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High Resolution Measurements of Cosmic-ray Air Showers with the Track Imaging Čerenkov Experiment

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Abstract: The Track Imaging Čerenkov Experiment (TrICE) is a prototype imaging atmospheric Čerenkov telescope designed to use a high resolution method for measuring cosmic-ray composition at TeV-PeV energies. The method aims to separate the fast and compact direct Cerenkov signal produced by primary cosmic-ray nuclei in the upper atmosphere from the light produced by the subsequent air shower cascade. Efficient discrimination of the direct Čerenkov signal benefits from the use of small camera pixels to improve the angular resolution of the air shower image. Multi-anode photomultipliers are used in the TrICE camera to achieve 0.086° pixel spacing over a 1.5° field of view. The telescope was completed in late 2006 at Argonne National Laboratory. We present the results from the first observations with TrICE.

Introduction

TrICE[1] is a prototype telescope designed to explore high resolution imaging of air showers produced by cosmic-ray nuclei. Simulation studies show that the direct Čerenkov (DČ) light produced by a primary nuclei can be distinguished from the light produced by the subsequent air shower by using imaging Cerenkov telescopes [2]. The successful measure of the intensities of both stages of the interaction would allow a precision measurement of the charge and energy of TeV-PeV cosmic rays on an event-by-event basis.

The current Imaging Atmospheric Čerenkov Telescopes (IACTs) have detected this phenomena [3, 4]. However, the fast and spatially compact properties of the DC signal exceed the angular and time resolutions of exisiting instruments. The TrICE prototype serves as an initial step in developing the instrumentation required to improve the application of the DČ method. Specifically, the TrICE prototype uses an MAPMT camera [5] to achieve high resolution images of cosmic-ray air showers.

In this paper, we first discuss the DČ method and how it is applied in TrICE. The status of the TrICE prototype is briefly reviewed. Finally, preliminary results obtained from observations made using the recently completed 256-pixel camera are presented.

Method

The DČ method is targeted at a difficult energy range for cosmic-ray composition measurements. Cosmic rays at TeV to PeV energies near the "knee" are detected through air shower particles reaching ground level. The measurement is highly dependent on hadronic models used to simulate the air shower development in the atmosphere over many radiation lengths. In this energy range, very few particles reach ground level, making detection by arrays and accurate energy measurements difficult. Also, the particle identification must be made using properties of the shower development that are susceptible to large fluctuations and simulation uncertainties.

At sub-PeV particle energies, balloon-borne detectors are used to measure cosmic rays interacting within the detector medium. This has been highly successful, but is limited at higher energies by the area of the detector.

The idea of detecting Čerenkov radiation from a primary nucleus has been around for some time [6]. The expectation was that the light from a primary nucleus would be indisitinguishable from Čerenkov light from the ensuing air shower particles at ground level. This was indeed the case for the early ground-based Čerenkov telescopes designed to search for gamma rays. Searches for the DČ component were more naturally attempted by several balloon-borne instruments[7, 8].

The imaging capability of current ground-based Cerenkov telescopes, such as those used for VERITAS, H.E.S.S., and MAGIC, is more applicable to searches for direct emission than previous instruments. The direct Čerenkov technique was proposed by Kieda, Swordy, and Wakely [2] to exploit the ability of IACTs to detect the signal from cosmic rays reliably using a high resolution camera and fast timing. The DČ signal, coming from the upper atmosphere before the first interaction, is spatially compact and short in duration. Exploiting both of these features produces a clearly separable signature that gives the particle charge with good resolution and a measure of the particle energy. Simulations suggest that desirable resolutions for detecting direct radiation are around 0.01° and 0.5 ns respectively. Both of these exceed the specifications of current IACTs, but are not terribly far from them.

A clear benefit of the DČ technique is the use of the Čerenkov light to more accurately define the primary particle and air shower characteristics. This not only allows the measurement of charge on an event-by-event basis using the DČ intensity, but also removes the worst of the simulation modelling uncertainties by not relying strongly on the hadronic shower component.

The realization that an IACT viewing a cosmic-ray air showers at a preferred impact distance would detect a single bright pixel near the origin of the shower image has renewed interest in searching for DČ emission. The use of IACT arrays makes this much more feasible by increasing the chance to view showers at the preferred impact distance and to distinguish DČ light from other single pixel effects by finding correlated bright pixels in several images of a shower. The H.E.S.S. and VERITAS experiments have detected events revealing the DČ emission component [3, 4]. [3] includes an extension of the iron spectrum to 200 TeV. Even more encouraging for the technique is the agreement of the spectral measurement made by this method with those from other balloon-borne cosmic-ray detectors. However, the current IACTs are not perfectly suited to the detection of DČ radiation. Enhanced angular resolution, increased time resolution, and optimal telescope baselines could all contribute to extending the ranges of charge and energy that may be measured by this method.

Status

The design and structure of the TrICE prototype telescope are described in detail in [1]. To briefly review, the telescope has been constructed as a prototype instrument to allow the development and testing of one element of the requirements for a DČ telescope, a high resolution camera. Current IACTs most commonly use single-anode photomultiplier tubes as camera pixels. Typically pixels are larger than 1 cm. The scaling of this type of camera to higher resolutions becomes difficult, and so the use of multi-anode photo-multipliers (MAPMTs) has been explored as one possible solution to meet the DČ resolution requirement [5]. The Hamamatsue R8900 MAPMT selected for use in TrICE is instead a 4×4 array of 6×6 mm pixels housed within a 26 mm×26 mm frame. In the TriCE optics, this translates into an angular width of 0.086° per pixel.

The TrICE prototype infrastructure was completed in early 2006. The installation of the electronics and commissioning of a preliminary 4-PMT test camera took place during Spring 2006. Much of the early work addressed adaptations of the MAPMT base electronics to handle the constant high currents caused by night sky background light and the development of the DAQ read out for the MAPMT signals. The Argonne site is not particularly dark, but the modifications that were developed allow a stable and linear response for the MAPMTs over the range of interest. A 9-PMT version of the camera was tested in late Spring 2006. By early 2007, the completed 16-PMT camera was ready for installation and commissioning. During this time, the installation and alignment of the optical system was ongoing. See [1] for details of the alignment and other telescope systems.

The MAPMTs underwent a series of lab measurements before their inclusion in the camera. The goals of this were to develop a good knowledge of the gain response and other properties of the MAPMT pixels, such as linearity and crosstalk, at operating gains (2×10^5 in gain at 600 V). Also, it allowed for the selection of those MAPMTs with the least pixel-to-pixel gain variations for installation in the portion of the TrICE camera used for triggering. The typical gain variation for the Hamamatsu R8900 MAPMTs used in TrICE is a factor of 2 or 3 over a single MAPMT. The 4 MAPMTs selected for use in the trigger vary by a factor of 2 or less.

Commissioning of the camera included checks to confirm the proper operation of all pixels. The voltages applied to each MAPMT were adjusted using a uniform light source to bring the mean gains into approximate equality. Pixel-to-pixel gain variations prevent this from being achieved within a single MAPMT. However, relative differences can be corrected for in the analysis.

Uniform gain response at the pixel level is most critical for the trigger. In TrICE, a coincidence of 2 MAPMT dynode signals above a threshold is required. The dynode signal is effectively a sum over the entire unit. The response of the dynode trigger used in TrICE will only be as uniform as the pixel-to-pixel variation. Only the central 4 MAPMTs participate in the trigger, and so those with the most uniform gain response were selected for these positions. A more sophisticated electronics system could compensate for differences in the anode signals and apply a more detailed triggering algorithm. The dynode scheme was found to be sufficient for the purposes of this preliminary work.

Results

Commissioning work was ongoing and observations were taken during early 2007. The preliminary results from that period include the first images of air showers made by TrICE using the completed camera and aligned mirrors. The optimal configuration for most data from that time made use of 4 of the 8 spherical mirrors. Two mirrors showing optical anomalies were excluded from data runs. The additional 2 mirrors were excluded due to alignment issues that were not resolved until later times. This reduced the primary mirror collection area to $\sim 3\mathrm{m}^2$. Due to the small collection area and high NSB light levels, the energy threshold for TrICE is higher than IACT arrays. The resulting rate of collected and reconstructable events is on the order of 1 per minute.

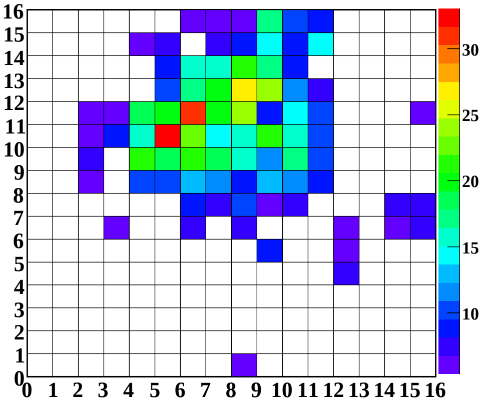

Figure 1: A cosmic-ray air shower image recorded by the TrICE prototype. The scale is given in relative charge for each pixel within a 38 ns integration window. The angular width of a pixel is 0.086°

Examples of air shower images taken with the TrICE prototype are shown in Figures 1 and 1. The angular size of the pixels is 0.086°. The full field of view is 1.5°. The images are displayed in units of relative charge. Pixels with charge falling below an image “cleaning” threshold appear as blanks in these images.

Conclusions

The TrICE prototype telescope is complete and commissioning is nearly finished for the high resolution imaging Cerenkov camera. This instrument is designed to test instrumentation that will allow

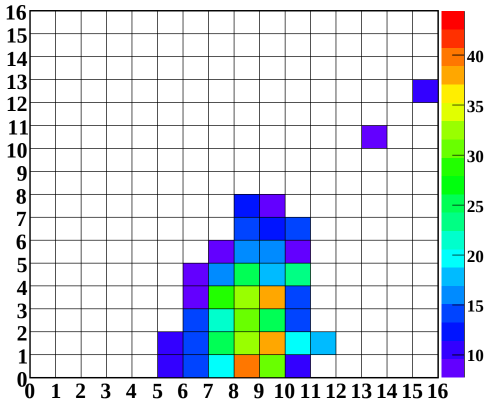

Figure 2: Same as Figure 1

improved measurements of DČ emission from primary cosmic rays. Several challenges to adapting MAPMT technology to an IACT camera have been addressed. The air shower images shown here demonstrate the preliminary performance of the high resolution camera.

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