $\varepsilon_{vv'}$

- Gas properties: P, T, h, …

- Absolute calibration: number of photons, number of electrons, deposited energy
  - Y [MeV^{-1}] or $\varepsilon_{vv'}$ [m^{-1}]
  - Narrow (v-v') or wide spectral wavelength (e.g. 300 – 400 nm)

Fluorescence yield versus electron energy

Assumption: Fluorescence yield is independent on electron energy,

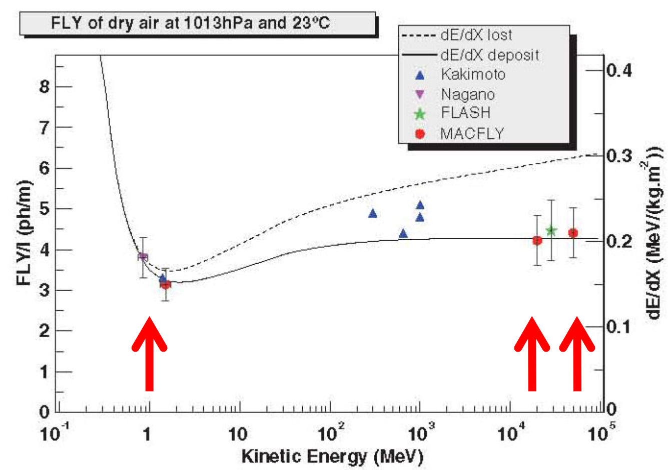
Theoretical demonstration using a MC simulation which follow electrons down to a few eVs

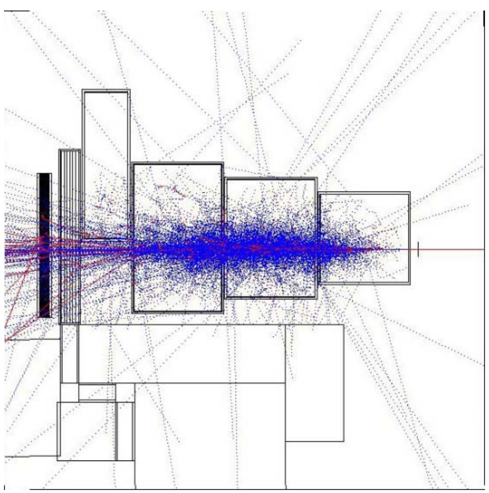
AIRFLY (5th FW, El Escorial 2007)

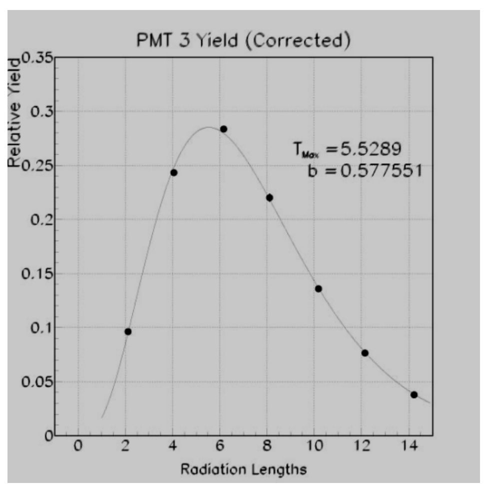
APS	6 – 30 keV
Argonne Wakefield Accelerator +	
Van de Graaff	0.5 – 15 MeV
BTF Frascati	50 – 420 MeV

Proportionality (± 5%) inside E intervals.
Relative calibration

MACFLY Astropart. Phys. (2007)

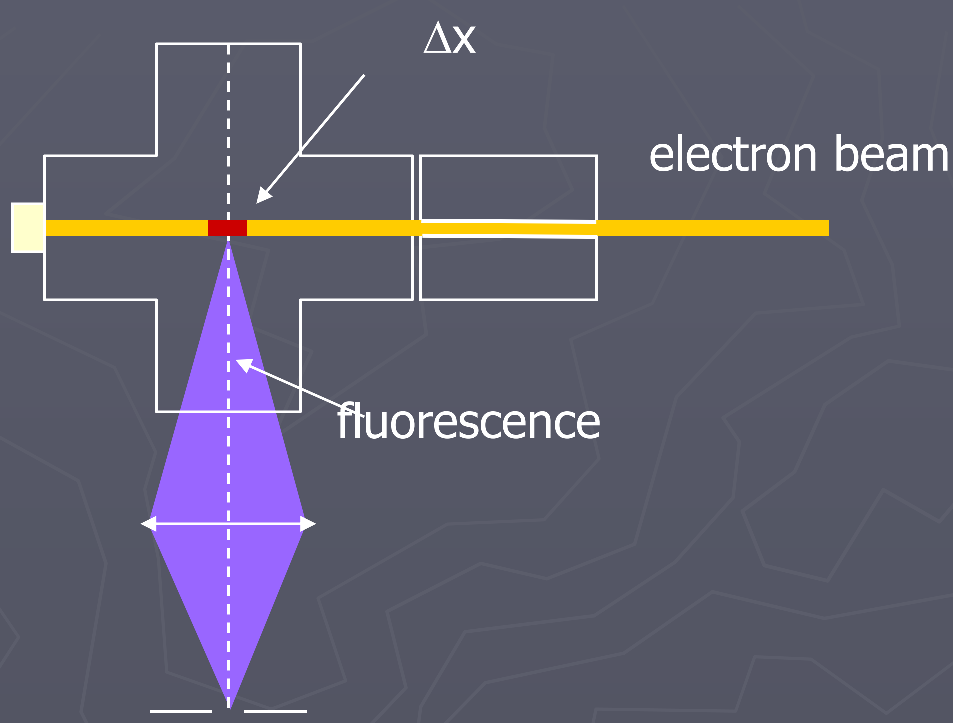




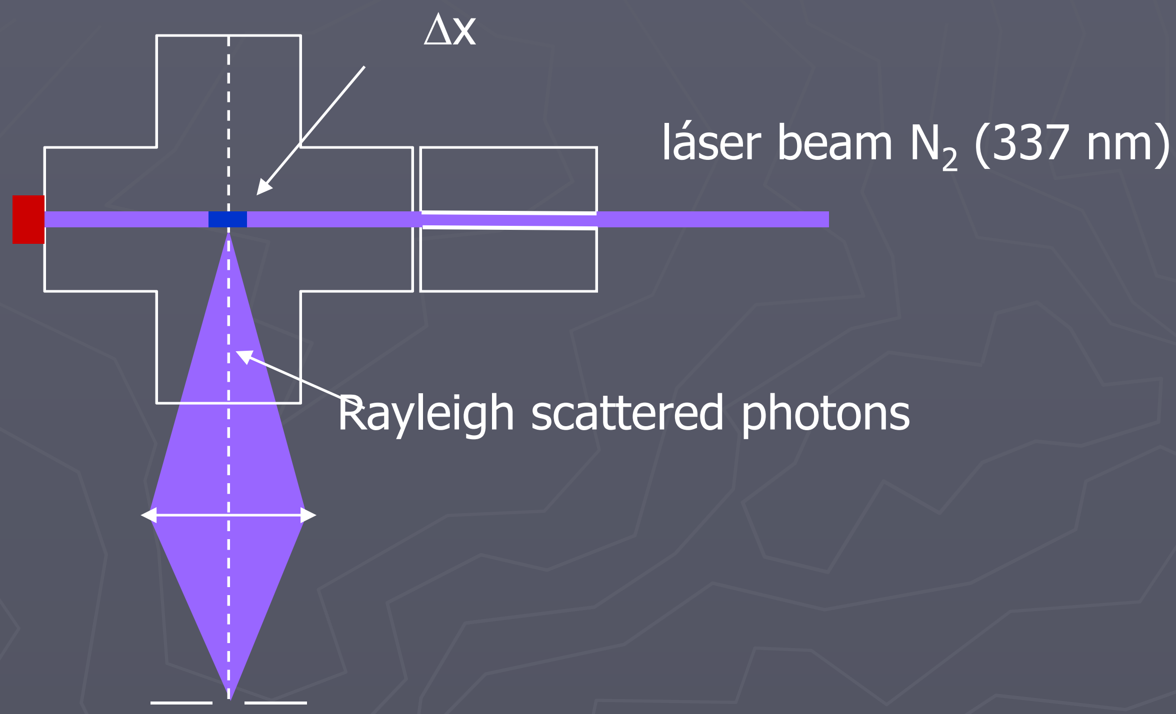


FLASH (THICK TARGET)
Astropart. Phys. (2006)
5th FW, El Escorial 2007

Absolute calibration with Rayleigh scattering



Absolute calibration with Rayleigh scattering



Absolute value of the Fluorescence Yield

Experiment	E [MeV]	337 nm		Wide spectrum	
		m^{-1}	MeV^{-1}	m^{-1}	MeV^{-1}
AIRFLY (prel.)	350		4.12		
FLASH	2.85×10^{4}				20.8
MACFLY	$1.5 - 5.0\times10^{4}$				17.6
Nagano et al.	0.85	1.02	5.03	3.81	
Lefeuvre et al.	0.85			4.23	
AIRLIGHT	0.25 – 2.0		5.68		
Kakimoto	$1.4 - 10^{3}$		5.7		

In summary

- Detection of air fluorescence provides a very useful tool for UHECRs detection.
  - Calorimetric measurement of the primary energy.
- The processes leading to the generation of fluorescence are well known.
  - The role of secondary electrons is very important
- Fundamental assumption: Fluorescence intensity proportional to deposited energy.
  - Theoretical and experimental tests.
- Accurate measurements of the dependence of the fluorescence yield on atmospheric parameters are being carried out. P’(T, h).
- Absolute measurements with uncertainties below 10% are being published.
  - Some disagreements.

More experimental results needed.

Detailed information:

5th Fluorescence Workshop, El Escorial, Madrid – September 2007
http://top.gae.ucm.es/5th_FW/

- Proceedings to be appear in Nucl. Instr. Methods A
- A summary of the workshop is already available at arXiv:0807.3844