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LA-UR- 98-1526

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Author(s): Gus Sinnis*, Todd J. Haines
P-23

Cyrus M. Hoffman
P-DO

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Abstract

This is the final report of a three-year, Laboratory Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). The goal of this project was to develop a new technique using ground-based measurements to determine the cosmic-ray composition at energies around 10^{15} eV (the "knee" in the cosmic-ray spectrum). Cosmic rays are high-energy nuclei that continuously bombard the earth. Though cosmic rays were first detected in the 1870s it wasn't until 1915 that their cosmic origin was established. At present, we still do not know the source of cosmic rays. At energies above 50 TeV (1 TeV = 1 trillion electron-volts) we do not know the composition of the cosmic rays. At about 5 PeV (1PeV = 10^{15} eV) the cosmic ray spectrum steepens. Knowledge of the composition above and below this point can help determine the origin of cosmic rays.

Background and Research Objectives

The origin of cosmic rays has eluded researchers for nearly a century. The

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*Principal Investigator, e-mail: gus@lanl.gov composition of the cosmic rays is perhaps the single most important clue to this fundamental problem in cosmic-ray research. The cosmic-ray spectrum Figure 1 is well characterized by a broken power law. At energies below ~5 PeV the differential spectral index is –2.7. Above this energy the spectrum steepens and follows an $E^{-3.0}$ power law. This feature, known as the "knee" in the cosmic-ray spectrum, is not understood. It may be due to the confinement of cosmic rays within our galaxy or it could be an indication of the presence of another source of cosmic rays, perhaps an extragalactic source. If the cosmic-ray composition is predominantly heavy (iron) and does not show a change across the knee, than the galactic confinement mechanism is favored. If the composition gets progressively lighter across the knee (i.e. from iron to protons) this would favor the presence of an extragalactic source of cosmic rays. Our goal was to measure the cosmic-ray composition above and below the knee in the cosmic-ray energy spectrum.

Balloon experiments have measured the composition of cosmic rays with energies up to about 50 TeV; however, the low flux at higher energies necessitates experiments with larger effective areas than can be flown in balloons or satellites. Therefore ground-based experiments that detect the cascades of secondary particles (extensive air showers or EAS), which are produced as the energy of the primary cosmic ray is dissipated in the atmosphere, have been employed at energies above 100 TeV. This natural amplification comes at great expense. The nature of the primary particle must be inferred from a measurement of the secondary particles. Previous attempts to do this have met with limited success.

We have developed a new approach to ground-based measurements of the cosmic-ray composition. This new approach involves the measurement of the lateral distribution of the Cerenkov light generated by an extensive air shower. The Cerenkov density near the "core" of the EAS (the location that the primary particle would have hit the ground in the absence of the atmosphere) depends on the height of shower maximum (the altitude at which there are a maximum number of electrons). Since higher mass primary particles interact higher up in the atmosphere one can determine the primary composition by measuring the height of shower maximum. The technique we developed provides a measure of the height of shower maximum.

This was the first experiment to make use of this technique, which was invented by one of the authors to measure the cosmic-ray composition above 100 TeV. Since our experiment has been completed, three other groups have begun similar experiments. We took a new idea and fully developed it into a working experiment. Our results have appeared in several conference proceedings are and now being prepared for publication in a refereed journal.

Importance to LANL's Science and Technology Base and National R&D Needs

Basic scientific research has long been a priority at LANL. The development of innovative techniques to solve longstanding problems is a strength for which LANL is recognized throughout the world. We have developed a new technology from its theoretical inception to its realization as a successful experiment. Los Alamos has a long history in cosmic ray and astrophysics. The CYGNUS detector was the first of a new class of air shower arrays, with more than an order of magnitude greater sensitivity than existing arrays. Milagro is again a first, a water Cerenkov detector used to observe cosmic gamma rays.

This experiment has brought a new expertise to LANL's experimental capabilities – the air Cerenkov technique. The experiment has led to the formation of a larger collaboration of scientists from UNM, NMSU, UC Riverside joining with the Milagro experiment to extend the technique into an energy regime where direct comparison with balloon experiments can be performed. This new experiment will further develop the existing technology of air Cerenkov telescopes.

Relatively small experiments such as this one provide a unique opportunity for the training of students. Students on this experiment were able to work on the entire project from inception to completion, and had the opportunity to affect the design and setup of the experiment. One of the students (who will shortly receive his thesis) had essentially full responsibility for building and running the experiment. This type of hands-on opportunity is becoming rare in today's research climate. Yet, it is probably the best training available for young scientists.

Scientific Approach and Accomplishments

When a high-energy cosmic ray enters the earth's atmosphere, it dissipates its energy by producing energetic particles via nuclear and electromagnetic interactions. These particles go on to produce more particles. This multiplication process continues until the average energy in each particle is roughly 80 MeV. At this point mechanisms such as ionization dominate the energy loss and the number of particles in the air shower falls. The number of electromagnetic particles is a maximum at this altitude, known as shower maximum. The particles in the air shower travel together in a thin pancake that grows laterally as it penetrates the atmosphere. The charged relativistic particles generate Cerenkov light in the atmosphere. (Cerenkov light is generated when a charged particle travels through a medium faster than the speed of light in that medium, and is similar to a sonic boom.) The more massive the primary cosmic ray the faster it dissipates its energy, and the higher is shower maximum.

The bulk of the Cerenkov light originates at shower maximum and the total amount of light produced is proportional to the total energy of the incoming cosmic ray. This picture leads to a very simple geometric understanding of the technique we employ to determine the cosmic-ray composition. Since the Cerenkov light is beamed in a narrow cone (opening angle ~1 degree), the density of the light is directly proportional to the distance from the source of light. Therefore, for a given-energy cosmic ray the density of the Cerenkov light on the ground is a measure of the height of shower maximum. In addition, at some distance from the core the density of Cerenkov light is independent of the height of shower maximum (dependent only on the total energy in the primary cosmic ray). Again, there is a simple geometric explanation. The higher the altitude of shower maximum the more spread out will be the pancake of Cerenkov light on the ground. Therefore, the density of Cerenkov light will falloff more slowly as one moves away from the core. So while the Cerenkov light density at the core is smaller the higher shower maximum, the density falls off more slowly for such showers. So there must be a distance at which the densities are equal for the two showers. Thus by simultaneously measuring the Cerenkov light density, near and far from the core one can determine the energy and composition of the primary cosmic ray.

We constructed six large angle air Cerenkov telescopes within the CYGNUS II extensive air shower array at LANL (Alexandreas et al. [1]). Figure 2 shows a layout of the CYGNUS II array and the Cerenkov telescopes. The telescopes were arranged in two groups of three detectors. This geometry maximized the event rate of useful air showers. (To be useful the event must have a good measurement of the Cerenkov light density both near to and far from the core of the air shower.) We collected data and refined the detector for the first two years of the project. During the final year, we analyzed the data. A student (Sean Paling) will complete his Ph.D. on this project in the next several months.

Data was collected during 6 dark periods (clear moonless nights) over the first two years of the project. The Cerenkov signal must be detected in the presence of the night-sky background, which on a clear moonless night has an intensity of roughly 2 trillion photons per square meter per second for a detector looking at the entire overhead sky. Since the Cerenkov light is both beamed and pulsed, (the duration is roughly 5 nanoseconds (billionths of a second) fast electronics are used to detect the Cerenkov pulses. For this experiment, the signals from the telescopes were fed into waveform digitizers with a sampling time of 20 nanoseconds. The data from the waveform digitizers was correlated with the data from the CYGNUS II array. The signals from the CYGNUS II array were used to reconstruct the shower parameters (incoming angle, core position, and number of electrons at ground level). The data from the Cerenkov detectors was then used to determine the intensity of the Cerenkov light near to and far from the shower core.

Figures 3 and 4 show our results along with the predictions from Monte Carlo simulations of extensive air showers and our detectors. In Figure 3 we show the average lateral distribution of all the data taken. The flatness of this distribution indicates a heavy (primarily iron) cosmic ray composition at these energies. Figure 4 shows the measured distribution of a parameterization of the flatness of the lateral distribution. The parameterization we used is the light density close to (40 meters) and far from (140 meters) the core. Shown for comparison are the expected distributions for iron, oxygen, and proton primaries. Again, the data indicate a predominantly heavy composition. However, the width of this distribution indicates that there is an admixture of lighter nuclei in the primary cosmic-ray flux. In Figure 5 we show the measured height of shower maximum (as determined by the measurements of the lateral distribution of the Cerenkov light) as a function of primary cosmic ray energy. Our data indicate that the cosmic ray composition does not change over this energy interval.

We have successfully built and operated an experiment to measure the cosmic-ray composition near the knee in the cosmic-ray energy spectrum. This experiment was the first to successfully employ this technique (developed by one of the authors). Our results support the theory that the cosmic rays are accelerated within our galaxy and the knee in the spectrum is a feature of the galactic confinement mechanism.

Like all ground-based techniques, we are making an indirect measurement of the cosmic-ray composition. Thus, while our measurement is fairly direct (the height of shower maximum), the interpretation in terms of the cosmic-ray composition is dependent upon Monte Carlo simulations of particle interactions. We have used our experience with this detector to design a follow-on project. This will be the first ground-based experiment capable of measuring the cosmic-ray composition at an energy where it has been directly measured by high-altitude balloon experiments (~50 TeV). This will allow for the first direct check of any ground-based measurement of the cosmic-ray composition.

Publication

Paling, S., et al., "Results from the CACTI Experiment: Air Cerenkov and Particle Measurements of PeV Air Showers at Los Alamos", Proceedings of the 25th International Cosmic Ray Conference, **Vol. 5**, p. 253, (1997).

Reference

[1] Alexandreas, D., et al.. "The CYGNUS Extensive Air Shower Array", *NIM* **A311**, p 350-367, (1992).

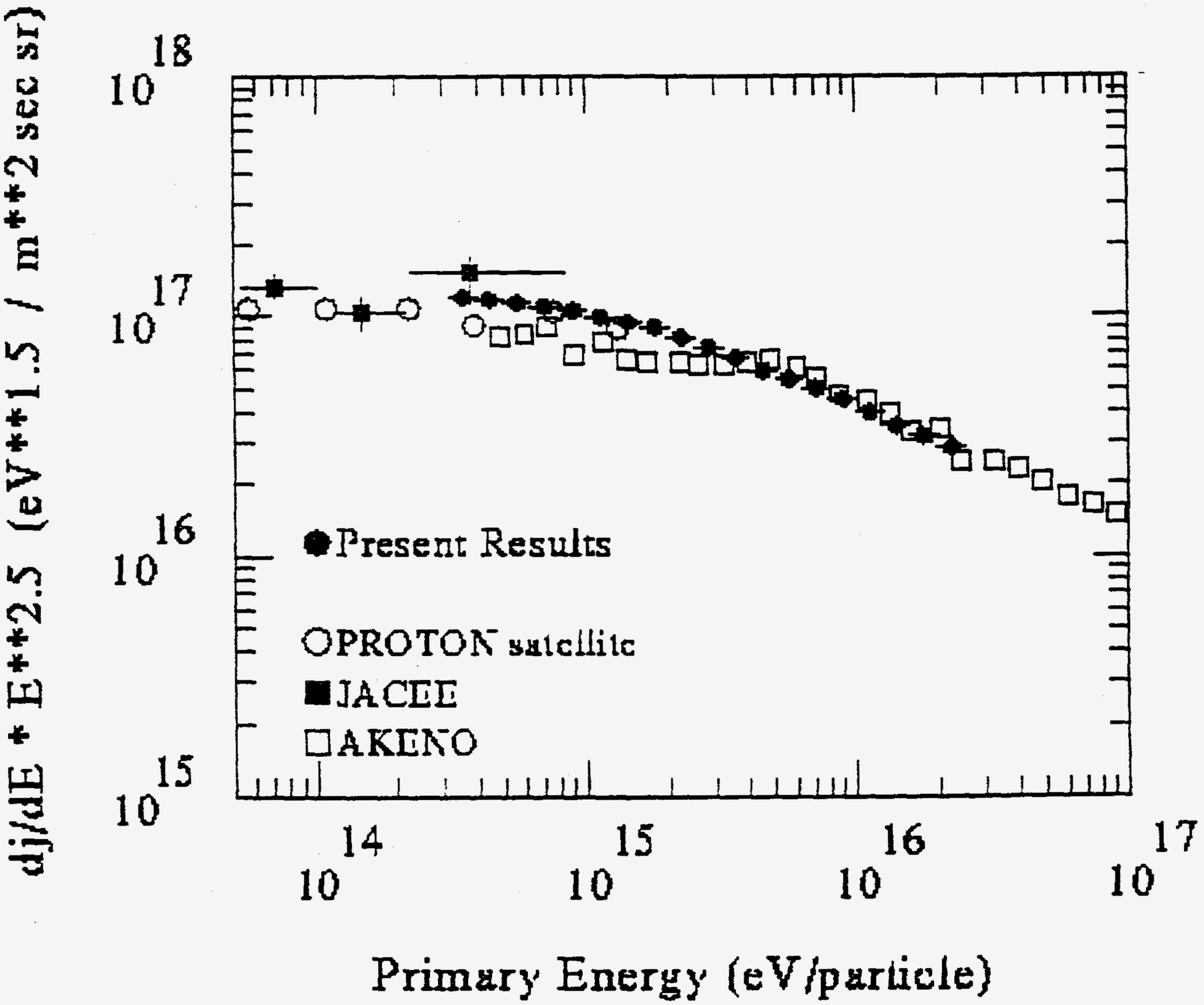

Figure 1. The all-particle cosmic ray energy spectrum. To bring out the features in a steeply falling spectrum the flux has been multiplied by $E^{2.7}$.

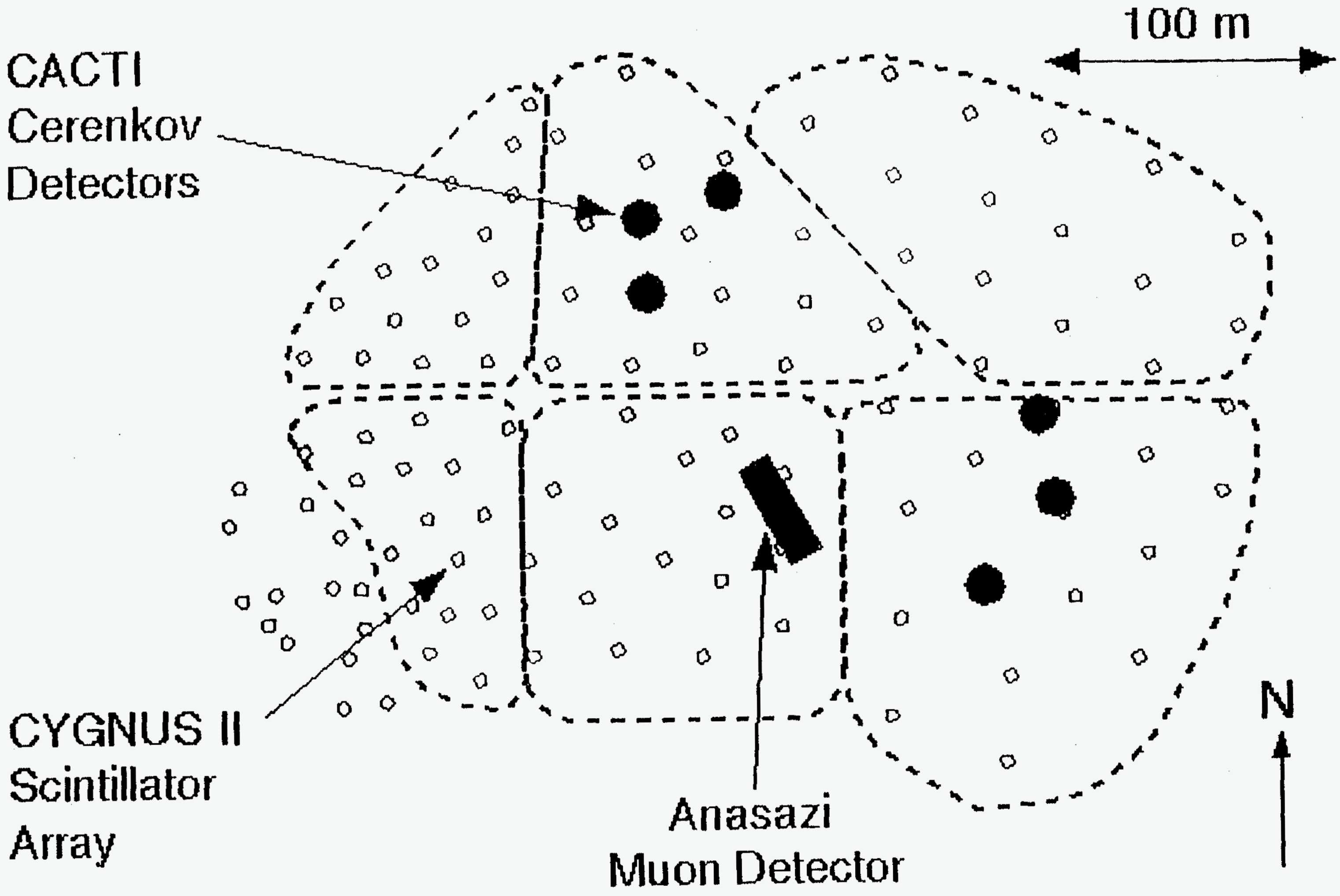

Figure 2. A schematic layout of the CYGNUS II air-shower array and the CACTI air Cerenkov telescopes. The two groups of telescopes are separated by about 150 meters.

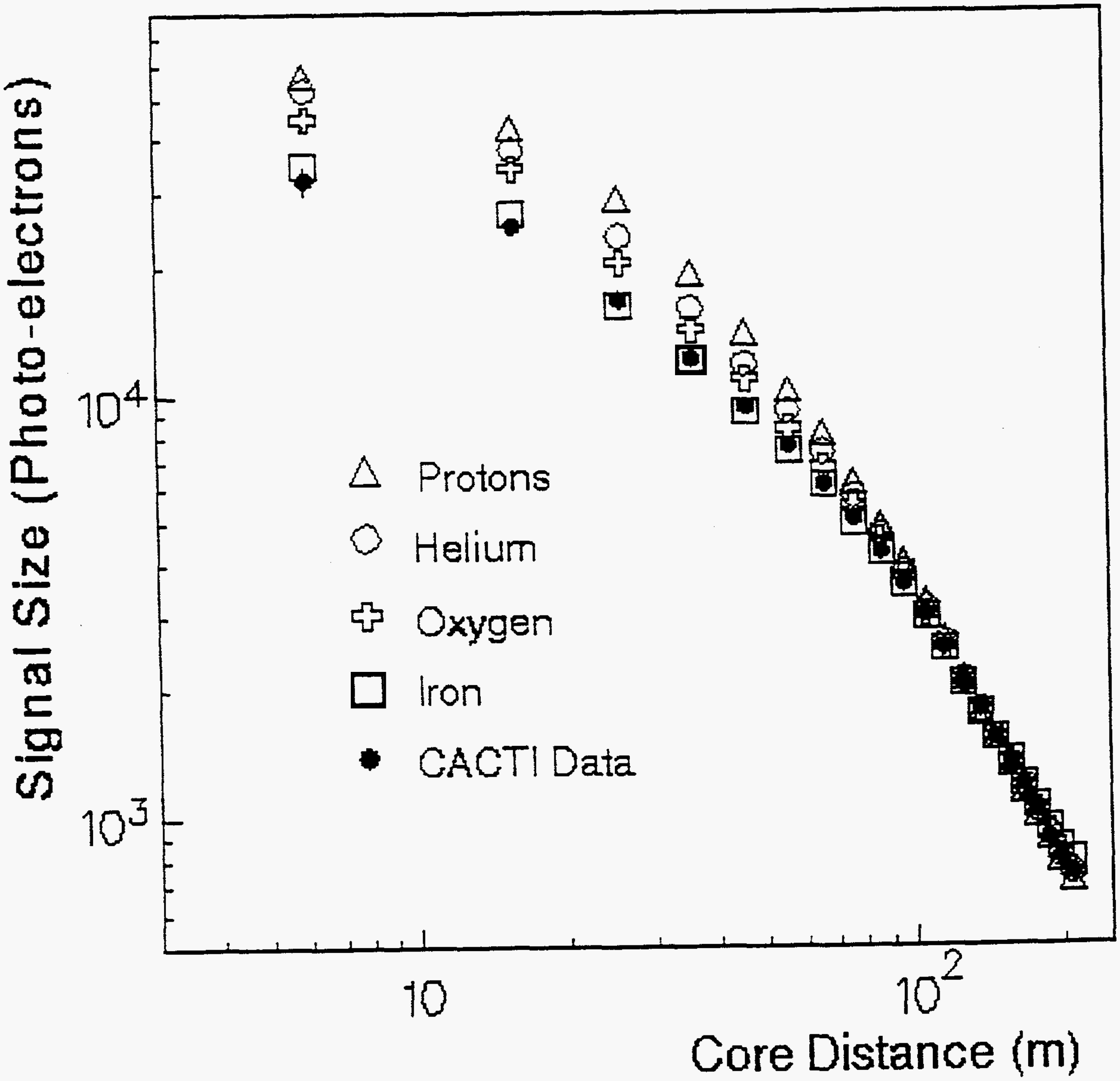

Figure 3. The measured average lateral distribution of Cerenkov light for all showers. Also shown in the figure are the theoretical expectations for iron, oxygen, helium, and proton cosmic rays. The data are well fit by a pure iron composition.

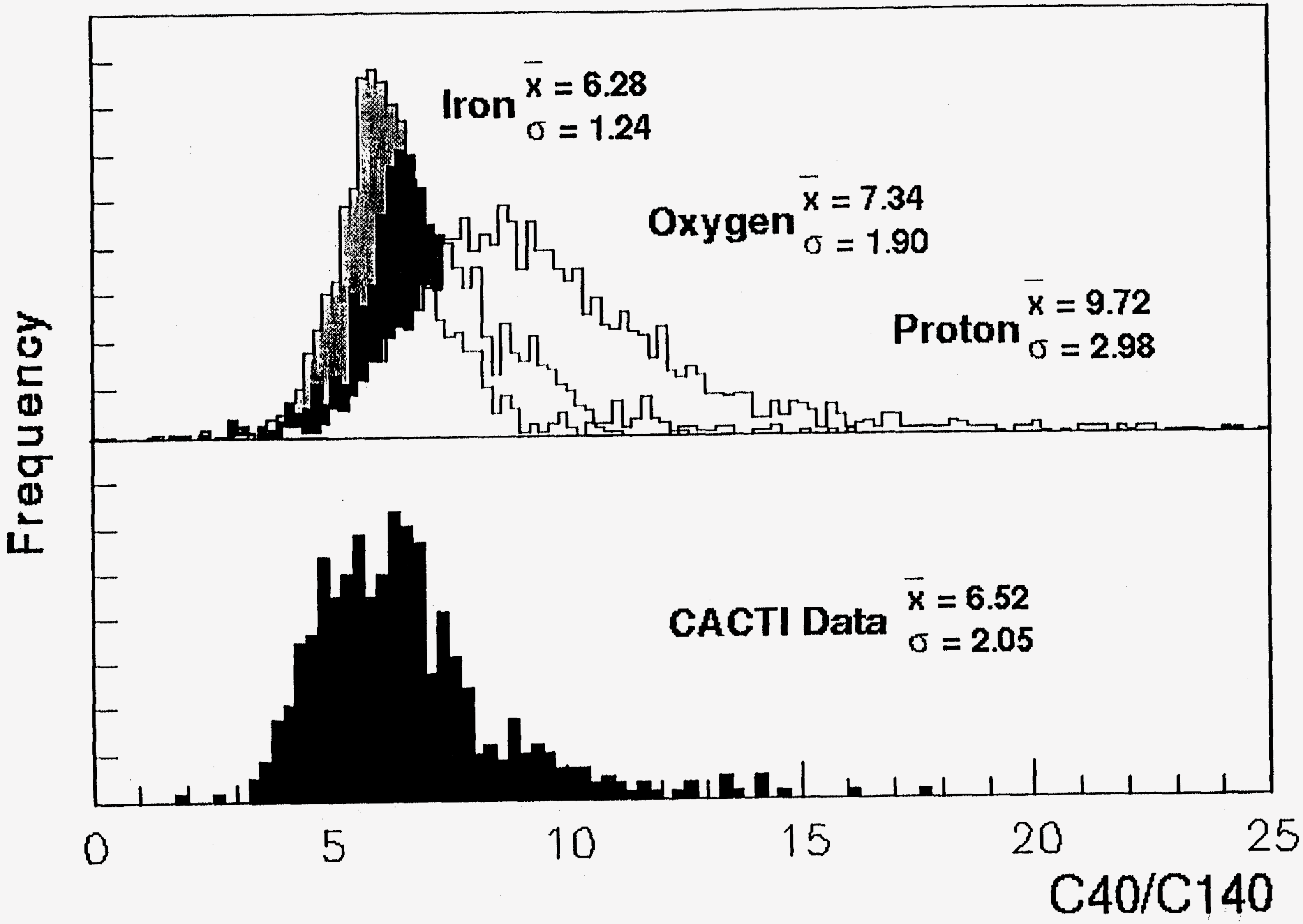

Figure 4. The measured distribution of C40/C140, the density of Cerenkov light at 40 and 140 meters from the shower core. Also shown are the theoretical expectations for iron, oxygen, and proton cosmic rays. In agreement with Fig. 3, the average value is consistent with a pure iron composition. However, the width of the distribution indicates that there is an admixture of lighter cosmic rays.

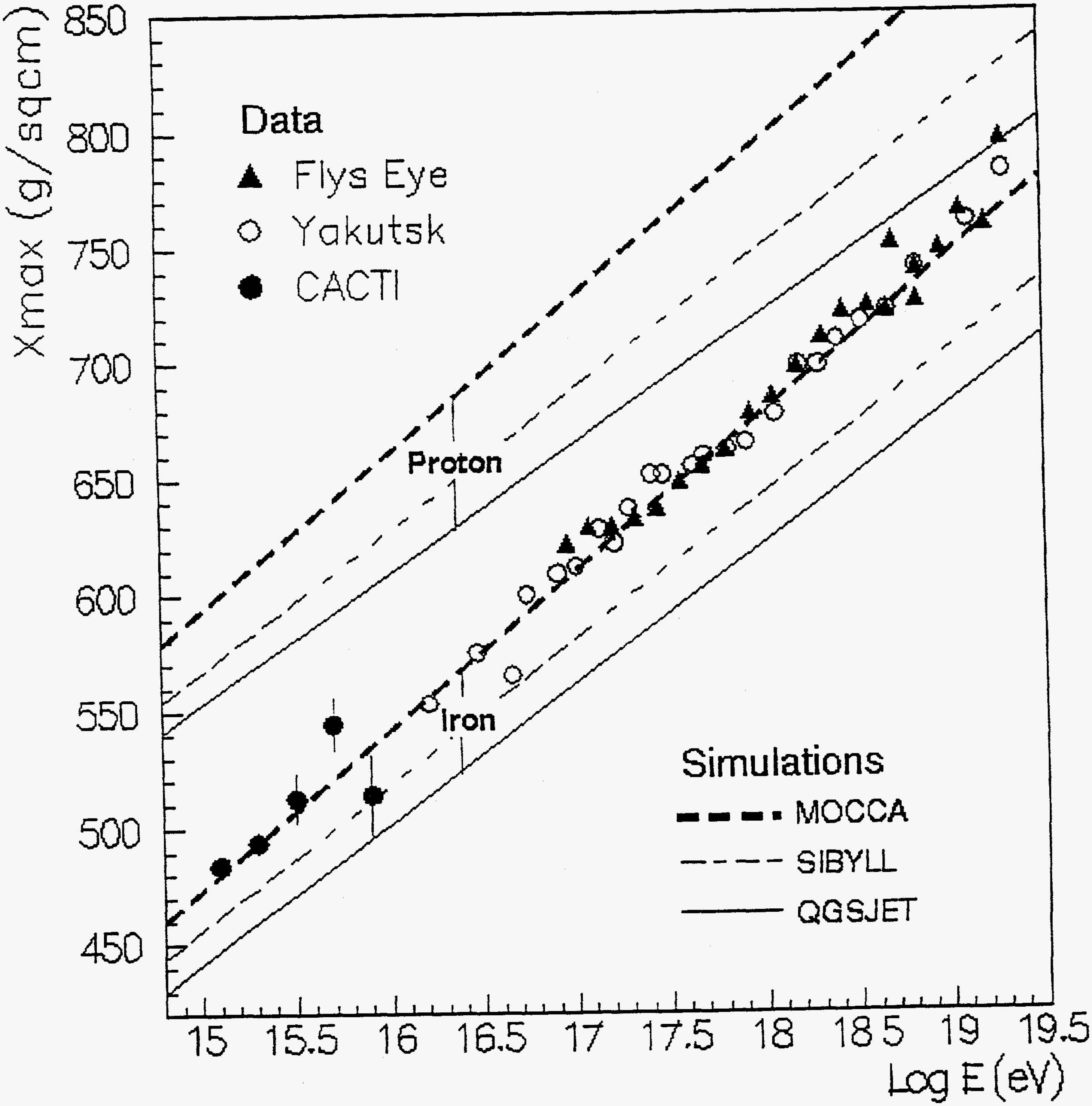

Figure 5. The measured height of shower maximum as a function of cosmic-ray energy. Also shown in the figure are several model predictions for proton and iron cosmic rays and results from experiments performed at higher energies.