MEASUREMENT OF THE COSMIC-RAY ENERGY SPECTRUM AND COMPOSITION FROM 10\(^{17}\) TO 10\(^{18.5}\) eV USING A HYBRID TECHNIQUE

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ABSTRACT

We study the spectrum and average mass composition of cosmic rays with primary energies between 10\(^{17}\) and 10\(^{18}\) eV using a hybrid detector consisting of the High Resolution Fly's Eye (HiRes) prototype and the Michigan Muon Array (MIA). Measurements have been made of the change in the depth of shower maximum as a function of energy. A complete Monte Carlo simulation of the detector response and comparisons with shower simulations leads to the conclusion that the cosmic-ray intensity is changing from a heavier to a lighter composition in this energy range. The spectrum is consistent with earlier Fly's Eye measurements and supports the previously found steepening near 4 \times 10\(^{17}\) eV.

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1. INTRODUCTION

The source of cosmic rays with particle energies above 10\(^{14}\) eV is still unknown. Models of origin, acceleration, and propagation must be evaluated in light of the observed energy spectrum and chemical composition of the cosmic rays. Several experiments have attempted to determine the mean cosmic-ray composition through the "knee" region of the spectrum, up to 3 \times 10\(^{16}\)eV (Fortson 1999; Kampert et al. 1999; Arquerés et al. 2000; Glasmacher et al. 1999b). While the results are not in complete agreement, there is some consensus for a composition that becomes heavier at energies above the knee, a result consistent with charge-dependent acceleration theories or rigidity-dependent escape models.

In the region above the knee, the Fly's Eye experiment has reported a changing composition from a heavy mix around 10\(^{17}\) eV to a proton-dominated flux around 10\(^{19}\) eV (Bird et al. 1993). This result makes this particular energy region much more interesting than the expectation from a naive rigidity model. This changing composition may imply that there are multiple sources of cosmic rays. The AGASA experiment shows broad agreement with this trend if the data are interpreted using the same hadronic interaction model as used in the Fly's Eye analysis (Hayashida et al. 1995; Dawson, Meyhandan, & Simpson 1998).

The recently reported High Resolution Fly's Eye/Michigan Muon Array (HiRes/MIA) (Abu-Zayyad et al. 2000a) hybrid observation of the cosmic-ray composition in a narrower energy region, 10\(^{17}\)–10\(^{18}\) eV, shows a general agreement with Fly's Eye experimental result. The new result gives a somewhat more rapid change in the composition. The reliability of these experimental results depends on how well the development of all components of extensive air showers (EAS) produced by cosmic rays is understood, how well the response of the detector to the EAS is modeled, and how well the EAS reconstruction is done. In this paper, we address all these issues in detail. We begin with a general description of the techniques of cosmic-ray composition measurement in the high-energy region.

1.1. Existing Techniques of Composition Measurement above 10\(^{17}\) eV

The Fly's Eye and AGASA experiments use different techniques to study composition. The Fly's Eye experiment technique is based on the assumption that the rate of development of an EAS depends on the mass of the primary particle: a heavier nucleus induces earlier EAS development in the atmosphere. The rapid breakup of a heavy nucleus at the start of the air cascade leads to a higher multiplicity than that produced by a light nucleus or a proton at the same depth in the atmosphere. The EAS is then built up by a superposition of smaller subshowers induced by nuclear fragments. Since the subshowers have lower energies, the EAS will have a shower maximum higher in the atmosphere than in the case of a proton primary. The Fly's Eye experiment is designed to measure the size, or total number of charged particles, of an EAS as a function of atmospheric depth. It is thus an ideal detector to measure the depth of maxima of showers directly.

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In practice, the intrinsic fluctuations in the depth of shower maximum and detector resolution effects imply that one cannot directly resolve the type of primary nucleus on an event-by-event basis. What one can do is to extract an average EAS primary composition by comparing the data to a Monte Carlo simulation with a given primary composition. Since the shower development is somewhat dependent on the choice of a hadronic model, this method leads to results that have some model dependence.

The other method for studying composition depends on the assumption that the muon content of EAS produced by a superposition of subshowers (as in the case of heavy nuclei) is larger than those with fewer subshowers. This is due to the fact that the dissociation of a heavy nucleus produces a relatively higher multiplicity in its interaction with atmospheric nuclei. The resulting sharing of the primary energy between the nuclear fragments makes the secondary pions less energetic. As a consequence, those pions have a greater probability of decaying into muons than those produced by a lighter nucleus in the early stage of shower development. This leads to a difference in the muon content between the EAS’s induced by heavier and lighter nuclei, e.g., iron and protons. This difference shrinks with energy because the available path for the decay of the high-energy pions decreases as the shower develops deeper in the atmosphere. According to simulations, the difference is still resolvable in the energy region $10^{17}$–$10^{18}$ eV.

In principle, one can obtain information about the composition of the primary particle by measuring either the total number of muons in the EAS or the local density of shower muons at a specific distance from the core of the shower. As in the previous method, the fluctuations are large compared to the separation between the different nuclear species, so that the resolvability is not strong. The hadronic model dependence of the predicted $\mu$-content from a particular composition is also significant for this method.

### 1.2. Advantages and Challenges for the HiRes/MIA Experiment

The HiRes/MIA hybrid experiment is designed to combine the two methods using two independently developed co-sited experiments. The two experiments share a trigger to simultaneously record both the longitudinal development information and the EAS muon density. This results in a unique data set useful for the investigation of cosmic-ray composition. Results of the comparison of the fluorescence and muon methods have been previously published (Abu-Zayyad et al. 2000a). In this paper, we use the MIA array to improve the geometrical reconstruction and concentrate on the fluorescence technique for composition and spectrum studies.

The hybrid timing information enhances the accuracy of the determination of the geometry of the EAS. This accurate shower geometry plays a crucial role in the subtraction of the Cerenkov light component of the EAS and in the corrections for detector acceptance. These turn out to be the two key issues in the shower longitudinal development profile determination. This profile directly provides the size at shower maximum and its location, while the integral of the profile yields the shower energy. The improvement in shower geometry determination over what is possible with a monocular fluorescence detector is the main advantage of a hybrid experiment. The other advantage resulting from the coincident measurement with the surface muon array is the existence of a fully efficient triggering region in the central detector volume. This is very helpful for the cosmic-ray energy spectrum measurement.

One of the challenges for this experiment is that the two devices are separated by only 3.3 km. Because the MIA detector cannot be triggered by remote showers, most of the triggered events are located $\sim$4 km away from HiRes detector. This short shower-detector distance gives rise to difficulties for reconstruction of those EAS’s. The lateral distribution of shower electrons is no longer a negligible effect. The broadened source of light increases the uncertainty in the shower geometry determination and in the acceptance correction of the signals. The limited effective trigger area of MIA largely suppresses the aperture of the HiRes detector. The energy coverage of these data is 1 decade of magnitude over 3 yr of observation, much smaller than that from the Fly’s Eye experiment. The geometry of the triggered events is such that the fraction of Cerenkov light is often large. This implies the need for tight criteria for event selection to reduce Cerenkov contamination, which in turn may cause a bias. A balance between the tightness of the selection criteria and the minimization of bias must established. The resolution of these problems is described in the following sections.

### 2. HiRes and CASA/MIA Experiments and Hybrid Observation

This experiment uses a hybrid detector consisting of the prototype HiRes air fluorescence detector and the MIA. The detectors are located in the western desert of Utah, at longitude 112° west and latitude 40° north. The HiRes detector is situated atop Little Granite Mountain at a vertical atmospheric depth of 860 g cm$^{-2}$. It overlooks the CASA-MIA arrays some 3.4 km to the northeast. The surface arrays are some 150 m below the fluorescence detector at an atmospheric depth of 870 g cm$^{-2}$.

#### 2.1. The HiRes Detector

The HiRes prototype has been described in detail elsewhere (Abu-Zayyad et al. 1999). It views the night sky with an array of 14 optical reflecting telescopes. They image the EAS as it progresses through the detection volume from 3° to 70° in elevation, 64° in azimuthal angle at the top and 32° at the bottom of the field of view. Nitrogen fluorescence light (in the 300–400 nm band) is emitted at an atmospheric depth $X$ in proportion to the number of charged particles in the EAS at each depth, $S(X)$. The triggered tube directions and the time of arrival of light signals can be used to determine the shower-detector plane and the tilt angle of the shower in this plane, denoted by $\psi$. Part of the shower development profile (at least 250 g cm$^{-2}$ long) can be mapped by measuring the light flux arriving at the detector. Assuming $S(X)$ to be the Gaisser & Hillas (1977) shower development function and correcting for Cerenkov light contamination and atmospheric scattering effects, one can measure the primary particle energy, $E$, and the depth, $X_{\text{max}}$, at which the shower reaches maximum size (Baltrusaitis et al. 1985a, 1985b).

#### 2.2. The MIA Detector

The MIA detector (Borione et al. 1994), consisting of 16 patches formed with 64 scintillation counters each, covers about $370 \times 370$ m with the active area over 2500 m$^2$. The
patches are buried about 3 m under the surface. The data-acquisition system records the identity and firing time of each counter participating in a given event. The EAS muon arrival times are measured with a precision of 4 ns, and all hits occurring within 4 µs of the system trigger are recorded. The average efficiency of MIA counters for detecting minimum ionizing particles was 93% when they were buried, and the average threshold energy for vertical muons is about 850 MeV. The MIA detector determines the muon density via the number and pattern of hit counters observed in the shower (Green 1990).

2.3. The Hybrid Trigger and Event Sample

The HiRes detector collects data on clear moonless nights. A focal plane camera, consisting of 16 × 16 photo-multiplier tubes (PMT), is triggered if two of its 4 × 4 "subclusters” contain at least three fired tubes (two of which must be physically adjacent) in a 25 µs interval. Tubes trigger if the signal generates a voltage greater than a threshold, set at approximately 4 e above night-sky background noise. This yields a mirror trigger rate of about 30–120 per minute. Once a trigger is formed, HiRes sends a xenon light flash to MIA as a confirming trigger for a coincident event.

MIA has a 100% duty cycle and a trigger rate of about 1.5 Hz, formed by requiring that at least six patches fired (with at least three hits found in each patch). However, a coincident event is not selected until it is either confirmed by a HiRes light flash communication signal received within 50 µs, or the event triggers CASA (a surface scintillation detector array for EAS electron observation; Borione et al. 1994) simultaneously and is coincident with a HiRes event within ±3 ms according to the WWVB clocks in each site. More details about the trigger formation and coincident event matching can be found in Brain (2000).

During the lifetime of this hybrid experiment between 1993 August 23 and 1996 May 24, the total effective coincident exposure time was 1532 hr. A total of 2881 coincident events were recorded. For each event, the shower trajectory, including arrival direction and core location for each event, is obtained in an iterative procedure using the information from both HiRes and MIA (Brain 2000). A total of 2491 events survive this reconstruction procedure. Further cuts are performed in order to achieve the high resolution in energy and shower maximum essential to the composition study. The initial trial shower arrival direction is determined by fitting the muon arrival time with a flat shower front. Projecting this direction onto the shower-detector plane yields the tilt angle of the shower, ψ, defined as the angle between the shower axis and the horizon in the shower-detector plane.

Once ψ is known, the light arrival time, t, on the ith fired HiRes tube is fitted to the timing formula,

\[ t_i = t_0 + \frac{R_p}{c} \cot \frac{\chi_i + \psi}{2}, \]

in which \( \chi_i \) refers to the elevation angle of the ith fired tube. Here \( t_0 \) and \( R_p \) are two parameters indicating the time as the shower front passes the detector and the perpendicular distance from the shower axis to the detector, respectively, and \( c \) is the speed of light (see sketch in Fig. 1).

The core location can be found by using the shower-detector plane normal vector, \( \psi \), and \( R_p \). The shower front shape can now be more accurately represented as a cone with the delay parameter \( \Delta = ar + br^2 \), where \( \Delta \) is the delay of a conical muon front relative to the original flat front at a perpendicular distance, \( r \), to the shower axis. This procedure is iterated after additional corrections, including correction to the shower-detector plane direction. This iteration stops when the difference between the core parameters is less than 10 m. The details of this iterative procedure can be found in Brain (2000). The distributions in \( R_p \), \( \theta \), and \( c \) are shown in Figures 6 and 7 below, and compared with Monte Carlo predictions.

2.5. Shower Longitudinal Development Reconstruction

The HiRes tube signal, consisting mainly of the fluorescence light produced by charged particles from the shower, can be used to reconstruct the shower development, i.e., to calculate the shower size at the corresponding depth in the atmosphere. However, the raw tube signal requires a number of corrections.

![Fig. 1.—Illustration of shower geometric parameters in the shower-detector plane. Here \( \chi_i \) is the elevation angle of the ith fired tube; \( t_0 \) and \( R_p \) indicate the time as the shower front passes the detector and the perpendicular distance from the shower axis to the detector, respectively; and \( \theta_i \) is the viewing angle between the detector pixel viewing direction and the shower axis.](image)
If a triggered tube has a center that is not exactly in the shower-detector plane, its signal requires correction for a number of effects. These include the finite transverse width of the shower due to multiple scattering of shower electrons, the finite size of the optical spot on the face of the focal-plane camera, the response function of the PMT cathode, gaps between the pixels, and the effective light-collecting area of the mirrors. All these effects can be taken into account by performing a “ray-tracing” procedure; namely, the photons from the source direction, which can be wider than a line source because of the lateral distribution of the photons from the source direction, which can be wider than a line source because of the atmosphere. Because the photon distribution is consistent with measurements by Richards & et al. 1999). Therefore, when the shower points toward the detector, the estimate of the Cerenkov light contributing to the size error in each bin. The errors are due to Poisson fluctuations and the pointing directions of each effective angular bin. Note that the parameter $X_0$ is the depth at which $N = 0$ according to equation (2). There is no sensitivity to light from early shower development, and $X_0$ is fixed at $-20$ g cm$^{-2}$ in the fitting procedure. The justification for this is given below. The choice of this EAS longitudinal development curve has recently been experimentally confirmed (Abu-Zayyad et al. 2000b) as an accurate parameterization using the same data set.

An example of a reconstructed shower is shown in Figure 2. In Figure 2a, the four components of light contributing to the best-fit results are plotted: fluorescence light (thick solid line), direct Cerenkov light (thin solid line), Cerenkov light from Rayleigh scattering (dotted line), and Cerenkov light from aerosol scattering (dashed line). In Figure 2b, the fit of the sum of all the components to the bin signals (filled circles) is given. This shower reaches its maximum size of $(1.65 \pm 0.03) \times 10^8$ at a depth of 627.7 $\pm 9.8$ g cm$^{-2}$.

The error bars in Figure 2 represent the best estimate of the size error in each bin. The errors are due to Poisson fluctuation in the photo-electron number and propagated error from the shower geometry as it affects PMT acceptance corrections.

Figure 3 shows a distribution of residues from the shower longitudinal development fit for the total data set. The residue is defined as $[S_i - S(X)]/\epsilon_i$, where $S_i$ is the signal measured at the $i$th angular bin centered at atmospheric depth $X_i$, $\epsilon_i$ is the estimated error in this bin signal, and $S(X)$ is the corresponding fitting function value. Figure 3 shows a distribution of residues from the shower longitudinal development fit for the total data set. The residue is defined as $[S_i - S(X)]/\epsilon_i$, where $S_i$ is the signal measured at the $i$th angular bin centered at atmospheric depth $X_i$, $\epsilon_i$ is the estimated error in this bin signal, and $S(X)$ is the corresponding fitting function value. Figure 3...
2.6. Shower Energy Determination

Once the longitudinal development profile of an EAS is known, it can be integrated over its depth to calculate the total path length of all shower charged particles, and the total energy, $E_{em}$, deposited by the charged particles in this shower can be evaluated, i.e.,

$$ E_{em} = \int \frac{E_d}{L_0} N(X) dX, $$

where the critical energy and the radiation length of electrons in air are $E_c$ and $L_0$, respectively. A recent study (Song et al. 2000) based on the Monte Carlo simulation package CORSIKA verifies this formula and reevaluates the constant $E_c/L_0$ as 2.19. Since some of the primary energy is carried away by neutrinos and muons penetrating the ground, a correction for this effect must be applied. In that study, the authors establish a new empirical formula for converting $E_{em}$ into the total energy of the shower, $E_0$. It reads

$$ E_0 = \frac{E_{em}}{A - B E_{em}}, $$

where $A = 0.959 \pm 0.003$, $B = 0.082 \pm 0.003$, and $\kappa = -0.150 \pm 0.006$. These parameters are determined by taking an average between proton- and iron-initiated showers, since it is impossible to know the primary particle mass in advance of reconstruction. This causes a systematic uncertainty in $E_0$ of less than 10%.

3. MONTE CARLO STUDY OF DETECTOR RESOLUTIONS

In order to test this complex EAS reconstruction procedure and evaluate the resolution in shower geometry, shower depth of maximum, and energy based on this reconstruction scheme, a Monte Carlo code has been developed to simulate the EAS shower and the detector. It has been made as realistic as possible both for shower development in the atmosphere and for the response of our detector to the shower. This section describes this event generator, including the production and propagation of light through the atmosphere, the acceptance and response of the detector to the light, and the final resolution functions and their relationship to the event quality cuts.

3.1. Shower Generation: CORSIKA Package and Hadronic Interaction Models

The driver of the shower simulation is a series of parameterizations of the results from a full EAS simulation using the CORSIKA package (Heck et al. 1998). This is one of the most modern and complete simulation codes for EAS development. It traces shower particles from very high energy at the top of the atmosphere down to the threshold energy of 100 keV. A “thinning” technique is used in the simulation to reduce the size of the calculation. Only one secondary particle is traced if the interaction energy falls below the thinning threshold, e.g., $10^{-5}$ of the shower total energy. A weight is assigned to this traced particle to represent those not being traced. Depending on the degree of realism required in the fluctuations, the user can set an appropriate thinning threshold if the CPU time limit allows. Another advantage of the CORSIKA code is that the user can switch between several optional hadronic interaction models. The authors have made efforts to test the program for primary...
particle energies up to $10^{16}$ eV, but do not claim reliability for energies higher than $10^{17}$ eV. However, it is one of the best EAS models currently available. Low-energy shower particles, down to the tens of keV level, are treated carefully by employing the well-known EGS package (Bielajew 1993; Bielajew & Rogers 1993), etc.

In our simulation using CORSIKA Version 5.624, the thinning threshold is set to $10^{-5}$ of the shower energy, and the QGSJET (Kalmykov, Ostapchenko, & Pavlov 1997) and SIBYLL (Fletcher et al. 1994) hadronic interaction models are selected. The number of EAS electrons as a function of depth and EAS muon information, including arrival direction, time, and energy for every muon above 870/cos $\theta$ MeV at 870 g cm$^{-2}$ are recorded. Five hundred events were simulated for each of the 5 $\times$ 4 grid points in energy from $3 \times 10^{16}$ to $5 \times 10^{18}$ eV and zenith angle from 0° to 60°. The same number of events were generated for proton- and iron-induced showers and under different hadronic interaction model assumptions.

### 3.2. Shower Longitudinal Development Profile Parameterization

All the distributions of EAS parameters, such as the first interaction depth $X_1$, shower decay constant $\lambda$, shower maximum $N_{\text{max}}$, its position in depth $X_{\text{max}}$, and the correlations between them were parameterized based on this large simulated event data set. As an example, the $X_{\text{max}}$ distribution is shown in Figure 4. It is clear that the proton-induced showers possess larger fluctuation in $X_{\text{max}}$ than iron-initiated ones. Although they overlap each other, the means for each distribution are about 100 g cm$^{-2}$ apart, which is resolvable if sufficient statistics are available. The model dependence appears to be significant, but is smaller than the proton-iron separation. The comparison between the histogram for simulated data and curves for parameterized results shows that the parameterization faithfully represents the fluctuation in $X_{\text{max}}$. A similar situation is found for the other parameters. Among the parameters, we find that $\lambda$ and $N_{\text{max}}$ are correlated, and this correlation is put into the generator.

The parameter $X_0$ is found to be quite insensitive to the type of primary particle and energy when the G-H function (eq. [2]) is used to fit the longitudinal development of simulated showers. The fitting quality is maximized when $X_0$ is fixed at a value of $-20$ g cm$^{-2}$. The other parameter $\lambda$ is found to have a slow variation with energy and mass of the primary particle, with a central value of 70 g cm$^{-2}$. Both are fixed at the values suggested here in the reconstruction procedure for real events. One of the benefits of fixing those relatively insensitive parameters is to reduce the chances of the parameter search being trapped at a local $\chi^2$ minimum.

Once the shower parameters are determined as a function of energy, the number of electrons can be calculated by using the G-H function (eq. [2]) at depth $X$. The electrons are distributed laterally according to the Nishima-Katama-Greisen (NICG) function (Katama et al. 1958) at the corresponding age $s$ of the shower. The fluorescence and Cerenkov light and the corresponding signal appearing at the HiRes detector can then be generated.

### 3.3. Muon Lateral Density and Arrival Time Distribution

The simulation of muons in an EAS is much more complex. The dependence on both zenith angle and energy is important, since the observation is done at a fixed altitude. In order to simulate the MIA trigger correctly, the muon density, $\rho_m(R)$, at a distance $R$ to the core according to the muon lateral distribution is generated. Then $\rho_m(R)$ and its fluctuation behavior are parameterized based on simulations. The muon density generated based on these parameterization is plotted in Figure 5a. For comparison, the AGASA muon lateral density function (LDF; Hayashida et al. 1995) and the Greisen LDF are plotted in the same figure. The simulation, represented by the triangles, agrees with the AGASA LDF well except in the small core distance area, in which our simulation is closer to the Greisen function.

The arrival time of the EAS muons is essential in the simulation of MIA triggering. The distribution of arrival time for each muon in the shower disk within different annular rings at a distance $R$ from the core, and at all zenith angles and energies in the grid mentioned above, is parameterized. The shape of the arrival time distribution changes quite rapidly with $R$, as can be seen in Figure 5c. Note that the vertical scales are different for the different cases. A single function,

$$\frac{dN}{dt} \propto t^\alpha \exp \left(-\frac{t^\beta}{\tau}\right),$$

is used to describe all of these distributions. The parameters $\alpha$, $\beta$, and $\tau$ are tabulated as functions of $R$, energy, and zenith angle. The parameters are generated with due regard to correlations if they exist, and the muon arrival times are generated individually depending on how many muons are generated at $R$ and a specific direction. The median time for muons generated in an annular ring at $R$ reveals the curvature of the shower front. Figure 5b shows two examples at zenith angle $\theta = 0°$ and 40°. The small differences between proton- and iron-induced showers are also shown in the figure. The lines represent the CORSIKA simulation results directly, while the points are produced from our generator, which is based on the parameterization.

### 3.4. Detector Response and Resolution

Once the shower is generated by the CORSIKA-based driver, fluorescence and Cerenkov light contributions are calculated for each 0°:04 angular bin along the axis of the
showers with a spectrum of trial energies from \(10^{17}\) are written in the same format as the real data. Account in the simulation. Both the HiRes and MIA signals accepting counter hits, and noise muons are taken into counter efficiencies, trigger formation, time windows for through the electronics sequentially. Dead counters, given counter is built up by passing all the muon signals generate the arrival time for each of them. The pulse from a shower axis, then run over all muons in each counter to R\(\mu\)ons for each counter at the perpendicular distance \(R\) for the HiRes sample-and-hold electronics.

The MIA signal is generated by sampling the number of muons for each counter at the perpendicular distance \(R\) to the shower axis, then run over all muons in each counter to generate the arrival time for each of them. The pulse from a given counter is built up by passing all the muon signals through the electronics sequentially. Dead counters, counter efficiencies, trigger formation, time windows for accepting counter hits, and noise muons are taken into account in the simulation. Both the HiRes and MIA signals are written in the same format as the real data.

We generate 7000 proton- and 6000 iron-induced showers with a spectrum of trial energies from \(10^{17}\) to \(6 \times 10^{18}\) eV. The differential spectral index is set as \(-3\). All the simulated events are passed through the same reconstruction procedure as the real data, and all geometrical and shower development parameters are determined. Events must pass the “quality cuts” defined below. The overall distributions of simulated events and data are compared in Figures 6, 7, and 8. In those figures the dashed lines represent the showers induced by protons, and the dotted lines those induced by iron nuclei. There is a slight discrepancy found in the \(R_p\) distribution. This reflects the difference between the energy spectrum assumed in the simulation \((E^{-3})\) and the real spectrum, which has more suppression at high energy than the \(E^{-3}\) spectrum. At larger distance, observed events tend to have higher energies. The consistency between the data and simulation builds confidence in the simulation, and hence in the resolution functions we now present. Since the input parameters for every simulated event are known, the detector response and the corresponding resolution function can be studied on an event-by-event basis. In Figure 9, the resolution functions in shower arrival direction, core location, energy, and \(X_{\text{max}}\) are plotted for iron-induced showers. Figure 9a plots the distribution of the “opening angle” between the “real” shower axis vector given by the input shower and the “reconstructed” shower axis vector, which is determined by using the timing information from both HiRes and MIA. Similarly, Figure 9b shows the distribution of the distance between the input shower core and the reconstructed core position. Those two geometrical resolution functions peak at zero, but the long tails imply that some events are measured poorly.

The resolution functions in primary energy and shower maximum depth, respectively, are shown in Figures 9c and 9d. These are the most important results for the energy spectrum measurement and the composition study described in this paper.

3.5. Hybrid “Good” Event Criteria versus Resolution

The better the geometrical parameters of a shower are determined, the better the shower development profile can be extracted. Of all geometrical parameters, the shower-detector plane is the most crucial and depends strongly on how many tubes are triggered and how long the track formed by those tubes is. The number of muons detected by MIA is the other contributor to precise time fitting. In order to locate the shower maximum, it and a good fraction of the rest of the profile must be seen by the detector. Moreover, as mentioned before, we must avoid those events that are dominated by Cerenkov light. Poorly fitted events are also to be rejected. The set of quality cuts listed in Table 1 addresses these issues.

The first four criteria in this table are self-explanatory, while the fifth throws out events that come toward the detector and are dominated by Cerenkov light. This cut reduces the Cerenkov light contribution to less than 75% of the total amount of light in each event. The average Cerenkov light in each event is then about 25%. The last two cuts control the fitting quality.
After these tight cuts, the means and widths of the resolution functions, as shown in Figure 9, are summarized in Table 2. The resolution is significantly improved compared to the Fly's Eye experiment. In that experiment, the energy resolution was 33% (monocular) and 24% (stereo) below $2 \times 10^{18}$ eV (Bird et al. 1994), and the $X_{\text{max}}$ resolution was 50 g cm$^{-2}$, averaged over a broader energy range up to $10^{19}$ eV (Bird et al. 1993). Most importantly, there is no bias observed in the present experiment with these cuts. The resolution functions show negligible systematic shifts, except in energy. Those shifts go in opposite directions for proton- and iron-induced showers. This is discussed further in §2.6.

The other important issue is the energy dependence of those resolution functions. Because of the constraint from MIA, all the well-reconstructed showers are at a similar distance from the HiRes detector. The energy and $X_{\text{max}}$ variables, which are mainly determined by HiRes, have a resolution function that varies slowly with energy. They appear slightly worse at $10^{17}$ eV because of the closeness to the detector threshold. The width of energy resolution...
changes from 48 to 41 g cm

10

shown as Figure 9

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In summary, the validity of the full Monte Carlo code for

the HiRes/MIA detector and for the reconstruction pro-

ceedure is established. The resolutions for all interesting vari-

ables are presented and optimized by selecting “good” events with a set of tight cuts that do not cause bias. With these criteria, 929 real events above $10^{17}$ eV remain. They form the database for this measurement of the energy spectrum and cosmic-ray composition.

4. PHYSICS RESULTS

The cosmic-ray intensity as a function of energy and the cosmic-ray composition in the energy range from $10^{17}$ to $3 \times 10^{18}$ eV is measured using this experimental data set and the detailed Monte Carlo study described above.

4.1. Aperture Estimation

As shown in Figure 8, the shower energy distribution peaks at $3 \times 10^{17}$ eV. This points to a fully efficient detector operation above $4 \times 10^{17}$ eV. The distribution falls off rapidly below $3 \times 10^{17}$ eV because of trigger inefficiency. In order to measure the cosmic-ray energy spectrum, a correction for the detector aperture is necessary.

There are two ways to estimate the aperture of the hybrid detector. The first is to use the full simulation code (calculating the observation efficiency with the same reconstruction) and event selection criteria at several fixed energies in this energy region. The second way is to use the measured core location and arrival direction distributions of the observed events directly.

Above a certain energy, the hybrid detection scheme becomes fully efficient. The detector aperture as a function of energy thus exhibits a plateau. This is also indicated by almost constant event distribution for the events above $4 \times 10^{17}$ eV in an area centered on MIA having a near-zenith solid angle. This flat distribution drops sharply to zero at $1.3 \pm 0.1$ km from the center of MIA and at zenith angles of $\theta > 33^\circ \pm 3^\circ$. Assuming 100% trigger efficiency, this yields an aperture of $5.4 \pm 1.1$ km$^2$ sr. The error mainly comes from the uncertainty in determination of the distribution boundary in both core distance squared to the MIA center and $\sin^2 \theta$. This method avoids the model dependence inherent in the MC simulation. However, the poor statistics (about 200 events) result in a large uncertainty in the aperture. This resulting error box is shown in Figure 10 by the dashed line.

The Monte Carlo method provides a more precise estimate. Based on the 7000 proton and 6000 iron Monte Carlo events mentioned before, plus 2000 simulated events at every point above $10^{18}$ eV for both protons and iron, Figure 10 shows the detector aperture as a function of energy. Above $10^{17.6}$ eV, this simulation shows that the detection efficiency is saturated, and this aperture is consistent with the experimentally estimated result within the errors. Since these two estimates agree with each other well, the Monte Carlo result will be used for the energy spectrum measurement. The feature of a flat aperture as a function of energy, due to the MIA detector, is very useful for the cosmic-ray intensity measurement. The price for this feature, however, is that the aperture is rather small. The MC method provides a calculation of the aperture near detector threshold with good precision. The fluorescence detector has a sharp threshold around $10^{17}$ eV. Since the efficiency drops to lower than 10% below $10^{17.2}$ eV, events below this energy are not included in the analysis.

The Monte Carlo method is also useful for studying the dependence of the detector aperture on the type of primary

![Figure 9](image)

**Figure 9.** Resolution functions of iron-induced showers for (a) arrival direction, (b) core location, (c) shower total energy, and (d) depth of shower maximum. The figures show differences between the generated MC values of those variables and those obtained from the reconstruction of the simulated detector output. The energy error in (c) is defined as $(E - E_m)/E_m$, where $E_m$ is the input from the simulation.

**Table 1**

| Variable                  | Cut       |
|---------------------------|-----------|
| Track angular length      | $> 20^\circ$ |
| $R_{500}$                 | $< 2$ km  |
| $X_m$                     | $X_1 < X_m < X_h$ |
| Depth span                | $X_h - X_1 > 250$ g cm$^{-2}$ |
| $\theta_h$               | $> 10^\circ$ |
| $\Delta X_m$             | $< 50$ g cm$^{-2}$ |
| $\chi^2$ per DOF         | $< 10$    |

Note.—$X_h$ refers to the depth of the highest section and $X_1$ to the lowest section of the shower track seen by the detector; $\Delta X_m$ is the estimated error in $X_{max}$.

**Table 2**

| Variable                  | Proton | Iron |
|---------------------------|--------|------|
| QGSJET                     |        |      |
| $E$ ($\%$)                | 12     | 5    |
| $X_{max}$ (g cm$^{-2}$)  | 47     | 12   |
| $X_{core}$ (m)            | 42     | -2   |
| $Y_{core}$ (m)            | 57     | -2   |
| Space angle               | 0^\circ| 0^\circ|

Note.—Quality cuts have been applied. Space angle errors are median values.
cosmic rays. Our simulation using proton and iron primaries shows that the aperture is very similar even near the detector threshold. The event selection criteria and the requirement for a minimum number of $\mu$s to reach the ground and trigger MIA diminishes any difference between the triggering induced by protons or heavier nuclei.

4.2. Energy Spectrum

Figure 11 shows the cosmic-ray energy spectrum from $10^{17.2}$ to $10^{18.3}$ eV. In order to see the detailed structure of the energy spectrum, the intensity is multiplied by $E^3$. The data support an overall power-law spectrum with an index of about $3.090 \pm 0.066$ and a intensity of $10^{-29.7 \pm 1.5}$ eV$^2$ m$^{-2}$ sr$^{-1}$ s$^{-1}$ at $10^{18}$ eV. A maximum likelihood estimate has been employed for this fitting. The data for this spectrum are listed in Table 3, including the number of events (NOE) and aperture at specific energies. Only the Poisson error in intensity $J$ is listed. At low event numbers, the Poisson error is an underestimate of the true error. Various authors have proposed better approximations to the true error (see, e.g., Regener 1951). The fit results are insensitive to these refinements, however.

As a comparison, the stereo Fly’s Eye (Bird et al. 1993) measured energy spectrum is plotted in the same figure. The difference between the two measured intensities is less than 28% below $3 \times 10^{17}$ eV. The absolute energy scale has a systematic uncertainty of about 25% (Abu-Zayyad et al. 2000a) in this experiment and 40% (Bird et al. 1994) in the Fly’s Eye experiment. The corresponding uncertainties are shown in Figure 11 by the two slant arrow bars. The two measurements of the cosmic-ray energy spectrum are consistent within errors.

The six data points below $5 \times 10^{17}$ eV strongly support a $E^{-3.01}$ spectrum with good statistics. A maximum likelihood fit to those six points is shown by the dashed line in Figure 11. The logarithm likelihood is evaluated by choosing a Poissonian distribution function, i.e., the likelihood is

| log$_{10}(E/eV)$ | $J(E)$ ($10^{-28}$ eV$^{-1}$ m$^{-2}$ sr$^{-1}$ s$^{-1}$) | $\Delta J$ ($10^{-28}$ eV$^{-1}$ m$^{-2}$ sr$^{-1}$ s$^{-1}$) | NOE | Aperture (km$^2$ sr)
|-----------------|---------------------|---------------------|-----|------------------|
| 17.254          | 3.95                | 0.32                | 147 | 1.6              |
| 17.351          | 2.10                | 0.17                | 145 | 2.4              |
| 17.449          | 1.19                | 0.10                | 130 | 3.1              |
| 17.548          | 0.551               | 0.054               | 104 | 4.2              |
| 17.649          | 0.235               | 0.028               | 69  | 5.2              |
| 17.746          | 0.133               | 0.018               | 53  | 5.7              |
| 17.873          | 0.0513              | 0.0069              | 55  | 5.7              |
| 18.096          | 0.0091              | 0.0022              | 17  | 5.9              |
| 18.299          | 0.00207             | 0.00084             | 6   | 5.8              |

* Number of events.
defined as
\[ \xi = \prod_i \frac{e^{-a_i \mu_i^0}}{n_i}, \]
where the index \( i \) runs over all the data points, and the expectation value \( \mu_i \) in the \( i \)th energy bin is the expected number of events. If the \( E^{-3.01} \) spectrum is assumed also to be true for the remaining three points at higher energy, a combined test over these three points shows that the probability is 5.9\% (Eadie et al. 1971). This indicates a marginal conformation for the spectral break in the cosmic-ray spectrum measured by the Fly's Eye and Haverah Park (Watson 1991) experiments.

4.3. Resolvability of Composition: \( X_{\text{max}} \) and ER

As mentioned in the introduction, the distribution of \( X_{\text{max}} \) can be used with the help of Monte Carlo simulations to extract an average composition of primary cosmic rays. The results depend on the hadronic interaction model, the EAS simulation model, and the resolution of the detector in energy and \( X_{\text{max}} \). In this paper, data are compared with the predictions of two hadronic models: QGSJET and SIBYLL. Other, lower multiplicity models have been shown to be inconsistent with any normal composition of cosmic rays.

According to the simulation, the average \( X_{\text{max}} \) for showers induced by protons is separated from the average for iron by about 100 g cm\(^{-2}\), and this separation is almost independent of energy in the range from \( 10^{17} \) to \( 10^{18} \) eV. Since the resolution of the detector is 44 g cm\(^{-2}\), it is possible to tell if the data are closer to one than the other. The absolute position of \( X_{\text{max}} \) for a given composition assumption is model dependent (about 25 g cm\(^{-2}\) shift). At any given energy, a measurement of \( X_{\text{max}} \) implies a particular composition, which is thus systematically uncertain. On the other hand, an apparent departure of the data points from either of the predictions based on proton or iron showers as a function of energy will reveal information regarding the change in the composition of cosmic rays. The rate of this change can be much more reliably determined than the absolute composition itself.

The variation of the separation between the measured and simulated pure composition \( X_{\text{max}} \) can be quantitatively evaluated using the so-called "elongation rate" (ER). Models show that the average \( X_{\text{max}} \) increases with energy logarithmically over the energy range of interest. The "elongation rate" is symbolized by \( \alpha \) in this paper and is defined by
\[ \overline{X_{\text{max}}} \propto \alpha \log E. \]
It is remarkable that the elongation rates are almost the same for proton- and iron-induced showers and nearly independent of the interaction models. They are 58.5 ± 1.3 g cm\(^{-2}\) per decade of energy for proton showers and 60.9 ± 1.1 g cm\(^{-2}\) per decade of energy for iron showers according to the QGSJET model. Any other values for ER observed from the data will indicate a change in composition.

An important issue associated with measuring the elongation rate is the possible existence of a bias caused by tight cuts. To test this, the average \( X_{\text{max}} \) as a function of energy is compared using simulated events. One data set is based on all the CORSIKA-sampled events, and the other is based only on those that trigger the detector, are able to be reconstructed, and pass the tight cut criteria. As shown in Figure 12, no matter what interaction model is used, no bias is seen using the cuts set in Table 1. The thin lines in the figure show the sampled events, and the circles and squares show the reconstructed results (see figure legend for details).

4.4. The Changing Cosmic-Ray Composition

The HiRes/MIA experimental data as shown in Figure 12 demonstrate an unambiguous change in average \( X_{\text{max}} \) with energy. This indicates a progression toward a lighter mix of nuclei in the average composition from \( 10^{17} \) to \( 10^{18} \) eV. The magnitude of this change in composition can be evaluated by using the measured elongate rate, i.e.,
\[ \alpha = 93.0 \pm 8.5 \pm (10.5) \text{ g cm}^{-2}, \]
where the number in parentheses represents the systematic error discussed below. In comparison with the predicted number for an unchanged or pure composition mentioned above, the difference is larger than any known uncertainties. The uncertainty in predicted elongation rate due to hadronic model dependence is small.

The change in the composition in the form of the average logarithm of atomic number of the primary nuclei can be estimated to be \( \Delta \ln A = -1.5 \pm 0.6 \) over the energy range covered by the data. The systematic uncertainty in \( \alpha \) is included here. The absolute value of \( \ln A \) is strongly model dependent, as implied by Figure 12. However, \( \Delta \ln A \) is quite model independent as long as elongation rates are equal for all different pure compositions.

4.5. Uncertainties in \( X_{\text{max}} \) and Energy

Uncertainties in \( X_{\text{max}} \) come from both the choice of theoretical models and detector resolution. In Figure 12, the average difference in \( X_{\text{max}} \) at any given energy between the predictions based on QGSJET and SIBYLL models is about 25 g cm\(^{-2}\). Both are compatible with the data and...
both lead to the same qualitative conclusion of a lightening in the composition. However, the value of the average $\ln A$ at any given energy is model dependent.

A detailed effort has been made to understand the systematic errors in shower $X_{\text{max}}$ and energy. Systematic errors for $X_{\text{max}}$ include the atmospheric transmission of light and in the production of Cerenkov light. These are related, since scattered Cerenkov light can masquerade as fluorescence light if not accounted for properly. For atmospheric scattering, there is uncertainty in the aerosol concentration and its vertical distribution. The uncertainty, equivalent to 1 standard deviation with respect to the mean, is expressed as a range of possible horizontal extinction lengths for aerosol scattering at 350 nm (taken as 11–17 km based on measurements using xenon flashers; Abu-Zayyad et al. 1997) and a range of scale heights for the vertical distribution of aerosol density above the mixing layer (taken as 0.6–1.8 km). For Cerenkov light production, the angular scale for the Cerenkov emission angle is taken as an exponential function of the angle from the shower axis, with a scale of $4^\circ \pm 0^\circ.3$ (Fortson et al. 1999). Those uncertainties are shown by the shaded area in Figure 12.

The systematic error in the energy is about 25% and comes from fluorescence efficiency uncertainty (Abu-Zayyad et al. 1999), detector calibration uncertainty (Abu-Zayyad et al. 1999), and the atmospheric corrections (Bird et al. 1994). The first two are intrinsically independent of the primary particle energy over this range. The fluorescence efficiency has been measured with an error of 10%. The percentage atmospheric corrections are also independent of energy because the sample of showers is restricted to core locations within 2 km of the MIA detector center. Therefore, there is no significant atmospheric path length difference between an EAS and the detector for different energies. An energy-independent systematic fractional error in energy has no effect on the measured elongation rate. The magnitude of the systematic error in energy due to atmospheric attenuation can be estimated by varying the atmospheric parameters over the range described above. It is not greater than 10%. The detector calibration systematics is less than 5%.

4.6. $X_{\text{max}}$ Distribution

Figure 4 shows that the fluctuations about the average $X_{\text{max}}$ for simulated proton showers is larger than that for iron showers. The fluctuations for both proton- and iron-induced showers are too large to distinguish one from the other on an event-by-event basis. However, the gross properties of the composition can be determined statistically. Figure 13 shows the predicted distributions of $X_{\text{max}}$ for proton and iron showers together by dotted and dashed lines, respectively. The detector response has been folded into those distributions. By studying those distributions in different energy ranges, as shown in the figure, one can compare the data to pure proton and pure iron composition distributions. The data clearly require a mixed composition of light and heavy particles to account for the width and peak value of the $X_{\text{max}}$ distribution.

4.7. Comparison with Previous Experiments

The cosmic-ray energy spectra measured by all modern experiments are summarized in Figure 14, covering the

Fig. 13.—$X_{\text{max}}$ distributions. Experimental (filled circles) and simulated data (dashed histogram: iron; dotted histogram: protons) are compared. All distributions are normalized. They imply a mixed composition in all energy ranges.
whole energy range from $3 \times 10^{14}$ to $3 \times 10^{18}$ eV. The consistency between this experiment and the Fly's Eye stereo data has been discussed previously. The present experiment marginally confirms the break in the spectrum at $4 \times 10^{17}$ eV. By comparing with the observations (Nagano et al. 1984; Fowler et al. 2000; Glasmacher et al. 1999a; Swordy & Kieda 1999; Amenomori et al. 1996) in the “knee” region, both the intensity and spectrum index imply a good continuity with the results at energies lower than $3 \times 10^{16}$ eV. The change in cosmic-ray intensity around $3 \times 10^{17}$ eV is comparable in power-law index to the change that occurs around the “knee.” A confirmation of this break with better statistics and similar energy resolution is important. All the other experimental results are consistent with the Akeno result: the spectrum follows a single-index power law between $10^{16}$ and $10^{17}$ eV.

The only existing experimental result based on direct measurements of shower longitudinal development is from the Fly's Eye experiment. As a successor of that experiment, the HiRes/MIA experimental result qualitatively supports the old Fly's Eye's result, i.e., there exists a trend in the composition of cosmic rays to a lighter mix with energy. Quantitatively, they are consistent with each other, taking into account the systematic errors in the original Fly's Eye result of about 25 g cm$^{-2}$ on individual $X_{\text{max}}$ measurements. The elongation rate measured in the HiRes/MIA experiment is marginally larger than that in the Fly's Eye (Bird et al. 1994), which is $78.9 \pm 3.0$ g cm$^{-2}$ per decade, where the quoted error is statistical only. It should be noted that experimentally measured elongation rates are not corrected for acceptance. Differences in acceptance for two experiments could introduce differences in elongation rates. The safest method is to compare each experiment to its own simulated proton and iron data sets. The conclusion as to the composition of cosmic rays based on this kind of comparison is meaningful because the detector effects are counted in exactly the same way for both real and simulated events. For the present experiment, based on our simulation, the detector biases for the elongation rate are minimal. In summary, when all the errors are taken into account, the results on $X_{\text{max}}$ distribution and elongation rates from the two experiments are consistent, in spite of the differences in the analysis.

The other existing result on the elongation rate in the same energy range is from the Yakutsk experiment (Afanasiev et al. 1993) and the Haverah Park experiment (Walker & Watson 1981; Hinton et al. 1999). The systematic error is not provided in Yakutsk experiment, and the method using the ground-array experiments is more indirect than the present experiment. Nevertheless, the results are marginally in agreement with the result reported here.

There are several measurements of elongation rate at lower energies, between $10^{14}$ and few $10^{16}$ eV. These results and the present result are shown in Figure 15. The trend of a changing cosmic-ray composition shows a pattern correlated with breaks in the energy spectrum. It can be characterized qualitatively as follows. There is a rather clear break around $3 \times 10^{15}$ eV, which is related to the “knee” in the energy spectrum. This break seems to be confirmed by several experiments (Fortson et al. 1999; Kampert et al. 1999; Arqueros et al. 2000; Glasmacher et al. 1999b). The elongation rate shows an increasingly heavy composition around this knee. Above $3 \times 10^{17}$ eV, the composition changes to a lighter mix. It seems to be correlated to the spectral break observed by the Fly’s Eye experiment, which is marginally confirmed by this experiment. Those experiments imply a relatively unchanging region between $10^{16}$ and $10^{17}$ eV, but no measurements of the elongation rate exist between $10^{16.4}$ and $10^{17}$ eV.

5. CONCLUSION

The HiRes/MIA hybrid experiment has measured the cosmic-ray energy spectrum between $10^{17.2}$ and $10^{18.5}$ eV. The spectral index and intensity are $-3.090 \pm 0.066$ and

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**Fig. 14.**—Energy spectrum of cosmic rays from $10^{14.5}$ to $10^{18.5}$ eV. This intensity is multiplied by $E^2$. Data in the vicinity of $3 \times 10^{15}$ eV are adopted from Fortson et al. (1999) (Blanca paper). [See the electronic edition of the Journal for a color version of this figure.]

**Fig. 15.**—Average depth of shower maximum as a function of primary energy of cosmic rays. An arbitrary elongation rate of 60 g cm$^{-2}$ is subtracted. Again, the data in the lower energy region are adopted from Fortson et al. (1999) (Blanca paper). Dash-dotted lines represent the simulated result from iron showers, dashed-triple-dotted lines the proton showers. The thick lines are from Fig. 10 of Fortson et al. (1999), and the thin lines from this experiment. [See the electronic edition of the Journal for a color version of this figure.]
10^{-29.7 \pm 1.5} \text{ eV}^2 \text{ m}^{-2} \text{ sr}^{-1} \text{ s}^{-1}, \text{ respectively, at } 10^{18} \text{ eV.}\nThe result is in agreement with the Fly's Eye experiment within errors. This result marginally supports the Fly's Eye stereo observation of a break in the energy spectrum around $4 \times 10^{17}$\text{ eV.}

The HiRes/MIA hybrid experiment confirms the Fly's Eye experimental result that the elongation rate is different from that of a simulation with an unchanging composition. Modern hadronic interaction models and improved detector resolutions in energy and $X_{\text{max}}$ do not change the original conclusion. Within errors, the elongation rate observed in this experiment, $93.0 \pm 8.5 \pm (10.5) \text{ g cm}^{-2} \text{ per decade, is consistent with previous experiments, such as Fly's Eye, Haverah Park, and Yakutsk (Afanasiev et al. 1993). While the conclusion regarding the absolute value of $\ln A$ of the primary composition depends on the interaction model used, this study shows that the elongation rate is stable with respect to choice of models. In light of this, the amount of the change in the average composition, i.e., $\Delta \ln A = -1.5 \pm 0.6$, is largely model independent, no matter what value of $\ln A$ the change starts from.

Putting all experimental results together from $3 \times 10^{14}$ to $3 \times 10^{18}$\text{ eV}, there seem to be correlated patterns in the energy spectrum and elongation rate or $\bar{X}_{\text{max}}$ versus energy plot. Measurements in both energy spectrum and $X_{\text{max}}$ imply a continuity from lower to higher energies, with a flat bridge between $10^{14}$ and $10^{17}$\text{ eV.}

Following the break, the Fly's Eye experiment (Bird et al. 1993) reports a hardening of the spectrum near $5 \times 10^{18}$\text{ eV}. This has been interpreted as evidence for the emergence of an extragalactic component above a softer galactic component (Bird et al. 1993). A change from a heavy to a light composition in this energy region also gives support to a changing origin for those cosmic rays. The lack of a strong galactic anisotropy at the highest energies would also rule out galactic sources for energetic protons (Bird et al. 1999). A number of new experiments, such as HiRes, the Pierre Auger Project, the Telescope Array, the Extreme Universe Space Observatory (EUSO), and the Orbiting Wide-Angle Light Collectors (OWL) will address this issue.

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