Atmospheric Cherenkov Detectors at Milagro to Measure Cosmic-Ray Composition Above 50 TeV

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Abstract

The Wide Angle Cherenkov Telescope (WACT) experiment is currently being constructed at the Fenton Hill Observatory, located near Los Alamos, New Mexico. WACT consists of six air Cherenkov telescopes, each with 3.8 m^2 mirrors, distributed over an area of about 60,000 square meters. WACT samples the lateral distribution of Cherenkov light from cosmic rays at various distances from the core and is thus sensitive to the height of maximum shower development. WACT is being built around the Milagro gamma-ray observatory. Milagro has the ability to locate the core and measure the hadronic and muon content of the extensive air showers. These features are crucial to the determination of the cosmic-ray composition. WACT will be the first ground based detector capable of determining the cosmic-ray composition from above 10^{16}eV down to energies where it has been directly measured by balloon-borne instruments. A general overview, construction status, and preliminary simulation results will be presented.

1 Introduction:

Nearly a century after the discovery of cosmic-rays there is still a great deal we do not know about them. Detection of cosmic-rays is usually accomplished in one of two ways. Cosmic rays are directly measured with balloon and space borne emulsion detectors, or other types of particle detectors high in the atmosphere. This technique is limited by the size of the detector and is not well suited for measuring cosmic-ray fluxes at energies above 10^{15}eV. The second technique uses extensive air showers (EAS) in which the primary creates a cascade of secondary particles that can be detected. These secondary particles can be observed by the Cherenkov radiation they emit, by direct detection of the particles in scintillator arrays, with underground detectors, or by nitrogen fluorescence in the atmosphere. These methods can have large effective areas, but are complicated in that one does not directly observe the primary particle (Cronin, 1999).

The observed energy spectrum of cosmic rays is a power law that falls like $E^{-2.7}$ (Gaisser, 1990). Above 10^{16}eV the spectrum steepens to $E^{-3.0}$. This change in spectral index, known as the knee, occurs between 10^{15}eV and 10^{16}eV and has been of great interest. If the knee represents a change from Galactic to extragalactic cosmic-rays, then one would expect an increasingly lighter composition at higher energies. This could be due to a change in predominant accelerations mechanisms or photo-disassociation of heavier nuclei in the sources. If the knee is a result of increased leakage from the Galaxy, then one would expect to see a heavier composition above the knee. This is a due to magnetic confinement effects in the Galaxy. The ability of the Galaxy to confine a particle is a function of that particles rigidity, pc/Z. Thus, the larger the rigidity the less likely a particle is to be confined in the Galaxy. Unfortunately the knee occurs in an energy regime where the preferred experimental technique also changes and is therefore difficult to measure. The primary objective of WACT is to measure the cosmic ray composition in this region.

Most of the information that we currently have on composition below the knee has been obtained by balloon and space based experiments. Balloon and space experiments can determine the cosmic-ray composition on an event-by-event basis. However they have small effective areas and thus cannot make measurements above the knee due to the smaller flux. Measurement of cosmic-ray composition above the knee has been done with the EAS technique. There are many different type of EAS techniques, but the primary goal is to observe the particles in the shower. Recent experiments using EAS techniques have shown that the knee is not as sharp, as was previously believed (Amenomori et al., 1996). There are, however, some discrepancies in the results of different EAS experiments in regards to composition. For instance DICE (dual imaging Cherenkov experiment) reported a trend towards lighter nuclei above the knee (Boothby et al., 1997), while other experiments have reported a more massive composition (Bernlöhr et al., 1998). Better measurements of composition in this energy regime are necessary to achieve an understanding of the physical processes governing the acceleration of cosmic-rays. Figure 1 shows different shower max measurements from various experiments. Shower max is a measurement of the depth at which one finds the largest number of particles in an EAS. This depth is sensitive to composition.

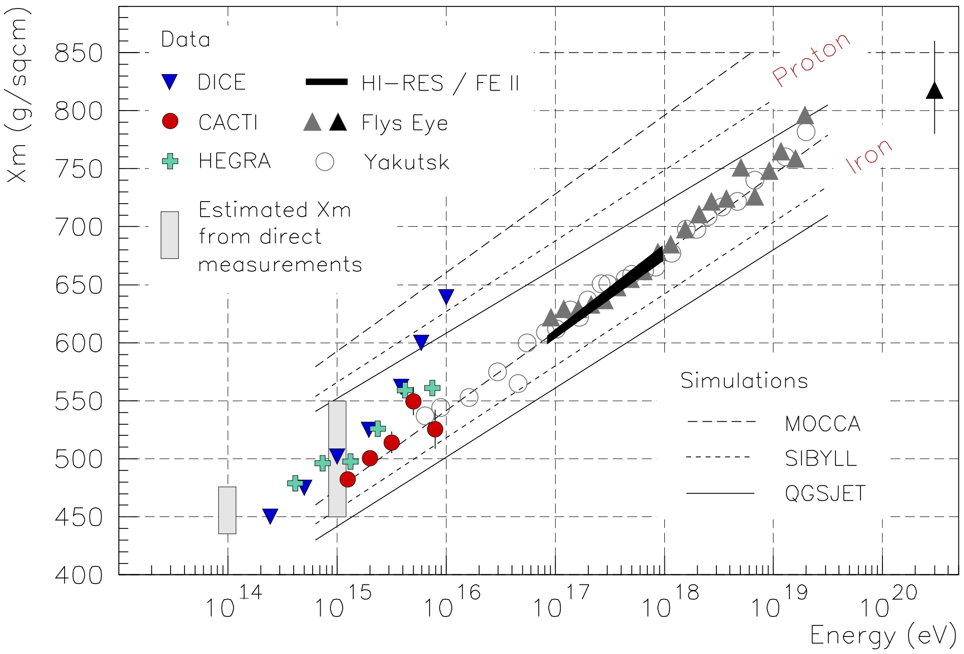

Figure 1: Measured and inferred shower max from different experiments. The solid and dashed lines represent expected shower max from different simulations. Note the trend towards lighter nuclei reported by DICE. It should also be noted that the last to DICE points have large error bars that are not shown (Paling, 1997).

2 Experimental Technique and Description

The technique that WACT will use to determine cosmic-ray composition is based on the sensitivity of the lateral distribution of Cherenkov light to the depth of shower max (Patterson & Hillas, 1983). Most of the Cherenkov light generated in an EAS is created at shower max. One would expect to see a flatter lateral distribution for showers initiated by particles that interact higher in the atmosphere. Therefore, a measurement of the Cherenkov distribution will yield the depth of shower max. The number of Cherenkov photons in an EAS depends on the energy of the primary particle.

To determine the energy of the primary particle and the species WACT will make measurements of the Cherenkov light at various distance from the core. The intensity of the Cherenkov light far from the shower core determines the energy of the primary. CORSIKA simulations have shown that the logarithm of lateral distribution of Cherenkov light varies with the distance to shower core but is close to linear over the region from 50 to 200 meters. The slope of the fitted line depends on composition as seen in Figure 2, and the intercept at 140 meters is a good indicator of primary energy.

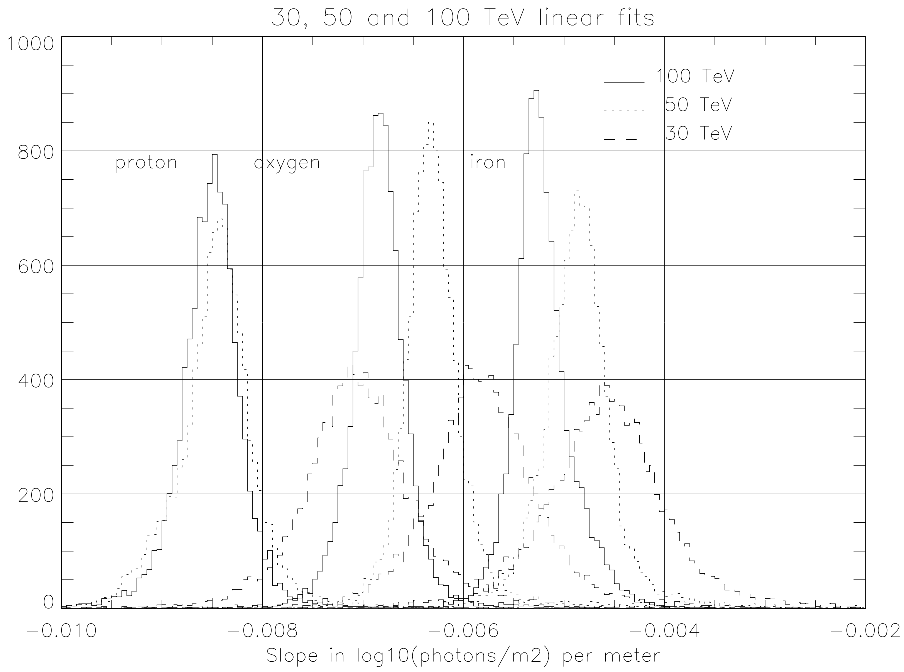

Figure 2: Measured slopes from CORSIKA simulations for different energy and different species. These slopes are measured in the linear region of the lateral distribution of Cherenkov radiation.

WACT will consist of six Cherenkov telescopes surrounding the Milagro gamma-ray observatory; 3 telescopes at about 60 m from the center of the pond and 3 telescope at 120 meters from the pond. Each telescope has a 3.8 m^2 spherical mirror of focal length 2.35 meters. Suspended over the mirror will be a camera consisting of 20 to 25 two-inch diameter PMT's each with a light cone to give a field of view of 2 degrees per PMT. Each telescope is placed on a cement pad and is covered by a steel frame cloth building that can slide off the pad during periods of operation. WACT will have an effective area of about 60,000 m^2 for showers with 2 telescopes close to the shower core (30 meters) and two or more located around 100 meters from the core.

Milagro is a gamma ray observatory that detects the Cherenkov light generated in water by the secondary particles of the EAS. It consists of a covered pond that has a geometric area of about 5000 square meters located at 2650m above sea level (750g/cm^2). Two layers of PMT's are suspended in the water. The top layer of tubes is below 1.5 meters of water and the bottom layer (hadron layer) is below 6.5 meters of water. Unlike other ground arrays, Milagro has a fully sensitive area, thus it can directly observe nearly all the particles (in the 5000 m^2 area) in an EAS at ground level. The combination of Milagro and WACT will allow a measurement of the atmospheric Cherenkov light from the shower, the core location, the electron, muon, and hadronic content of the shower, and the energy and direction of the primary. It is this combination that allows us to make a complete picture of the EAS. The WACT data will be bundled with the Milagro data stream and will use the same time over threshold (TOT) method used in Milagro to measure the PMT signal size. The TOT method works, as the name implies, by measuring the time that the signal from a given tube is above a predetermined threshold. This time is approximately proportional to the logarithm of the pulse charge (Atkins et al.). By using the TOT method we can use the electronics already developed by the Milagro experiment with minor modifications. This not only simplifies the development of the electronics, but is also less expensive in that the TOT method does not require the use of analog to digital converters.

3 Status and Future

The WACT experiment is in the early stages of construction. The mirrors are the prototypes from the Hi-Res Fly's Eye cosmic-ray experiment and have been prepared for use with WACT. Construction of the building for the first telescope will be completed by the end of April 1999. PMT testing is being done at Los Alamos National Lab and electronics are being provided by the University of California at Santa Cruz. The night sky background has been measured and is low enough to use the TOT method. By the end of the summer of 1999 we should have completed a prototype telescope at Fenton Hill. By the summer of 2000 we should have completed all six telescopes and will start full data taking. A full detector simulation is currently being prepared at Los Alamos and at New Mexico State.

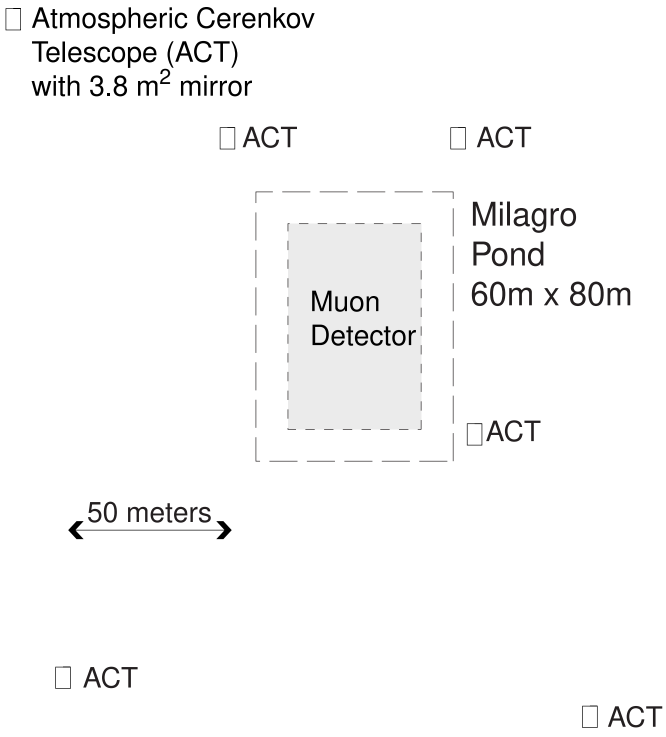

Figure 3: Placement of WACT telescopes relative to Milagro.

4 Conclusions

The WACT experiment will provide information about comic-ray composition above and below the knee, and will therefore be able to overlap with both direct and indirect measurements. The combination of WACT and Milagro will provide a more complete picture of extensive air-showers in this energy range above and below the knee. WACT will also provide a way of checking the energy resolution and angular resolution of Milagro.

5 Acknowledgements

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References

Amenomori, M. et al. 1996, ApJ 461, 408
Atkins, R. et al. 1999, Proceedings from the 26th ICRC
Bernlöhr, K. et al. 1998, Astrop. Phys. 8 253
Boothby K. et al. 1997, ApJL 491, L35
Cronin, J.W. 1999, Rev. Mod. Phys. 71 2 S165
Gaisser, T.K. 1990, Cosmic Rays and Particle Physics (New York: Cambridge University Press)
Paling, S.M. 1997, Ph.D. Thesis, Dept. of Physics and Astronomy, University of Leeds
Patterson, J.R. & Hillas, A.M. 1983, J. PHYS. G: Nucl. Phys. 9 1433