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Atomspheric flourescence yield

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Abstract. Several existing and planned experiments estimate the energies of ultra-high energy cosmic rays from air showers using the atmospheric fluorescence from these showers. Accurate knowledge of the conversion from atmospheric fluorescence to energy loss by ionizing particles in the atmosphere is key to this technique. In this paper we discuss a small balloon-borne instrument to make the first *in situ* measurements of the atmospheric fluorescence yield versus altitude. The instrument can also be used in the lab to investigate the dependence of the fluorescence yield in air on temperature, pressure and the concentrations of H_20 and other gases that present in the atmosphere. The results can be used to improve the accuracy of cosmic ray energy measurements and explore environmental effects for existing ground-based experiments and future space-based experiments.

1 Introduction

Chudakov and Suga first proposed the possibility of using atmospheric fluorescence (AF) to study the properties of ultra-high-energy cosmic rays in the 1950's. The mechanism for AF was well described by Bunner (1964) who made the first estimates of AF yield (AFY). The first unambiguous observation of AF induced by ultra high-energy cosmic rays was made by Bergeson et al (1976). The first Fly's Eye detector was started in 1982. Fly's Eye found the highest energy cosmic ray event ever recorded (3 x 1020 eV)(Bird et al., 1994), well beyond the predicted Greisen-Zatsepin-Kuzmin (GZK) cutoff (Greisen, 1966; Zatsepin and Kuzmin, 1966). The Fly's Eye has been followed by the High Resolution Fly's Eye (HiRes), and the Auger hybrid AF-ground-array. The next generation of AF experiments will be the Extreme Universe Observatory (EUSO) and Orbiting Wide-angle Light-collector (OWL) in space. These experiments will require improved knowledge of the AFY in the atmosphere worldwide.

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Bunner (1964) first measured the AFY in air in his Ph.D. thesis with the Cornell group. Bunner combined all the existing data and used kinetic theory to predict the pressure, and hence altitude dependence of this yield. Until recently, his work was the standard used to interpret all cosmic ray data from AF. The estimated systematic errors in the AFY were large, however, and approached 25%. Hartman (1968) measured the AFY for 750eV electrons at 70 microns of Hg (corresponding to an altitude of 65 km) producing results consistent with Bunner's parameterizations, but not more precise as a function of pressure.

What was needed was a measurement using electrons at the energies found in an extensive air shower and over a range of pressures corresponding from sea level to 15-20 km. Recently, Kakimoto et al (1996) measured the N_2 fluorescence yield in air for three pronounced spectral lines 337, 357 and 391 nm. Their laboratory measurements were made using 1.4, 300, 600 and 1000 MeV electrons from 20 mm of Hg to one atmosphere of pressure of air. These investigations have established the AF yield to an accuracy of 10%. They have also shown that the AFY (in photons/m) as a function of electron energy is proportional to the specific energy loss, dE/dX.

A number of outstanding issues remain, however. First, the precision of the measurement of yield (10%) is close in magnitude to the combined systematic error of other sources in existing and proposed AF experiments. A reduction in this systematic error to a few percent is thus important. Second, the energy dependence of the yield needs to be measured to lower electron energies than those of Kakimoto. While the median electron energy in an air shower is near 40 MeV, improved calculations of extensive air showers indicate that a significant contribution from < 1 MeV electrons exists. Since the yield appears to be proportional to dE/dX and the energy loss increases markedly with decreasing electron energy, it is important to experimentally verify how far down in energy this relation holds. Third, the pressure dependence of the individual spectral lines needs to be checked more carefully, both in the lab and in-situ.

The AF is a useful tool for cosmic ray measurements because its emission spectrum is in the near-ultraviolet (300-400 nm) where the atmosphere exhibits almost no absorption and a relatively long scattering length (10 – 20 km) and because the yield is approximately independent of altitude up to about 15 km. This altitude independence comes from competition between N_2 de-excitation by fluorescence and collisional de-excitation, primarily on O_2 molecules. As the air density increases, the proportion of de-excitation by collision increases in such a way as to cancel out the increased AF yield. This balancing act depends in detail on the ratio of N_2 to O_2 as a function of altitude. While this ratio is well known to be constant up the turbopause at altitudes of 100 km, one can not a-priori rule out that other molecules may become important in the collisional de-excitation process. Candidate molecules such as CO_2, Ar and H_2O may become important if their concentration is high enough at some altitude.

2 Atmospheric Fluorescence Measurement Technique

The instrument discussed here is based on the design of the instrument used by Kakimoto (1996). The same instrument will be used for laboratory measurements and balloon-borne measurements. The estimated weight of our balloon flight payload is 152 kg. Because of the instrument's lightweight and the requirement for data acquisition during ascent (and possibly descent), it is an ideal candidate to be flown 'piggyback' with another balloon payload. In that mode the estimated weight of our portion of the payload would be 118 kg.

Our approach is to design an apparatus that can be used measure the AF yield as a function of electron energy. In the lab, the apparatus will be placed in a vacuum chamber and operated at various pressures and temperatures. The composition of the air can be varied to see the effect. Flight data will be acquired during ascent with the apparatus in the airflow. The balloon ascent rate is nominally 305m/min. We have estimated the helium contamination from the balloon and concluded that it is negligible. If longer collection times are desired at high altitudes, data can also be acquired by valving the balloon down to float altitudes above 26 km.

The apparatus will use a 100 μC ^{90}Sr beta source for the electrons and employ single photon counting to measure the AF yield. The source strength is limited to 100 μC the license of the National Scientific Ballooning Facility. Because the enclosure containing the air must be dark enough for single photon counting while open to the atmosphere; a twilight launch may be necessary.

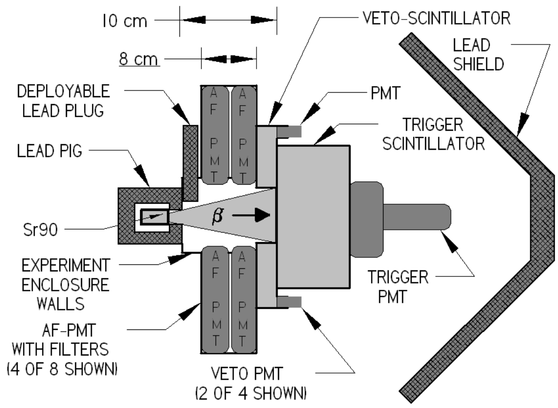

Fig. 1. The Atmospheric Fluorescence Yield Instrument Concept.

The instrument concept is shown in figure 1. The Beta particle source is in a lead pig with an aperture for electrons to enter air sample chamber. The beta particles stop in the trigger scintillator. This scintillator will be greater than 9 cm in diameter and is preceded by a separate anticoincidence scintillator with an 8-cm hole centered on the trigger scintillator. Four small PMTs in the corners view the veto scintillator. This pair of scintillators define the beam and provide triggering for the 8 photon counting PMTs viewing the air sample for measurements of the AF light produced in the chamber.

The experimental enclosure (figure 2) for the balloon flight constitutes a flow tube, allowing air to flow through the test volume while strongly attenuating stray light. The top and bottom of the enclosure will be fitted with air scoops. The ascent rate of the balloon will continuously force air though the test volume. Since data acquisition could also occur during the descent, an air scoop has been included on the bottom. The enclosure will be instrumented with pressure sensors to record the actual pressure in the test volume. Because of the source strength, the instrument is limited to measuring one air sample every 300 meters.

Where each air scoop attaches to the enclosure, a multi-layer baffle will be installed to restrict the light entering the test volume while allowing air to flow freely. Each baffle plate contains louver openings. These openings are offset in adjacent plates. This forces light passing through the openings in one plate to bounce between plates before passing through openings in the next plate and penetrating farther into the baffle. The interior layers of the light baffles will be coated with an anti-reflective paint to absorb stray light.

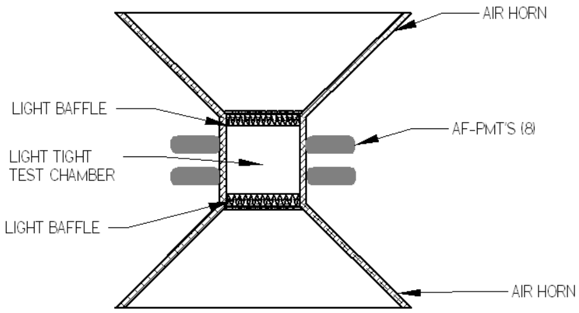

Fig. 2. Experimental enclosure with air-scoops attached. The interior surfaces of the enclosure have a white reflective coating.

The flow tube will be designed to insure the ambient air at each altitude is being sampled while strongly attenuating stray light. This involves a tradeoff between the degree of light attenuation by the baffles and their attenuation of the flow rate. We estimate that if the flow attenuation factor due to the baffle is 0.1, the air within the enclosure during ascent will have been collected in the preceding 10 meters of altitude. Since each measurement is an average over 300 meters, mixing the air samples on a scale of <10 meters will have no effect on the results.

The eight PMTs viewing the AF will be arranged in groups of four on either side of the test volume. The PMTs will be placed close to the electron beam and as near the source as possible in order to maximize the measured signals. The axes of the PMTs will be oriented perpendicular to the beam as shown in figure 1. Each tube will have a narrow bandpass filter. Three PMTs measure individual lines (337,357 or 391nm) and the fourth will have the HiRes filter (bandpass 300-400nm), covering all three lines. The AF measurements will be made redundantly by the second set of four tubes. The test volume will be painted with Munsell White Reflectance Coating (Munsell, 2001). This coating applied in a 1.5mm thickness provides a reflectance of 0.96-0.99 between 300 & 400 nm. With this coating, the light collection efficiency will be sufficient to allow measurements of the AF yield every 300 meters in several electron energy bands and at each of the 3 nitrogen emission bands as the balloon ascends.

The system consists of 8 PMTs used for counting the AF photons, 4 PMTs that view the veto scintillator and one PMT that views the thick trigger scintillator. The electronics system is a custom design specifically for this application and includes the coincidence logic and the gates and scalers used to collect the data specifically for this experiment.

The PMTs that count AF photons are selected to have a good signal/noise ratio for single photoelectrons (p.e.'s). The output of each of these tubes will be applied to fast electronics leading to a discriminator with the threshold set by a DAC that is controlled by the flight computer. The discriminator is set to distinguish single p.e.s from noise. The TTL pulse for each p.e will be fanned out to a group of gates, one for each electron energy bin. A counter follows each gate. The gates are controlled by the coincidence logic.

The signal from the trigger scintillator PMT is applied to fast electronics and fanned out to a group of discriminators with their threshold set by computer-controlled DACs. The outputs of these discriminators will be anti-coincidenced with the signal from the veto system and the resulting signals are used to create the gates for the AF-PMT signals, mentioned above. These gate signals will also be counted. In addition, the gate-opening signal corresponding to the lowest energy discriminator will be routed through a delay creating an additional gate not in coincidence with the electron. This signal will be used to measure the background in each AF PMT.

The front-end electronics also includes the calibration modes of the instrument. These calibrations are done light pulsers using visible and UV photodiodes that are kept in temperature-controlled ovens with the light routed to the PMTs by fiber optics. Charge injection pulsers also calibrate the AF-PMTs. All the data will be recorded onboard and transmitted to the ground.

3 Atmospheric Composition

The most abundant constituents of the atmosphere are N_2 (78.1%), O_2 (20.9%), Ar (0.9%) and CO_2 (0.03%). The relative concentration of these gases is considered to be invariant up to the limit of turbulent mixing in the atmosphere (about 100 km), Brasseur and Soloman (1986). Water may be present at highly variable concentrations, from > 1% near ground level to a few ppm by volume in the stratosphere. It is clear that de-excitation of N_2 excited states can occur by collision with another molecule before fluorescent emission occurs. The rate at which de-excitation occurs depends, to first order on the concentration of the energy-robbing molecules (such as O_2). This is simply because the mean time between collisions of an excited N_2 molecule and an atom or molecule of a minor constituent is much longer than the de-excitation time at the temperatures and pressures present in the atmosphere (Present, 1958). Polyatomic species (H_2O, CO_2, O_3, N_2O, etc.) have a higher collisional cross-section for de-excitation than O_2, or Ar, but their effectiveness must still be limited by low concentration. For this flight, the air samples will be collected during the experiment ascent phase in order to provide coordinated test samples for comparisons with specific fluorescence measurements. The air sampling system will be designed with computer-controlled valves to extract air from both the measurement chamber and from an external port. These samples will be taken on a periodic schedule determined by the automated fluorescence measurement sequence. The method will store bulk atmospheric samples in custom-designed stainless steel cylinders for later mass spectrum analysis.

In the lab the AFY will be measured from 10 to 760 torr and as a function of temperature from –70°C to +40°C. This will allow us to check the temperature dependence of the FY reported by Bunner (1964). Because the de-excitation time for the nitrogen lines in the 300-400 nm range is <5 ns, we do not expect minor constituents of the atmosphere to effect the AF yield. We plan to investigate the effect of varying major constituents of the atmosphere. We introduce water vapor and CO_2 to investigate their effects on AF yield. The water vapor is present in the lower troposphere in potentially significant amounts and quite variable. The CO_2 content is normally invariant and rather low, but could be enhanced in the planetary boundary layer due to agricultural burning, forest fires or volcanic activity. We will also vary the content of Ar and oxygen although we expect their abundance to be invariant.

4 Absolute Calibration

The experiment must be calibrated to make absolute AF yield measurements. This will be done by first making an absolute measurement of the fluorescence yield in pure nitrogen at 20°C and one atmosphere. We plan to determine the absolute yield at three wavelengths, 337.1, 357.7 and 391.4 nm. For this a separate setup with well-defined photon collection geometry will be used. The fluorescence yield in pure nitrogen is ~10 times higher than in air. The measurements will be made at a high electron energy threshold to minimize the variation in electron pathlengths due to scattering.

The tubes uses for this measurement will be calibrated at Optronic Laboratory in Orlando Florida using a precision light source that is maintained in calibration against the NIST standard. The source is used in conjunction with a spectrometer to create a source of mono-energetic photons of variable wavelength. The response of the PMT will be measured at various angles and at various wavelengths over the range from 300 to 400 nm. We will use this absolute measurement in pure N_2 to calibrate our experiment.

5 Summary

The key to analysis of cosmic ray measurements by the atmospheric fluorescence technique is accurate knowledge of the AFY. We have described plans for investigations of the AFY that are intended to measure the yield versus temperature, pressure, and atmospheric composition and to determine the absolute AFY to 3%. These measurements will establish the basis for analysis of data from the present ground-based experiments and future space-based experiments.

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