Fluorescence yields by electron in moist air and its application to the observation of ultra high energy cosmic rays from space

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Abstract: In order to explore the ultra high energy cosmic rays above 10^{20} eV (UHECRs), huge detection area is crucial. In the near future, UHECRs will be observed from space in projects such as JEM-EUSO, to cover huge area, and fluorescent and Cherenkov light will be detected from extensive air showers (EASs) induced by UHECRs. Since those space-based experiments will observe most of EASs above sea, it is necessary to take the effect of humidity into account to obtain their longitudinal developments from the fluorescence yields along their trajectories. We have measured humidity dependence of life time and of fluorescence yields in air fluorescence for 10 lines between 300nm and 430nm with Sr90 source. The fluorescence yields decreased with higher humidity: for example, ∼20% decrease was observed for ∼100% relative humidity at 1000hPa. The reference pressures determined from the fluorescence yields and the life time were consistent with each other for each line. If our results are applied to the UHECR observation from space above sea, fluorescence yields will be reduced about 25% near the sea surface at low latitude in summer of US standard atmosphere 1966. Most of the observed EASs by JEM-EUSO will be inclined (the typical zenith angle is 60 deg.), so that the shower maximum will be far from the sea surface. Therefore, the decrease of the yield by humidity at shower maximum might be small but not negligible.

Keywords: Fluorescence yields, Extensive air shower, Ultra high energy cosmic ray, JEM-EUSO

1 Introduction

Ultra high energy cosmic ray enters the atmosphere and induces a cascade shower. The main component is electrons, which excite nitrogen and produces fluorescence photons in near ultra-violet region. So called air fluorescence method was proposed in 1960's to observe UHECRs. The fluorescence yields are nearly proportional to the deposited energy in the atmosphere. This method has been used by experiments such as Fly's eye[1], High resolution fly's eye (HiRes)[2], Pierre Auger Observatory (Auger)[3] and Telescope array experiment (TA)[4]. It will be also used in future experiments from space like TUS[5], JEM-EUSO[6], KLYPVE[7], S-EUSO[8]. The principle of the air fluorescence method is simple, however, it is not straightforward when we apply it to the real measurement. Because we need to understand a lot of factors, such as the fluorescence yields in various atmospheric conditions, atmospheric transmittance, systematics of the detector and so on. Above all, the knowledge of the fluorescence yields is fundamental.

We have started the measurement of the fluorescence yields in dry air and published the results[9, 10], because the experiments on ground so far have been performed in dry area like a desert. However, an observation from a satellite orbit will be main stream in the future because a huge exposure is required for the UHECR observation. Therefore, most of showers will be observed above sea and the fluorescence yield in moist air must be examined.

2 Fluorescence yields in moist air

When an electron passes through air, an excited state of N_2 or N_2^+ will be produced and then fluorescence photons will be emitted with a certain probability. The fluorescence yields (ϵ_i) for wavelength (i) per unit length by an electron is expressed as a function of pressure p:

$$\epsilon_i(p) = \rho \frac{\mathrm{d}E}{\mathrm{d}x} \left(\frac{1}{h\nu_i} \right) \cdot \varphi_i(p) \,, \tag{1}$$

where ρ is the gas density, $h\nu_i$ is the photon energy, $\mathrm{d}E/\mathrm{d}x$ is the total energy loss of the electron. $\varphi_i(p)$ is the fraction of the energy emitted as photons to total energy loss[11]. Hereafter we omit the suffix i sometimes.

The reciprocal of the lifetime τ consists of three terms.

$$\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_q} + \frac{1}{\tau_c} \equiv \frac{1}{\tau_0} + \frac{1}{\tau_c} \,, \tag{2}$$

where τ_r is the lifetime of transition with radiation from an excited state to a lower state, τ_q is that of internal quenching (internal conversion plus inter-system crossing) and τ_c is that of collision de-excitation. The reciprocal of τ_c is expressed by

$$\frac{1}{\tau_c} = p\sigma\sqrt{\frac{8}{\pi\mu k_B T}}\,, \tag{3}$$

where σ is the cross-section of collision de-excitation between molecules, k_B is the Boltzmann constant, T is temperature, and μ is the reduced mass of the two molecules. Here, the reference pressure, p', is defined as the pressure when τ_c equals to τ_0 and

$$\frac{1}{p'} = \tau_0\sigma\sqrt{\frac{8}{\pi\mu k_B T}}\,. \tag{4}$$

Let us consider the effect of water vapor. Then p' is related to τ_0 with

$$\begin{aligned}\frac{1}{p'} &= (f_\mathrm{n}q_\mathrm{nn} + f_\mathrm{o}q_\mathrm{no} + f_\mathrm{w}q_\mathrm{nw})\tau_o \\ &= \left(1 - \frac{p_\mathrm{w}}{p}\right)\frac{1}{p'_\mathrm{dryair}} + \frac{p_\mathrm{w}}{p}\frac{1}{p'_\mathrm{H2O}},\end{aligned} \tag{5}$$

where f_n,f_o and f_w are proportional to partial pressures of N_2, O_2 and H_2O, respectively and normalized to $f_n + f_o + f_w = 1$. q_nn, q_no and q_nw are the quenching rate constants of the collisional de-excitation between N_2^* (or N_2^{+*}) and N_2, O_2 and H_2O, respectively. p_w is water vapor pressure. p'_dryair and p'_H2O are the reference pressures for dry air and water vapor, respectively.

Then the lifetime and the fluorescence yield for each wavelength band are expressed with p' as

$$\frac{1}{\tau} = \frac{1}{\tau_o}\left(1 + \frac{p}{p'}\right), \quad \text{and} \tag{6}$$

$$\epsilon(p) = \frac{Cf_n p}{1 + \frac{p}{p'}}\,, \tag{7}$$

where

$$C = \frac{1}{R_g T}\frac{\mathrm{d}E}{\mathrm{d}x}\left(\frac{1}{h\nu}\right)\cdot\varphi(0)\,. \tag{8}$$

$\varphi(0)$ corresponds to the fluorescence efficiency in the absence of collisional quenching[11] and R_g is the specific gas constant.

3 Experiment

A cubic chamber of 25 cm was used to keep air in various conditions[9, 10]. Decay electrons (0.85MeV on the average) from ^{90}Sr (74MBq) were collimated and the number of electrons which pass through the chamber was counted by a scintillation detector. Three 2” photomultiplier tubes (PMTs) selected for low noise were attached to three sides of the chamber to detect fluorescence photons through bandpass filters. The central wavelengths of the filters were 313, 325, 330, 337, 358, 370, 380, 391.4, 400 and 430 nm. The band widths were about 10 nm except the 391.4 nm filter with 5 nm width. The data were taken with the photon counting method. The charge of the signal from each PMT and the time difference between the electron signal and the photon signal were recorded for coincident events of an electron signal with signal from one of photon PMTs.

Air in the laboratory was taken into the chamber at various pressures between 1 hPa and 1000 hPa to determine the fluorescence yields in dry air. In order to study humidity dependence of the fluorescence yields, the total pressure was fixed at 30, 100 and 1000 hPa and the humidity was changed between 0% and 93% under the constant temperature around 20°C. In order to increase or decrease humidity, air was passed through water or silica gel. The humidity in the chamber was measured with two hygrometers, VAISALA HMP234 and Toplas TA502 which were confirmed to work also at lower pressure than 1 atmosphere by the manufacturers. Both hygrometers showed consistent humidity with each other during the measurement.

4 Results

Fluorescence yields per unit length per electron (ϵ) was derived with the following equation.

$$\epsilon = \frac{N_\gamma}{N_e l\eta f\Omega/4\pi(\mathrm{QE})(\mathrm{CE})}, \tag{9}$$

where N_γ is the number of detected photon signals, N_e the number of electron signals, η the transmission of the quartz window, f the transmission of the interference filter at the wavelength of the main nitrogen emission in study, Ω, QE and CE the solid angle, the quantum efficiency and the collection efficiency of the PMT, respectively, l the length of the fluorescence section. Fluorescence yields and lifetime at constant total gas pressure were measured and are shown in Figure 1 and Figure 2 respectively, as a function of water vapor pressure. Fluorescence yields and lifetime decrease with increasing water vapor pressure, because N_2 molecules are de-excited by collision with water molecules. These data are fitted by Eqs.(6) and (7), with the reference pressure in moist air expressed in Eq.(5), and then p'_H2O was determined. In this fitting process, p'_dryair was fixed to that determined from the dry air data[10]. p'_H2O derived from the yield data and the lifetime data are consistent with each other within 1-2 hPa.

Derived p'_H2O at $p = 30$ hPa for 10 lines are summarized in Figure 3. p'_H2O for 1N lines (391nm and 428nm) are about 0.4∼0.8 and are smaller than those for 2P lines, which are around 2-3 hPa. p'_H2O for 337nm and 358nm at total pressure 100 hPa and 1000 hPa were also determined. p'_H2O determined from the yield data at 30 hPa, 100 hPa and 1000 hPa are 1.36 hPa, 1.70 hPa and 1.66 hPa for 337 nm, and 1.23 hPa, 1.61 hPa and 1.27 hPa for 358 nm, respectively. Each error is 0.1-0.2 hPa. No significant pressure dependence of p'_H2O is observed. Our results are compared with those of AIRFLY[12], AIRLIGHT[13], Morozov *et al.* [14] and Pancheshnyi *et al.* [15, 16] in the same figure.

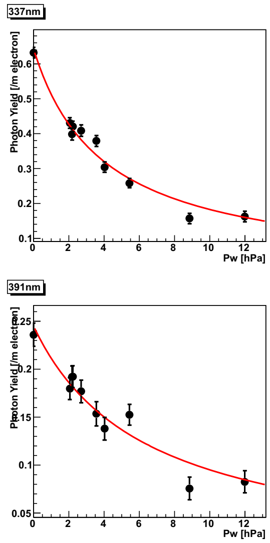

Figure 1: Fluorescence yields of 337nm, 358nm and 391nm lines as a function of water vapor pressure (p_{w}) at p =30 hPa. Solid lines show the best fit curves by Eq. (7).

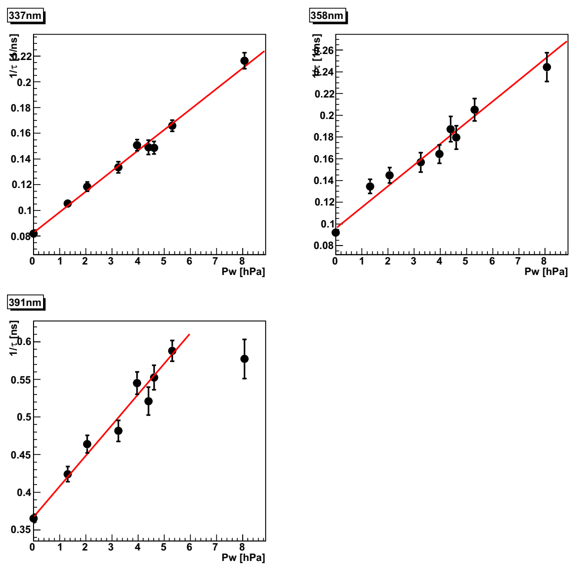

Figure 2: Reciprocal lifetime of 337nm, 358nm and 391nm lines as a function of water vapor pressure (p_{w})at p =30 hPa. Solid lines show the best fit curves by Eq. (6).

They are consistent one another, although the errors of our results are relatively large for some lines.

5 Application to UHECR fluorescence observation from space

US standard atmosphere 1976 model[17] (USstd76) has been used frequently in the field of UHECR observation. However there is only dry atmosphere model in the

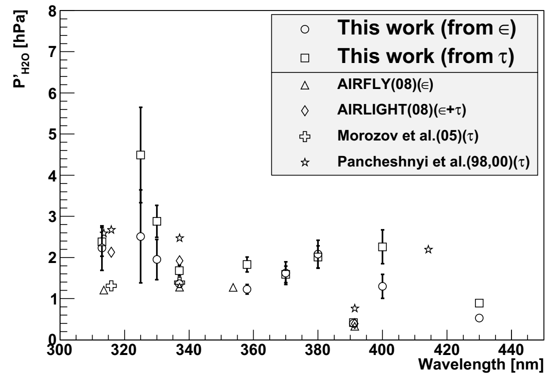

Figure 3: p'_{H2O} for 13 nitrogen lines. Our results are shown by circles (determined from the yield) and squares (from the lifetime). They are compared with those by AIRFLY[12] (triangles), AIRLIGHT[13](diamonds), Morozov *et al.* [14](crosses) and Pancheshnyi *et al.* [15, 16](stars).

USstd76. Therefore, we have used US standard atmosphere 1966 (USstd66) to see the humidity effect on fluorescence measurement from cosmic rays. Figure 4 shows water vapor pressure profile as a function of altitude. In winter at high latitude, water vapor pressure is relatively small, however, it increases up to 30 hPa, which corresponds to 80% relative humidity, in summer at low latitude.

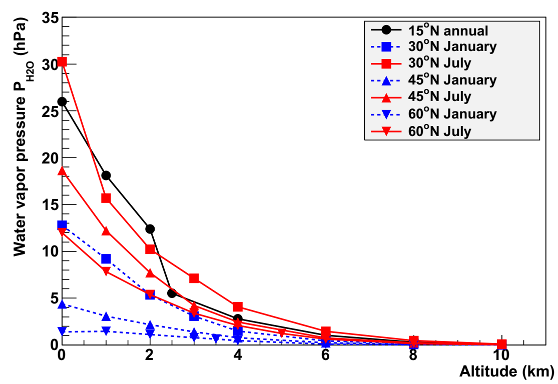

Figure 4: Water vapor pressure as a function of altitude from US standard atmosphere 1966 model. The data at 15°N are shown by solid circles, those at 30°N by solid squares, those at 45°N by solid triangles and those at 60°N by solid inverted triangles. January data are connected by dashed lines and July data are connected by solid lines.

Using not only the humidity data but also the temperature and pressure data of the USstd66 model, we have calculated expected total fluorescence yields between 300 and 430 nm as a function of altitude for winter and summer at four latitudes (15°N, 30°N, 45°N and 60°N). The fluorescence yields at each altitude was calculated with the following equation:

$$\epsilon = \left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)_{0.85\mathrm{MeV}} \sum \frac{\varphi(0)\rho}{h\nu(1+\rho R_g\sqrt{293T}/p'_{20})}, \quad (10)$$

where p'_{20} is the reference pressure at 20°C, and p' is defined by Eq.(5). Mean p'_{H2O} from the yield data and from the lifetime was used for each line. The yield for USstd76 model (dry air) is normalized to one. The decrease of the yield in summer at low latitude is about 25% at sea level (see Figure 5). In order to see the influence of the humidity in USstd66 model, the ratio for dry air is shown in the same figure for the 30N° July profile (labeled with "(humidity=0)" in Figure 5). The yield agrees well with that of USstd76 within a few %. Therefore the decrease in yield for 30N° July is understood to be caused by humidity, not by the difference in temperature or pressure profile of both models.

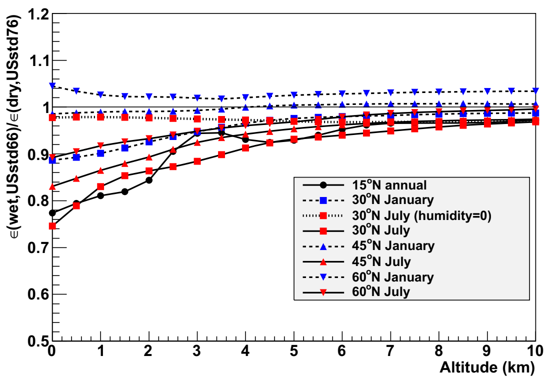

Figure 5: Ratio of total fluorescence yield between 300nm and 406nm in moist air from US standard atmosphere 1966 to that of US standard atmosphere 1976 (dry air) as a function of altitude. Same markers are used as in Figure 4.

For JEM-EUSO observation, median zenith angle of observed events will be around 60 degree. EAS with 10^{20} eV and $\theta = 60°$ is expected to reach its maximum development around 6 km high. The decrease due to humidity in summer is 10% or less there. For vertical showers, the maximum is lower, around 2-3 km high. The influence of humidity is larger, ~15%. Showers produced by neutrinos are expected to develop horizontally near sea level and hence will be darker by 10% in winter and 25% in summer at low latitude.

6 Conclusion

In the future the UHECR observation from a satellite orbit is indispensable to obtain huge acceptance. Since most of EASs will be observed above sea, the influence of water vapor on the fluorescence yields must be investigated. We have measured the quenching of nitrogen fluorescence by water vapor for ten lines and applied the result to the various atmospheric conditions from US standard 1966 model. Fluorescence from the typical EAS observed by JEM-EUSO (zenith angle=60°) will be decreased by several percent at shower maximum in summer at low latitude. For horizontal showers near sea surface, as are induced by neutrinos, the decrease will be larger up to 25%. We have shown here only the decrease of the fluorescence yields by humidity at emission point. Since the attenuation in atmosphere is relatively small for space-based observations, the photon yield in moist air would be applicable with little modification.

The decrease in the fluorescence yields by humidity is not negligible especially in summer at low latitude. It is necessary to take into account the characteristics of the detector in each project to estimate how much the humidity influences on the observation actually.

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