# New Photon Yields Measurement in Air and its Effect on the Energy Estimation of Ultra-high Energy Cosmic Rays

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**Abstract**

Photon yields in air excited by electron have been measured recently. Using new values, we discuss the effects on the energy estimation in fluorescent experiments which have been analyzed so far with the yields published before.

## 1. Introduction

Fluorescence technique was or is being used in the observations of ultra-high energy cosmic rays (UHECR), such as Fly's Eye, HiRes, Auger. We have measured photon yield by electron in dry air [6,7]. The total photon yield between 300 nm and 406 nm is 13% larger than that by Kakimoto et al. [4] and the relative yield of each line is quite different from theirs. Since attenuation by Rayleigh scattering depends strongly on the wavelength, it is necessary to take into account the wavelength dependence of various factors, in order to estimate the primary energies of cosmic rays.

## 2. Effect on the number of observed photons

The left panel of Fig. 1 shows the photon yield of our recent measurement [6,7] and that of used by HiRes experiment [1,2] (hereafter we refer as HiRes yields) as a function of wavelength. The total photon yield is $3.73 \pm 0.15$ (at 0.85 MeV) and 3.23 for our result and that of HiRes, respectively. HiRes yields of 337, 357 and 391 nm are larger than our results, however, those of their other lines are very small. The photon yield between 300 nm and 406 nm is shown as a function of altitude in the right panel of Fig. 1. The US standard atmosphere 1976 is assumed. The density $\rho$ and temperature $T$ dependence of the photon yield for the $i$-th line are determined by the following equation.

$$\epsilon_i = \frac{\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)}{\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)_{0.85\mathrm{MeV}}} \frac{A_i \rho}{1 + B_i \rho \sqrt{T}}, \qquad (1)$$

where $A_i$ and $B_i$ are coefficients listed in the Table 9 of Ref.[7].

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In the following calculation for comparison between HiRes yields and ours, the same $B_i$ as the present measurement is used for the HiRes yields, but $A_i$ is determined so that $\epsilon_i$ at 1000 hPa and 20°C is adjusted to the values of the HiRes yields.

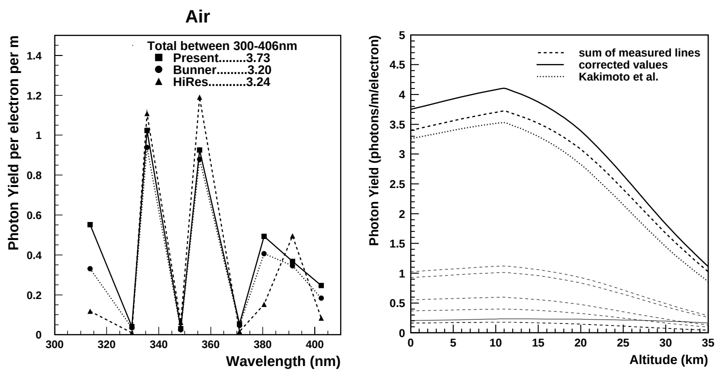


**Fig. 1.** Left: Comparison of photon yield in air at 1000 hPa. The solid line is our recent result and the broken line is the yield used in HiRes experiment. Right: Altitude dependence of photon yields by using the US standard atmosphere. The thick solid line is the corrected total yield of unmeasured lines and thick dashed line is that of the measured lines. The thick dotted line is the results in Kakimoto et al. by converting to at 0.85 MeV. The thin solid line and thin dashed lines are yields for 1N band (391 nm) and 2P bands, respectively.

The conditions for the calculation are summarized in the followings.

- CORSIKA 6.020 [3] with QGSJET model, Proton primary, $E$=$10^{19}$eV, $10^{20}$eV, $\theta = 0, 60°$, average shower of each 30 events was used. The shower trajectory with $\theta = 60°$ is perpendicular to the line of sight.
- d$E$/d$x$=2.19 MeV/(g/cm$^2$) is assumed for all electrons at any altitude.
- The observation height is 0 m a.s.l.
- Transmission by Rayleigh scattering ($X_R$=2974 g/cm$^2$):

$$T_R = \exp\left[ -\frac{|x_1 - x_2|}{X_R} \left( \frac{400[\text{nm}]}{\lambda} \right)^4 \right], \qquad (2)$$

where $x_1$ and $x_2$ are the slant depth of two points.

- Transmission by Mie scattering (scale height $H_M$ = 1.2km, horizontal attenuation length $L_M$ = 25km):

$$T_M = \exp\left( \frac{H_M}{L_M \cos\theta} \left[ \exp\left( -\frac{h_1}{H_M} \right) - \exp\left( -\frac{h_2}{H_M} \right) \right] \frac{400[\text{nm}]}{\lambda} \right), \qquad (3)$$

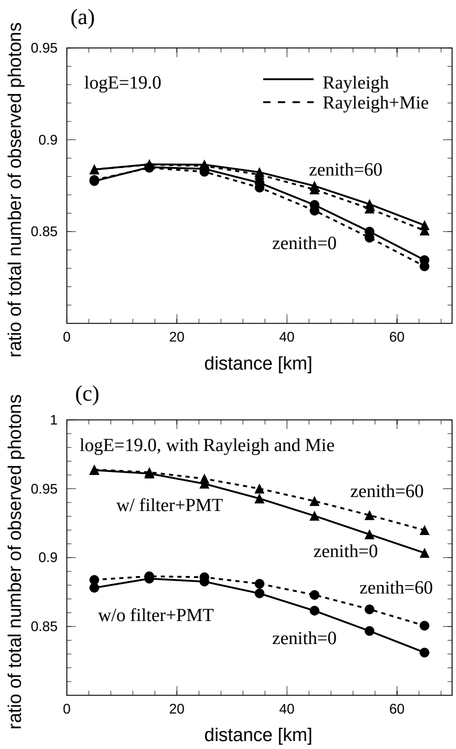


**Fig. 2.** Comparison of observed total photon number in various conditions. The ratio of that for HiRes yields to that for present result is plotted. (a) The effect of Mie scattering and zenith angle. Circles are for 0° and triangles for 60°. Solid lines are for the case that only Rayleigh scattering is taken in and dashed lines are for the case that Mie scattering is also taken in. (b) The effect of primary energy. Only Rayleigh scattering is taken into account. Solid lines are for $\log E = 19.0$ and dashed lines for $\log E = 20.0$. Circles are for 0°, Triangles for 60°. (c) The effect of HiRes filter+PMT. Circles are the cases without the HiRes filter transmission nor PMT Q.E. and triangles are for the case that the filter transmission and PMT Q.E. are taken into account.

where $h_1$ and $h_2$ are the heights of emission point and the detection point of the light, respectively.

- Altitude dependences of density and temperature of US standard atmosphere 1976 are used.
- Wavelength dependence of HiRes filter transmission and quantum efficiency (Q.E.) of HiRes PMT is used.

In Fig. 2, the ratios of number of total observed photons with HiRes yields to that with present yields are plotted for various conditions. The number of photons with HiRes yields is smaller than ours by −12% to −17% depending on the distance to the shower by Rayleigh scattering. In the case of the inclined shower, the change of ratios with distance is smaller than in the case of the vertical shower, and the difference is −15% at 65km. As far as the Mie scattering of the present assumption is incorporated, the ratio does not change very much. The ratio doesn't depend on the primary energy. However, if HiRes filter transmission and Q.E. of PMT are taken into account, the ratio of the number of the observed photons becomes closer to unity, −4% to −10%, depending on the distance. This tendency can be understood by the fact that HiRes filter and PMT have low detection efficiency around 310 nm, where the relatively large difference exists between the two photon yields.

## 3. Summary

Using recent results of the photon yield experiment, the number of observed fluorescence photons for simulated showers was studied. It depends on not only measured photon yield but also various factors in transmission and detection which are wavelength dependent. The difference of photons compared here affects the observed number by −4% at 5km and −6% at 40km if the HiRes filter transmission and PMT Q.E. are taken into account. In this paper, US standard atmosphere model was used, however, altitude distributions of the density and the temperature are actually different between in summer and winter. That is, the energy loss and hence its photon yields in the field of view of each PMT is different in season [5]. In the present calculation, we have not included the Cherenkov light. Its wavelength dependence is quite different from that of fluorescence light. Therefore the present estimation is not enough and we must use $\mathrm{d}E/\mathrm{d}x$ in meter at each height and subtract Cherenkov light according to the geometry of the shower for the energy estimation and the aperture estimation.

## References


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