Proceedings of the 30th International Cosmic Ray Conference
Rogelio Caballero, Juan Carlos D'Olivo, Gustavo Medina-Tanco,
Lukas Nellen, Federico A. Sánchez, José F. Valdés-Galicia (eds.)
Universidad Nacional Autónoma de México,
Mexico City, Mexico, 2008

Vol. 5 (HE part 2), pages 953–956

30TH INTERNATIONAL COSMIC RAY CONFERENCE

Fluorescence in air with moisture and its effect on the energy determination of ultrahigh-energy cosmic rays

N. SAKAKI[1], Y. WATANABE[2], M. NAGANO[2] AND K. KOBAYAKAWA[3].
[1]*Department of Physics and Mathematics, Aoyama Gakuin University, Sagamihara, 229-8558 Japan*
[2]*Department of Space Communication Engineering, Fukui University of Technology, Fukui 910-8505, Japan*
[3]*Graduate School of Human Development and Environment, Kobe University, Kobe 657-8501, Japan*
sakaki@phys.aoyama.ac.jp

Abstract: Photon yields in moist air are measured with ^{90}Sr β source and compared with those in dry air. Water vapors considerably reduce the photon yield. Since the ultrahigh energy cosmic ray observatories (HiRes, Auger, TA) with fluorescence technique on ground are at high altitude, the effect of the water vapor may be negligible for most cases. However, for the experiments from space like JEM-EUSO, the decrease of photon yield in moist air should be taken into account to interpret the longitudinal developments of extensive air showers near the sea surface, although the effects around the shower maximum for most showers may be small.

Introduction

We measured the photon yield in dry air using ^{90}Sr β source and reported the results in Refs.[1, 2]. For the experiments like JEM-EUSO[3], the photon yield in moist air is also important, because the fluorescence from extensive air showers (EAS) will be observed at various places over the earth. After the measurement in dry air, we have continued the measurement to study the pressure dependence of photon yields for radiation in moist air. Preliminary results in 21% and 56% relative humidities around 20°C at one atmosphere are described in Ref.[4].

Photon yield in moist air

In the present experiment, we measure the number of photons, ϵ_i, per unit length per electron for i-th band changing the total gas pressure, p, in the chamber. ϵ_i by the passage of electron in gas with the density, ρ, is expressed by

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

where $h\nu_i$ is the photon energy, $\mathrm{d}E/\mathrm{d}x$ is the total energy loss of the electron and φ_i is the fraction of the energy emitted as photons to total energy loss. We have called $\varphi_i(p)$ as the modified efficiency [4] and is related to the fluorescence efficiency, $\Phi_i(p)$, as $\varphi_i(p) = \kappa_i \Phi_i(p)$.

The reciprocal of the observed decay time, τ, can be expressed by the sum of three terms.

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

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

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

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, reference pressure, p', is defined as the pressure when τ_c

equals to τ_0. Then p' is related to τ_0 with

$$\frac{1}{p'} = (f_n q_{nn} + f_o q_{no} + f_w q_{nw})\tau_0 \ , \qquad (4)$$

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 collision de-excitation between N_2^* and N_2, O_2 and H_2O, respectively.

Using p', Eq.(1) and Eq.(2) are rewritten in the following;

$$\frac{1}{\tau_i} = \frac{1}{\tau_{i0}}\left(1 + \frac{p}{p'_i}\right) \ , \quad \text{and} \qquad (5)$$

$$\epsilon_i(p) = \frac{C_i p}{1 + \frac{p}{p'_i}} \ , \qquad (6)$$

where

$$C_i = \frac{1}{R_g T}\frac{\mathrm{d}E}{\mathrm{d}x}\left(\frac{1}{h\nu_i}\right) \cdot \kappa_i \Phi_i^\circ \ . \qquad (7)$$

Φ_i° corresponds to the fluorescence efficiency in the absence of collision quenching and R_g is the specific gas constant.

Experiment

The detailed experimental set up is described in Refs.[1, 2]. The central values of the narrow band filters used in the present measurement are 337.7, 356.3 and 392.0 nm and their bandwidths at half maximum are 9.8, 9.3 and 4.35 nm, respectively. (We designate each filter band as 337, 358 and 391 nm hereafter). The measurements have been done in dry air (mixture of 79% nitrogen and 21% oxygen) and in real air with different relative humidity, h_r, at p =1000, 750, 500, 200, 100, 30 and 10 hPa by using ^{90}Sr β source, of which average energy is 0.85 MeV. Each run took about 1 week and the average h_r and T, which were recorded every 30 sec with VAISALA HMP234 hygrometer during the run, are used to calculate specific humidity, h_s. h_s is defined by the ratio of the mass of water vapor, m_w, to that of moist air, $m_w + m_d$, where m_d is the mass of the dry air. Namely,

$$h_s \equiv \frac{m_w}{m_w + m_d} = \frac{0.622 e_s h_r}{p - 0.378 e_s h_r} \ , \qquad (8)$$

where e_s is the saturated vapor pressure at a given temperature, T. 0.622 means the ratio of the molecular weight of water vapor to that of dry air. Though h_s is dimensionless, hereafter h_s is written in g/kg for numerical values.

The photon yield, ϵ, is determined as the number of signal counts divided by the total number of electrons, the length of the fluorescence portion, the solid angle of the photomultiplier (PMT), the transmission of the window and the filter, and the detection efficiency of the PMT as described in Ref.[1].

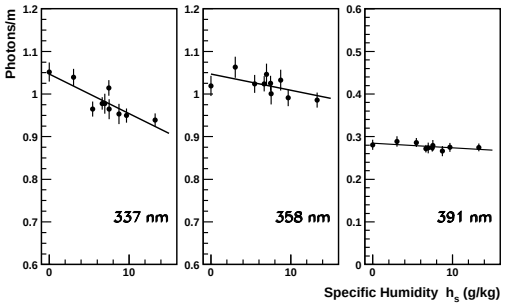

Figure 1: Fluorescence yields at 1 atm. are plotted as a function of specific humidity.

Fluorescence yields at the seven pressures as mentioned above are determined as a function of h_s. The example with $p = 1000$ hPa is shown in Figure 1. By assuming linear fitted lines as shown in Figure 1, we have decided ϵ at constant h_s and p. Then p' have been determined by fitting the obtained ϵ to Eq.(6) by the least square (LS) method and best fitted p' and C are determined.

p' can also be determined by fitting the lifetime, τ, to Eq.(5). p' from ϵ and τ agree with each other, although the errors are large. p' are calculated from Eq.(5) with the measured quenching rate constants in Refs. [5, 6, 7, 8] (hereafter p'_{cal}) and compared with our result. Our experimental value of p' increases with h_s, however, p'_{cal} decreases slightly. There are some discrepancies between ours and p'_{cal}, and we need further measurements to examine the difference.

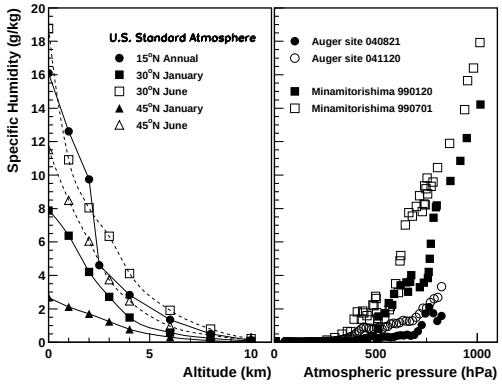

Figure 2: In the left panel, average h_s is plotted as a function of altitude at latitudes 30°N and 45°N in January and June. Average of annual values at 15°N are also shown. In the right panel, h_s are plotted as a function of atmospheric pressure at the Auger site [10] and at Minamitorishima[11] in summer and winter. Numbers listed mean the date of measurements. For example, 040821 stands for 21st of August, 2004.

Effect on the energy estimation of extensive air showers

In the left panel of Figure 2, average h_s is plotted as a function of altitude at latitudes 30°N and 45°N in January and June. Average of annual values at 15°N are also shown [9]. h_s is less than 3 g/kg above 5 km, irrespective of season.

In the right panel, h_s are plotted as a function of atmospheric pressure at the Auger observatory [10] and at Minamitorishima (small island) as an example over the Pacific Ocean [11]. h_s is less than 3 g/kg at the Auger site throughout the year. In case of the Pacific Ocean h_s may be less than 5 g/kg above 500 hPa throughout the year, however, it becomes quite high even in winter near sea level.

h_s dependence of p' in each 2P band is calculated as

$$p'(\lambda, h_s) = \frac{p'(\lambda = 337, h_s)}{p'(\lambda = 337, h_s = 0)} p'(\lambda, h_s = 0)\ . \tag{9}$$

For $p'(\lambda, h_s = 0)$ the values in Ref.[2] are used. The h_s dependent p' for 391 nm is used for 1N band instead of 337 nm. The total photon yields in Minamitorishima990701 and Auger041120 atmosphere are plotted as a function of altitude in Figure 3. The decrease of photon yield is less than 5% above 5 km for Minamitorishima atmosphere, however, near the sea surface, the decrease is $\sim$20%. It should be taken into account the quenching by water vapor for the energy estimation of horizontal EASs near the sea surface induced by such as neutrinos. If $p'_{\rm cal}$ is used, the decrease will be less than 10% at any altitude.

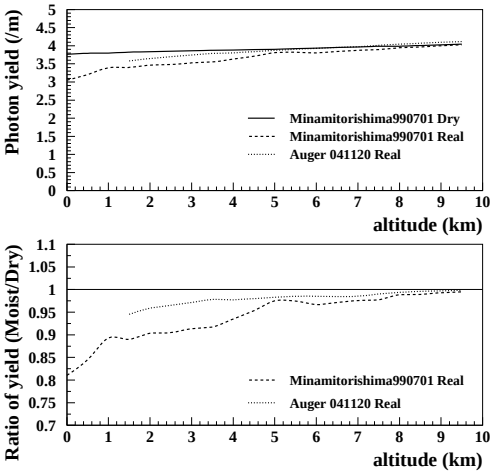

Figure 3: Photon yield between 300 and 406 nm for a 0.85 MeV electron as a function of altitude taking the humidity effect into account, for Minamitorishima990701 (dashed line) and Auger041120 (dotted line). The solid line shows the yield for the Minamitorishima atmosphere with the humidity set 0 artificially. In the lower panel are shown the ratios of photon yields to that for the Minamitorishima dry atmosphere.

In order to evaluate the effect on the observation of EASs, Proton showers with $E = 10^{20}$eV and $\theta = 0, 45, 60°$ are simulated with CORSIKA[12] for 30 events each. The average longitudinal development of fluorescence observed by JEM-EUSO at 430 km altitude is shown in Figure 4. The total number of observed photon and that at the shower maximum are decreased by $\lesssim$10% in Minamitorishima atmosphere, compared to those in dry air. If we take the Auger atmosphere, the decrease is

less than a few %. The decrease is $\lesssim$4% for EASs with zenith angle 45° and $\lesssim$2% for 60°, because the showers develop at higher altitude, where h_s is much smaller than near sea surface. Little effect of humidity is expected on the energy estimation of hadron showers observed from JEM-EUSO, because a fraction of the events with small zenith angles will be relatively small[13].

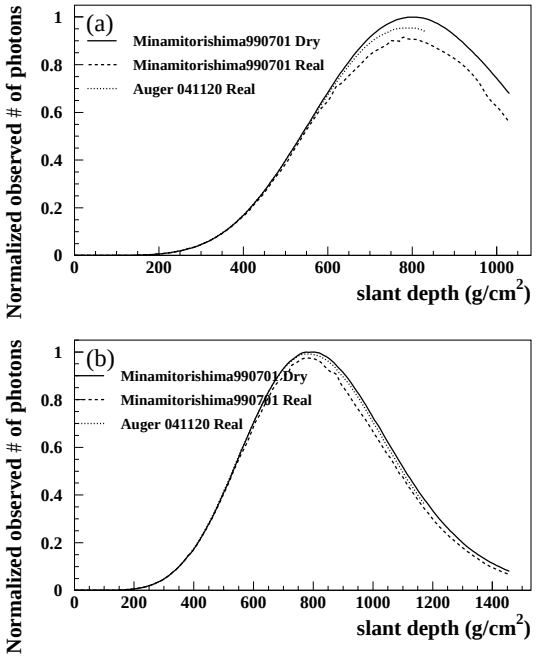

Figure 4: The expected number of observed photons for average proton shower with $E = 10^{20}$eV, and (a) $\theta = 0°$ and (b) $\theta = 45°$ in various atmospheres. The number at the shower maximum in Minamitorishima dry atmosphere is normalized to 1.

Conclusion

Photon yields in moist air were investigated and compared with those in dry air. Though the rate of the mole number of water to the total mole number is small in moist air, the decrease of photon yield may be 10-20% near sea surface. For EASs of neutrinos developed near sea surface, this effect cannot be ignored, but for hadron showers, the reduction may be limited to vertical showers whose fraction to total observed showers is relatively small. There are some discrepancies in p' between experiment and those expected from Eq.(4). For more detailed evaluation of the effects on the yields and the interpretation of the fluorescence properties of moist air, we need further refinements of the experiments.

Acknowledgments

This work is supported in part by the grant-in-aid for scientific research No.15540290 from Japan Society for the Promotion of Science and in part by the FUT Research Promotion Fund.

References

[1] M. Nagano, K. Kobayakawa, N. Sakaki, K. Ando, Astropart. Phys. 20 (2003) 293.
[2] M. Nagano, K. Kobayakawa, N. Sakaki, K. Ando, Astropart. Phys. 22 (2004) 235.
[3] T. Ebisuzaki, et al., in: This Conference Proc., 2007.
[4] N. Sakaki, K. Kobayakawa, M. Nagano, Y. Watanabe, K. Ando, in: Proc. of 29th Int. Cosmic Ray Conf., Pune, 2005, p. 185.
[5] H. Brunet, Ph.D. thesis, A L'université Paul-Sabatier de Toulouse (1973).
[6] P. Colin, Ph.D. thesis, Laboratoire d'Annecy de Physique des Particlules, IN2P3 (2005).
[7] A. Morozov, et al., Euro. Phys. J. 33 (2005) 207.
[8] S. V. Pancheshnyi, et al., Chem. Phys. 262 (2000) 349.
[9] COESA, US Standard Atmosphere 1966, U.S. Govern. Printing Office, Washington D.C., 1966.
[10] B. Keilhauer, private communication (2004).
[11] Radiosonde data, Japan Meteorological Agency, 1999.
[12] D. Heck, et al., Report FZKA 6019, Forschungszentrum Karlsruhe, 1998.
[13] E. collaboration, EUSO - report on the phase A study -, 2004.