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Fluorescence efficiency of electrons in the atmosphere above oceans

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Abstract. In order to observe the ultra-high energy cosmic rays above 10^{20}eV, a satellite-based telescope viewing 10^5 km^{2}sr is under preparation. In that experiment atmospheric fluorescent light from extensive air showers are observed. Since the atmosphere is not dry on the ocean where most extensive air showers are generated, the detailed study of fluorescence efficiency in damp air is required. The experiment to measure the atomospheric and vapor pressures dependence of fluorescence efficiency in damp air have been started by using a ^{90}Sr β source. As a first result fluorescent efficiencies in nitrogen gas and dry air are presented to compare with the previous experiments.

1 Introduction

Fluorescence technique was successfully used by the Fly's Eye detector to explore the cosmic rays in the ultrahigh-energy region(Baltrusaitis et al., 1985). From 1998 the HiRes detector, a successor to the Fly's Eye, has been operated with the improved resolutions of energies, arrival directions and the longitudinal shower developments(Sokolsky,1998). The fluorescence detectors will be provided along with the surface array at the Pierre Auger Observatory (Pierre Auger Project Design Report, 1997) and one of them is now under construction in Argentina. The Telescope Array under proposal in Japan is planned to be deployed in Utah, USA (Telescope Array Project Design Report, 1999). In all these experiments the atmosphere of quite low vapor pressure(dry) is used as a vast scintillator. On the other hands, in the case of a satellite-based telescope viewing downward (for example, EUSO Design Report, 2000), fluorescent lights from extensive air showers are observed mainly on the ocean where air is not dry.

So far the measurements of fluorescence efficiency with charged particles stopping in air summarized by Bunner (1967) using data before 1965 and that with electrons in dry air (Kakimoto et al. 1996) have been used in most cosmic ray experiments. Kakimoto et al. showed the fluorescence efficiency was proportional to electron energy loss from 1.4 MeV to 1000 MeV. However, the measurements were limited to three wave lengths, 337nm, 357nm and 391nm with 10nm bands. There are differences in measurements by Bunner and Kakimoto et al. at these wave lengths about 20-30%. Therefore the measurements with electrons at other wave lengths are needed, since optical filters between 300nm and 400nm are used in most cosmic ray experiments.

We have started a new measurement of the fluorescence efficiency of electrons in air with various vapor pressure to apply to the atmosphere not only on deserts but also on oceans. The efficiencies at 313nm, 380nm and 400nm with 10 nm band widths will be also measured.

2 Experiment

We chose a photon counting and thin target technique to measure the pressure dependence of fluorescence yield (the number of photons produced by an electron per meter of travel) in nitrogen and air following the method employed by Kakimoto et al. (1996). A cubic chamber used is shown schematically in Fig.1. Three photomultiplier tubes (PMTs), Hamamatsu photon counting H7195PX or H1161PX selected for low noise, are mounted on three sides of the chamber through quartz windows (photon counters). Electrons with the maximum energy 2.28MeV from β decay of ^{90}Sr$\rightarrow^{90}$Y$\rightarrow^{90}$Zr were beamed by a collimater and the number of electrons was counted by a scintillation counter (electron counter). The coincidence between the electron counter and any one of the photon counters was used to generate a gate for ADCs, and a start signal for TDC. The beam length of visible portion from the three photon counters was 10cm and the electron rate was about 1.3×10^3 s^{-1} at vacuum and 1.1×10^3 s^{-1} at 1000hPa. The electron energy was reduced by two mylar windows and the aluminum coverage of the source and the gas between

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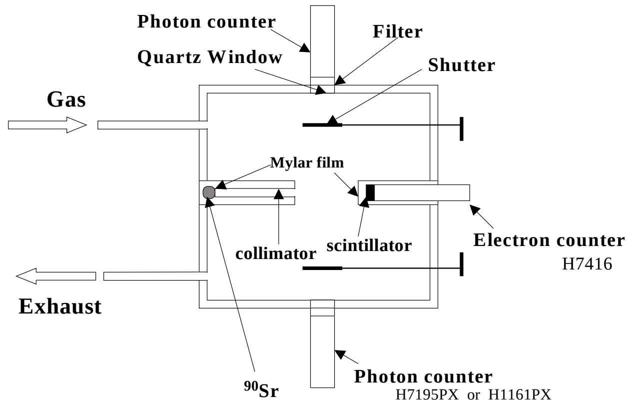

Fig. 1. Schematic drawing of the tank (top view). Number of electrons are counted by an electron counter. Three PMTs are mounted on the windows for viewing the fluorescent light (photon counter). Optical filters are mounted between the photomultiplier tubes and the quartz windows. Fluorescent region of electrons is 10 cm.

the source and the scintillator. The average energy was estimated about 1.4MeV. In the present measurements, three narrow band (10nm) filters of the central wave lengths of 337.7, 356.3 and 391.9nm were used.

In each run with certain condition, the number of electrons incident on the electron counter was registered. If there was a coincidence in 100 nsec between the electron counter and any one of three photon counters, ADC values of the electron counter and the corresponding photon counter were recorded. ADC value of the electron counter is used to estimate the energy of electrons and that of the photon counter to confirm observing a single photon. The time difference between the photon signal and the electron signal which was delayed by 160 nsec was also recorded in TDC. The distribution of TDC values is used not only to discriminate the backgrounds, but also to measure the life time of the fluorescence.

3 Results

An example of ADC and TDC distributions is shown in Fig.2, where an exponential decay is clearly seen between 250 and 350 (in 0.5 nsec) in signals of the lower figure. When the window of each photon counter inside the tank is shut, some signals appear even in vacuum runs. These seem to be attributed to the accidental coincidences between the electron counter and the photon counter due to local showers. The number of signal counts is obtained by subtracting background which is determined from the background parts clearly discriminated from the signal parts in the TDC distribution. Then the accidental counts from local showers is subtracted from the signal counts. Using the quantum efficiency and the collection efficiency of PMTs, the filter transmission, the quartz window transmission, the solid angle of the PMT, and the total number of electrons, the fluorescence yield is calculated.

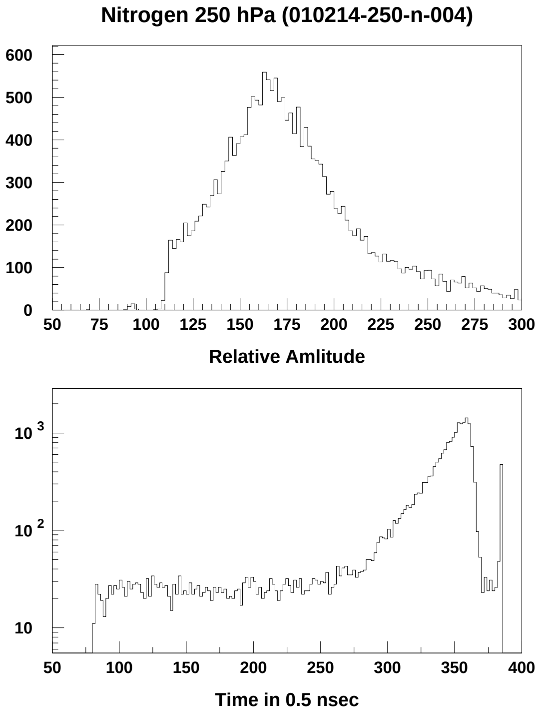

Fig. 2. An example of ADC and TDC distributions of photons at 338 nm at a pressure of 250 hPa of nitrogen. The upper one is a typical photon pulse height distribution and the lower one shows time difference between photon signals and electron signals whose incident times are delayed by 160 nsec.

3.1 Nitrogen

As a first step we have measured the fluorescence yield of electrons in nitrogen, so that we can compare with previous experiments and expected values from the theory. The pressure dependences of fluorescence yield at three wave lengths are shown in Fig. 3. The result of Kakimoto et al.(1996) is also shown by squares in the same figure. These are slighly larger than the present data and a possible reason will be discussed later.

3.2 Air

The fluorescence yield in the mixture of nitrogen gas of 78.8% and oxygen gas of 21.2% at 15°C is shown in Fig.4 along with the result of Kakimoto et al.(1996). This mixture may be similar response to dry air, if the effect of argon of 1% in air is negligible to the fluorescence efficiency. The values by Kakimoto et al. (1996) show again larger values than the present ones.

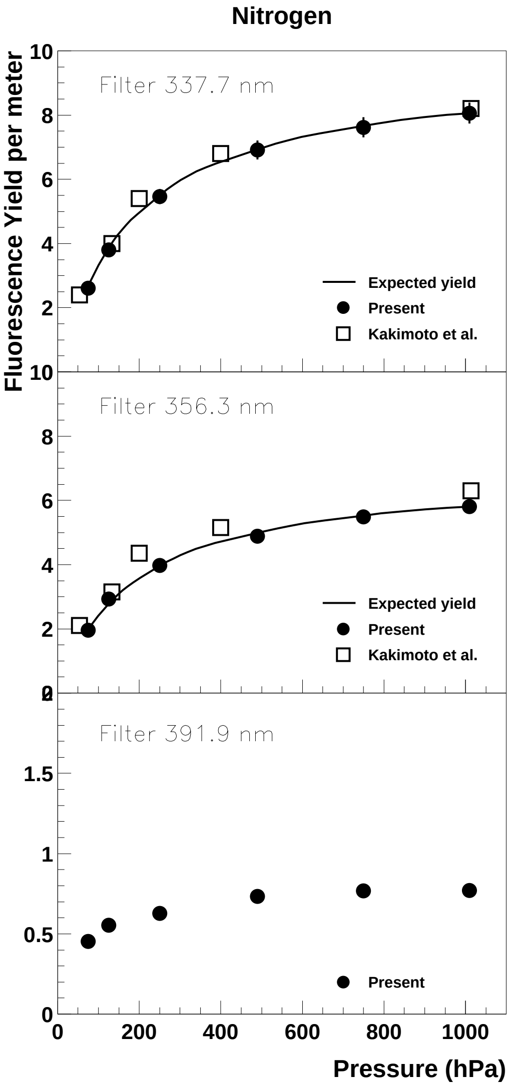

Fig. 3. Pressure dependence of fluorescence in nitrogen at 15°C with 1.4MeV electrons in three wave lengths.

4 Discussion

Fluorescence yield (ϵ) is proportional to the number of excited nitrogen molecules or pressure (p) of the gas and the observed decay time (τ) of the fluorescence. That is, $\epsilon \propto p \times \tau$. τ is related to the mean lives of the excited states for radiation to any lower state (τ_r), for that of collisional de-excitation (τ_c) and for that of internal quenching (τ_i) as follows (Bunner, 1967);

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

$$\tau_c = \frac{kT}{v \sigma_c p} = \frac{C}{p} \tag{2}$$

where v is the mean molecular velocity, σ_c is the cross-section for molecular collisional de-excitation, k is Boltzmann constant and T is the gas temperature. Therefore fluorescence yield is expressed by

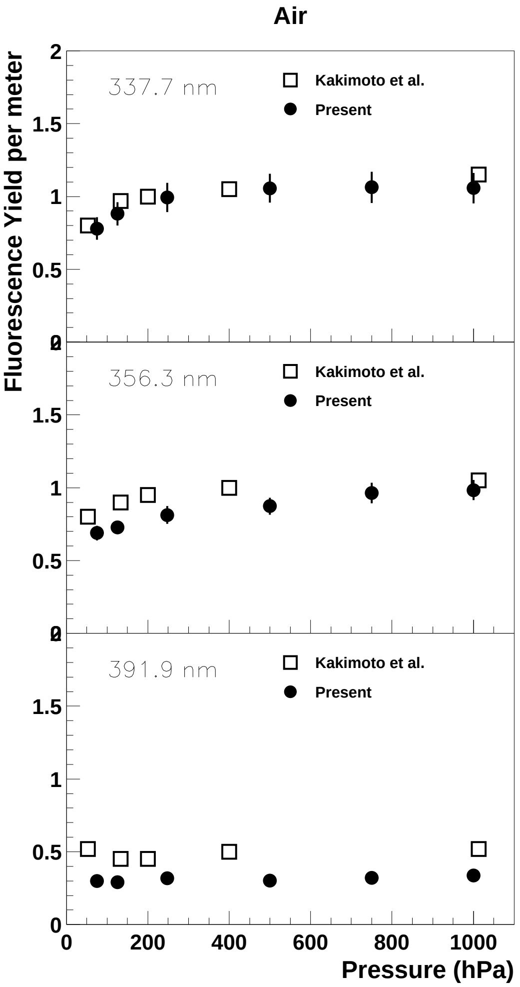

Fig. 4. Pressure dependence of nitrogen fluorescence in air at 15°C with 1.4MeV electrons in three wave lengths.

$$\epsilon \propto p \times \tau = \frac{pC}{p + \frac{C}{\tau_o}} \tag{3}$$

The pressure dependence of the inverse of the observed τ in nitrogen is shown in Fig.5. By fitting the results to Eqs.(1) and (2), τ_o=23.5nsec and C=4.34$\times 10^3$nsec·hPa are obtained. Solid lines drawn in Fig.3 are Eq.(3) by normalizing ϵ at 1000 hPa. In case of 391.9nm, the yield is so low that the accidental signals from local showers are not reliably subtracted in determination of decay constant. Then the expected curve is not drawn. The agreement of the expected pressure dependence from the decay time measurement with the present experiments is better than those by Kakimoto et al.(1996). This may be due to that the background from local showers was not subtracted in the measurements by Kakimoto et al.(1996).

As the case of 391.9nm in nitrogen, the yield in air is too low to derive the decay time of the fluorescence reliably,

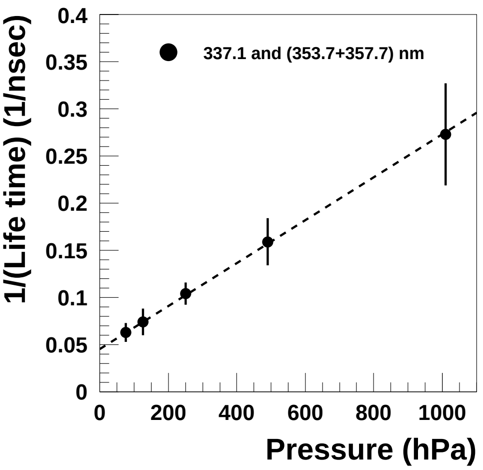

Fig. 5. Pressure dependence of inverse of life time (τ) of excited state of nitrogen molecule.

without subtracting the effect of local showers. We are now preparing an anti-counter of 0.25 m^2 area over the tank to prevent the contamination of local showers.

In Fig.6 the fluorescence yields of the present results are compared with the summarized values of experiments before 1965 (Bunner, 1967) by normalizing the yields around 338nm. Since two lines (354nm and 358nm) are included in our 356 band measurement, the fluorescence yields by Bunner are about 40% larger than the present results at 356 and 392 bands. This may be because the previous experiments before 1965 measured the fluorescence yield of charged particles stopping in air, while we measured it with the traversing electrons in air of 10cm interval.

5 Conclusion

Our experimental procedure to measure the fluorescence yield in gas has been established. Figs.3 and 5 show that our measurements and analysis are properly done. After the preparation of anti-counter over the tank, the measurement of fluorescence yield in air with water vapor will be made with narrow band (10nm) filters at wave lengths, 313, 338, 356, 380, 392 and 400nm.

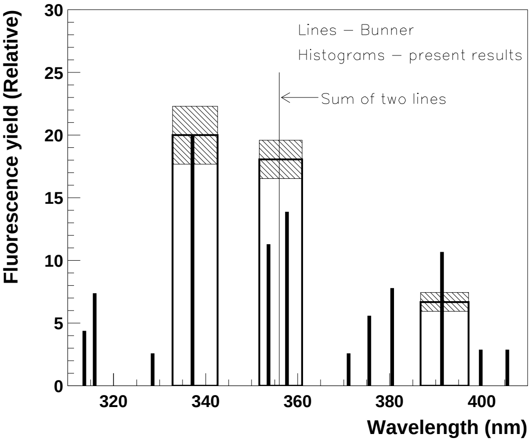

Fig. 6. Comparison of fluorescence yield of the present results and those summarized by Bunner (1967). The present results are shown by histograms. Shaded regions are experimental errors. The lines are those by charged particles stopping in air.

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