Fluorescence yield in moist air by electron and its application to space-based experiments

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***Abstract*. Fluorescence technique is used for observation of ultra-high energy cosmic rays. In order to estimate the primary energy accurately, good knowledge of fluorescence yield is essential. In the future, observation of fluorescence from extensive air showers (EASs) from satellite orbit will be the mainstream to increase effective area remarkably. For those experiments, the effect of humidity on the fluorescence yield is important. We have measured the effect on the fluorescence yield and lifetime with ^{90}Sr beta source for 337nm, 358nm and 391nm lines. About 20% decrease of the yield was found under the condition of 1000hPa, 20°C and 93% relative humidity, which will be a possible condition near sea surface. In order to estimate the effect on EAS observation, fluorescence yield was calculated as a function of altitude for the seven atmosphere profiles from US standard atmosphere 1966. About 25% decrease of the yield near ground at lower latitude in summer was found.**

***Keywords*: fluorescence yield, humidity, extensive air shower observation**

I. Introduction

A ultra high energy cosmic ray (UHECR) runs into the atmosphere and induces an extensive air shower (EAS), which consists of a lot of electrons. The electrons excite nitrogen molecules to emit fluorescence in the wavelength range of 300-400nm. Observation of high energy cosmic rays by the fluorescence is very useful especially in the region of UHE where the flux is very low, because the fluorescence is isotropically emitted and thus cosmic ray EAS can be observed at far away from the impact point in principle. Experiments for UHECR observation these days, such as Fly's Eye[1], HiRes[2], Telescope Array[3] and Pierre Auger Observatory[4], uses the fluorescence method. Future experiments, such as JEM-EUSO[5] in preparation for the launch in 2013, KLYPVE/TUS[6], S-EUSO[7] will also observe fluorescence from EASs with a telescope from satellite orbit to increase the detection area remarkably. Air fluorescence method is inevitable for the UHECR observation to acquire sufficient statistics.

Since the amount of air fluorescence is proportional to the primary energy of a cosmic ray, accurate fluorescence yield in air is very important to determine the energy of UHECR precisely.

The primary energy E of a cosmic ray is related to the observed number of photons($\Delta N_\gamma^{\rm obs}$) with the following equations:

$$E = \frac{1}{1-\alpha}\int_0^X \left(\frac{{\rm d}E}{{\rm d}X}\right)_{\rm dep} {\rm d}X \qquad (1)$$

$$\Delta N_\gamma^{\rm obs} = \left(\frac{{\rm d}E}{{\rm d}X}\right)_{\rm dep} \Delta X \sum_i \frac{\varphi(\lambda_i)}{h\nu_i} T(\lambda_i)\varepsilon_{\rm det}(\lambda_i) \ , \qquad (2)$$

where α is the energy fraction of unobserved particles like neutrinos, $({\rm d}E/{\rm d}X)_{\rm dep}$ is deposit energy, $h\nu_i$ is the photon energy of i-th line, $\varphi(\lambda_i)$ is the efficiency for radiation of wavelength λ_i, $T(\lambda_i)$ is the transmittance of the atmosphere and $\varepsilon_{\rm det}$ is the photon detection efficiency of the detector used.

We have measured fluorescence yield in air of various pressure with ^{90}Sr source. The results in dry air [8], [9] will be applicable to ground-based observations which are held in dry environment. However, future UHECR experiments such as JEM-EUSO will observe a lot of EASs developed in moist air above sea. The effect of humidity on the fluorescence yield is important for those experiments. After the measurement in dry air, we have started the measurement with the same chamber and reported some results[10].

In this paper, important parameters and their relations are introduced in section II. The experimental method and results of humidity dependence is described in sections III and IV. Application of our results to UHECR observation is reported in section V. Summary is given in section VI.

II. Fluorescence yield in moist air

The fluorescence yield (ϵ_i) per unit length for an electron for the i-th wavelength is expressed by

$$\epsilon_i(p, T, p_{\rm H2O}) = \rho\frac{{\rm d}E}{{\rm d}x}\frac{1}{h\nu_i}\varphi_i(p, T, p_{\rm H2O}) \ , \qquad (3)$$

where E is electron energy, p and T are pressure and temperature of air, respectively, $p_{\rm H2O}$ is pressure of water vapor, and ${\rm d}E/{\rm d}x$ is energy deposit. φ_i corresponds to the fluorescence efficiency of the i-th line, which is defined as the ratio of radiation energy to deposit energy[11]. Hereafter, the suffix i will be omitted. Generally the lifetime consists of three components,

- τ_r: lifetime of transition with radiation
- τ_c: lifetime of quenching by collision
- τ_i: lifetime of internal quenching.

In the case of Nitrogen, τ_i is not predicted theoretically and has not been observed experimentally. τ_r and τ_i are combined to define τ_o.

$$\frac{1}{\tau} = \frac{1}{\tau_i} + \frac{1}{\tau_r} + \frac{1}{\tau_c} \tag{4}$$

$$\equiv \frac{1}{\tau_o} + \frac{1}{\tau_c} \tag{5}$$

Here we introduce a reference pressure, p', which is the pressure when the lifetime for collisional quenching equals to that for the others ($\tau_c = \tau_o$). The reference pressure is related with τ_o as

$$\begin{aligned} \frac{1}{p'} &= (f_{\rm n}q_{\rm nn} + f_{\rm o}q_{\rm no} + f_{\rm w}q_{\rm nw})\tau_o \\ &= \left(1 - \frac{p_{\rm w}}{p}\right)\frac{1}{p'_{\rm dryair}} + \frac{p_{\rm w}}{p}\frac{1}{p'_{\rm H2O}}, \end{aligned} \tag{6}$$

where $f_{\rm n}$, $f_{\rm o}$ and $f_{\rm w}$ are proportional to the partial pressures of N_2, O_2 and H_2O, respectively, and are normalized to $f_{\rm n}+f_{\rm o}+f_{\rm w} = 1$. $q_{\rm nn}$, $q_{\rm no}$ and $q_{\rm nw}$ 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, and are expressed by:

$$q_{12} = \sqrt{\frac{8}{\pi\mu_{12}k_BT}}\sigma_{12} \ , \tag{7}$$

where the suffix 12 stands for one of nn, no and nw which are collisions of N_2^* with N_2, O_2 and H_2O, respectively. σ is the cross-section of collision de-excitation between molecules and μ is the reduced mass of two molecules. p is the total pressure of air and $p_{\rm w}$ is partial pressure of water vapor. $p'_{\rm dryair}$ and $p'_{\rm H2O}$ are reference pressures for dry air and water vapor, respectively.

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

$$\frac{1}{\tau} = \frac{1}{\tau_o}\left(1 + \frac{p}{p'}\right) \ , \quad \text{and} \tag{8}$$

$$\epsilon(p) = \frac{Cp}{1 + \frac{p}{p'}} \ , \tag{9}$$

where

$$C = \frac{1}{R_gT}\frac{{\rm d}E}{{\rm d}x}\left(\frac{1}{h\nu}\right) \cdot \varphi^\circ \ . \tag{10}$$

$\varphi^\circ = \varphi(1 + p/p')$ corresponds to the fluorescence efficiency in the absence of collisional quenching[11] and R_g is the specific gas constant.

III. Measurement of fluorescence yield in moist air

Decay electrons (0.85MeV in average) from ^{90}Sr (74MBq) are collimated and the number of electrons which pass through the chamber is counted by a scintillation detector(Fig.1). Three 2” photomultiplier tubes (PMTs) are attached to the chamber, perpendicular to the path of the electron and the number of fluorescence photons are counted by them. The detail of the chamber is written in ref.[8]. In this experiment, three interference filters were selected and put on the PMT windows. The center wavelengths and band widths of the filters are 337.7nm, 356.3nm and 392.0nm, and 9.8nm, 9.3nm and 4.35nm, respectively. Air in the laboratory was taken into the chamber at various pressures between 1hPa and 1000hPa. The temperature was kept around 20°C and the humidity was set in the range between 0% and 93%. 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 . Toplas TA502 was confirmed to work at lower pressure than 1 atmosphere by the manufacturer. Both hygrometers showed consistent humidity with each other during the measurement.

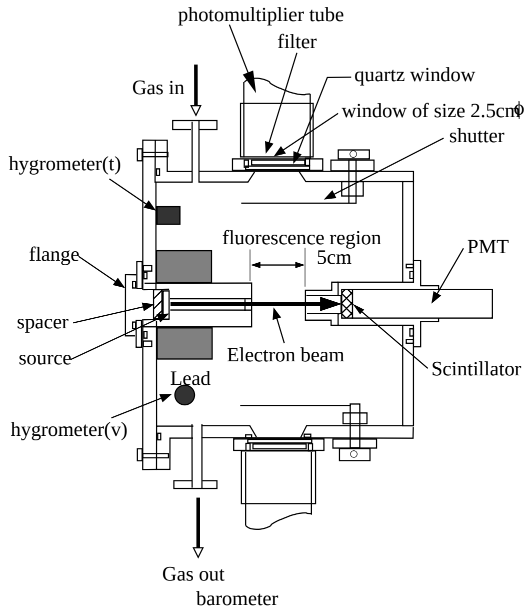

Fig. 1. Top view of the chamber. Laboratory air was passed through water or a desiccant to add or reduce humidity before filling into the chamber, respectively. The resultant humidity was measured by two hygrometers, hygrometer(v) (VAISALA HMP234) and hygrometer(t) (Toplas TA502).

IV. Results

Fluorescence yield and lifetime at constant total gas pressure were measured and are shown in Fig.2 and Fig.3 respectively, as a function of water vapor pressure. Fluorescence yield 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.(8) and (9), with the reference pressure in moist air expressed in Eq.(6), and then $p'_{\rm H2O}$ was determined. The lifetime for 391nm is too short to determine the humidity dependence, so that only the yield data were used for $p'_{\rm H2O}$ at 391nm. When fitting the humidity

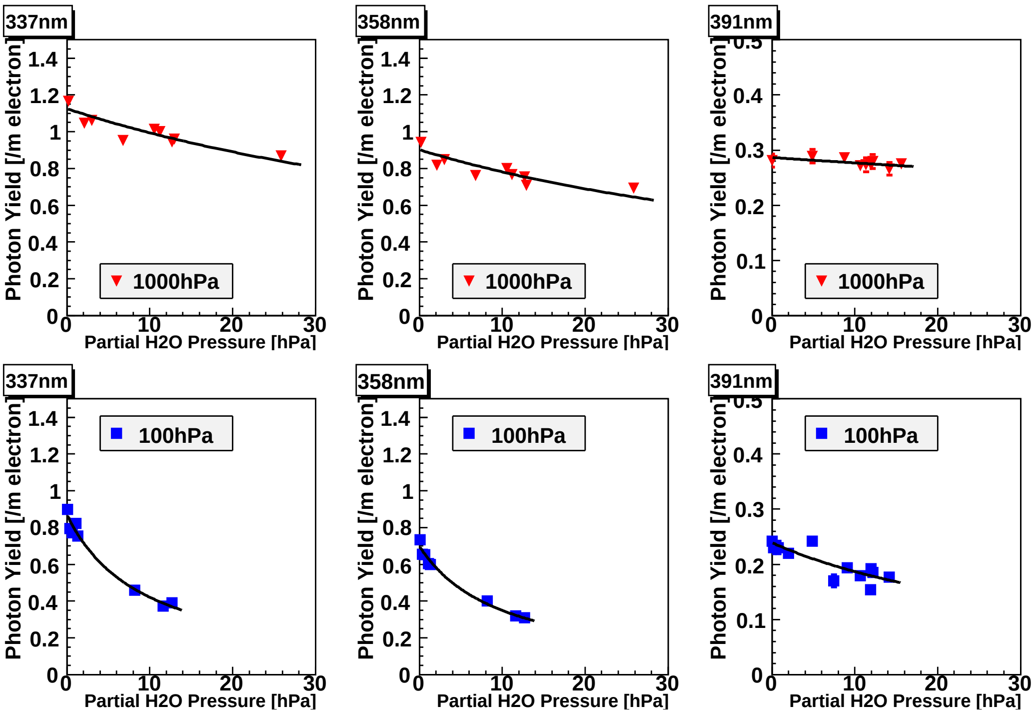

Fig. 2. Fluorescence yield of 337nm and 358nm line as a function of water vapor pressure at 1000hPa and 100hPa. Solid lines show the best fit curves by Eqs.(6) and (9).

dependence, $p'_{\rm dryair}$ was fixed to that determined from the dry air data[9]. $p'_{\rm H2O}$ are consistent with each other at 1-2 hPa derived from the yield data and the lifetime data.

V. Implication to the observation of fluorescence from UHECR EAS

Experiments employing fluorescence technique have used the profile of the US standard atmosphere 1976[12] (US atm.76). These days, real atmospheric profile is taken with radiosonde in experiments, such as Pierre Auger Observatory, Telescope Array and the effect of different atmospheric profile on the fluorescence observation is studied[13], [14]. In this paper, in order to see the effect of atmospheric profile and humidity, US standard atmosphere 1966[15] (US atm.66) was used. Fig.4 shows the humidity as a function of altitude in summer and winter at four different latitudes (15°N, 30°N, 45°N and 60°N). In winter, pressure of water vapor is relatively low, however, it goes up to 30 hPa in summer near ground at lower latitude.

Taking not only humidity but also temperature and pressure profiles of the US atm.66 into account, total fluorescence yields between 300-406nm were calculated and compared with that using the US atm.76 (dry air) (Fig.5). The yield at each altitude was calculated by the following equation, obtained by rewriting Eq.(9).

$$\epsilon = \left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)_{0.85\mathrm{MeV}} \frac{\varphi^\circ \rho}{h\nu(1+\rho R_g\sqrt{293T}/p'_{20})}, \quad (11)$$

where p'_{20} is the reference pressure at 20°C, and p' is defined by Eq.(6). The value of $p'_{\rm dryair}$ was taken from ref.[9] for each wavelength band. No significant difference of $p'_{\rm H2O}$ was found between 337nm and 358nm, so that the same value was used for all 2P bands. The yield for the US atm. 76 was normalized to one at each altitude. The decrease in yield is larger in summer and at lower latitude, up to about 25% near ground. In order to make a direct comparison of dry and moist air, the yield for dry air was calculated for the 30°N January profile (labeled with "(humidity=0)" in Fig.5). The yield agrees well with that of the US atm.76 at any altitude. The decrease in yield by humidity is about 10% in winter and about 25% in summer. Above 5 km, the decrease for winter may be negligible, however, small decrease remains in summer. Since 10^{20}eV shower reaches its shower maximum near ground, the decrease of observed number of photons will be significant around the maximum.

In order to evaluate correctly how much really affect the primary energy of UHECRs, wavelength dependence of transmittance in air and detection efficiency such as filter transmittance and PMT quantum efficiency should also be taken into consideration. As we reported in the previous paper[9], the energy decrease may not be as large as that of fluorescence yield in moist air, depending on the experiment. However, not so small influence will be expected for the energy estimation of horizontal showers.

VI. Summary

Humidity dependence of fluorescence yield is important for experiments to observe EASs of UHECRs

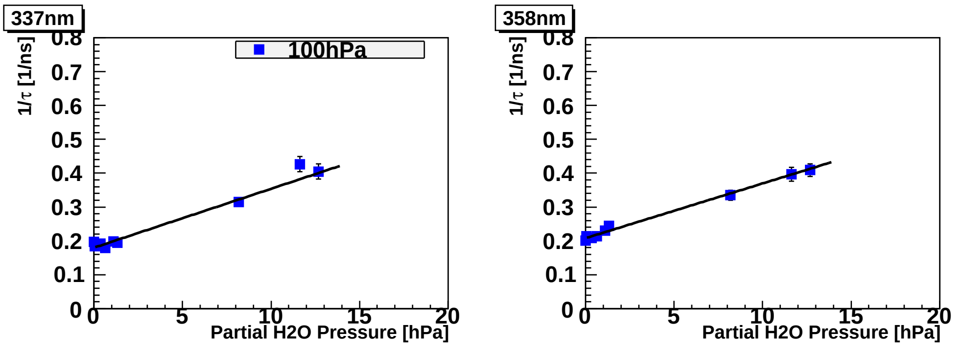

Fig. 3. Lifetime of 337nm and 358nm line as a function of water vapor pressure at 100hPa. Solid lines show the best fit curves by Eqs.(6) and (8).

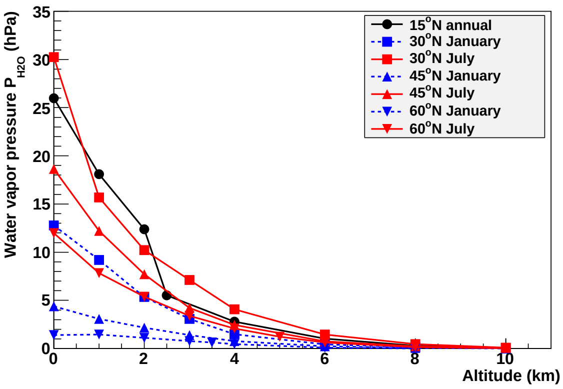

Fig. 4. Altitude profile of water vapor pressure from US standard atmosphere 1966. Annual profile at 15°N is shown by filled circles, that at 30°N by filled squares, that at 45°N by solid triangles and that at 60°N by solid inverted triangles. January data are connected by dashed lines and July data are connected with solid lines except for 15°N.

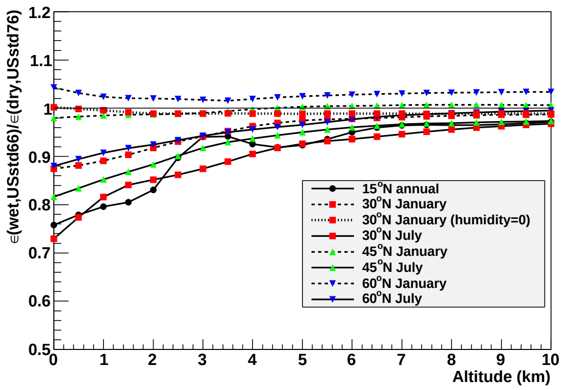

Fig. 5. Ratio of total photon yield between 300nm and 406nm in wet air from US standard atmosphere 1966 to that of US standard atmosphere 1976 (dry air) as a function of altitude. Fluorescence yield at 15°N is shown by solid circles, that at 30°N by solid squares, that at 45°N by solid triangles and that at 60°N by solid inverted triangles. January data are connected by dashed lines and July data are connected by dashed lines. In order to see the effect of humidity, the yield at 30°N without humidity is shown by solid squares connected with a dotted line.

from satellite orbit. We measured it for 337, 358 and 391nm fluorescence bands and about 20% decrease in fluorescence yield was found at relative humidity 93%, 1000hPa and 20°C. This decrease will lead to about 25% decrease of total fluorescence yield near ground at 15°N and 30°N in summer using US standard atmosphere 1966, although wavelength dependence of atmospheric transmittance and detection efficiency should be taken into account to evaluate how much the estimated cosmic ray energy will be decreased.

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