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RATE ESTIMATES FOR PROPOSED EXPERIMENTS USING THE FLY'S EYE AIR FLUORESCENCE DETECTOR

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We estimate data rates for experiments using the Utah Fly's Eye air fluorescence detector to (1) measure the primary cosmic ray spectrum for energies $10^{16} \leq E \leq 10^{21}$ eV (2) measure the proton-air interaction length (3) separate protons and heavy nuclei in primary cosmic rays. Rate estimates are normalized to experimental results obtained with the prototype Fly's Eye detector/Volcano Ranch intercalibration experiment. Rates for experiment (1) are near 10^6/yr while rates for experiments (2) and (3) are near 10^4/yr. The proton interaction length can be measured to ±10% while the component separation can be obtained to better than ±25%.

1. Introduction. Previous papers[1,2,3] have reported the successful observation of the passage of extensive air showers (EAS) through the atmosphere by means of nitrogen fluorescence light given off after excitation by the relativistic electrons in the shower. The instrument (called the Fly's Eye) designed to make these observations has been discussed in other papers.[4,5,6] Here we discuss the proposed program of experiments to be carried out with the Fly's Eye detector. In particular, for certain of those experiments we present detailed rate estimates based upon our intercalibration studies of EAS performed in cooperation with the Volcano Ranch Array (VRA) at Albuquerque, New Mexico.

We list those experimental investigations we currently believe feasible to undertake with the Fly's Eye detector: (1) make a precise measurement of the primary cosmic ray spectrum in the energy range 10^{16}-10^{21} eV, (2) make a direct measurement of the proton-air cross section in the energy range 10^{16}-10^{19} eV from an examination of the distribution of primary interaction "starting points" in the atmosphere, (3) separate the heavy component and the proton component in the primary cosmic ray beam, (4) search for anisotropies in arrival directions of the primaries, (5) look for neutrino-induced showers near 10^{20} eV. All of these experiments depend primarily upon the ability of the Fly's Eye to: (1) determine the geometry of the EAS event, (2) measure its energy (size), and (3) achieve a significant event rate for the energy range in question. We believe that in previous papers we have already successfully demonstrated the ability of the Fly's Eye to carry out the first two of these three tasks. In this paper, we intend to present evidence that, in fact, based upon event rates obtained with the prototype Fly's Eye, the third task is also within our grasp simply by scaling the prototype detector up to its full-grown size (Loh et al. 1977)

Finally, there is one additional experiment which looks feasible but difficult: (6) make a detailed study of proton interaction models by measuring directly the longitudinal development of a shower throughout a significant portion of its trajectory. The difficulty does not stem from an insufficiency of light generated by the shower thus rendering visual identification difficult. If anything, the difficulty that may afflict the observation is perhaps an over abundance of light. In particular, our VRA calibration study[3] seems to imply that our observed light yield is systematically too high, most probably as a result of scattered Cherenkov light contaminating the air fluorescence. If this proves to be the case, then the light we observe is a measure not only of the shower's current size at a particular point in its trajectory but also is a measure of its previous history. However, this effect should be most pronounced at the trailing edge of the shower while its early development should still prove to be more or less free from such contamination. How we choose to use this additional light for our benefit in performing experiment(6) remains to be seen.

2. Rates for Measuring the Primary Spectrum. The geometry of a detector like the Fly's Eye is quite complicated. In order to simulate the response to such a detector to EAS, we developed a Monte Carlo program which generates showers at random which are then "observed" by the detector. The program determines the minimum energy E which a shower of specified geometry must attain in order to "trigger" a sequence of N photomultiplier tubes, each of which is a certain minimum number of standard deviations above noise. Both N and the number of standard deviations can be chosen to optimize data rate limited only by chance rate and dead time considerations. The simplest trigger thus envisioned requires that at least four phototubes out of the entire Fly's Eye Array (~1000 tubes) have signals at least five standard deviations above noise. In actuality, four parallel triggers will be implemented for four different integration time scales in hopes of optimizing signal to noise for events which occur far away as well as close by the detector. The effect on data rate of any arbitrarily chosen triggering scheme can be tested by the program.

Showers were synthesized with random geometrical parameters and the energy of the shower is scaled up or down until it triggers the detector. The event rate is then

$$\text{Rate} = \int_{A\Omega} I(>E)\, d(A\Omega) \qquad (1)$$

where A is the detector aperture and I(>E) is the integral cosmic ray spectrum. Clearly, obtaining I(>E) is one of the design goals of the Fly's Eye. Hence, a way of measuring this spectrum involves fitting the observed data rates to the above integral function. Here, in order to a priori estimate datarates we carry out the inverse process. We use the spectrum I(>E) given by Greisen, 1965.[7] However, we normalize our rate calculation to the experimental results obtained with the prototype Fly's Eye detector operating in coincidence with the Volcano Ranch Array (VRA) at Albuquerque, N.M. during November 1976. There we achieved an event rate of 0.5/hr and a size threshold of $N_e \simeq (0.5\text{-}1.0)\cdot 10^8$ electrons at a distance of $R_\perp \approx 1$ Km. We then plot in Fig. 1 the results of our calculation normalized to that result. The rates have been readjusted to correspond to the brightness of the night sky at our Dugway, Utah experimental site which is not as severe as at Albuquerque, N.M. where the calibration experiment was performed.

We see from Fig. 1 that we can expect to see EAS at distances of $0.2 \le R_\perp \le 50$ km. The corresponding pulse widths range from $.07 \le \Delta t \le 17$ µsec. In order to trigger the detector, showers 50 km distant would have to have a size of $N_e \simeq 4 \cdot 10^{11}$ electrons (at ground impact) or an energy near 10^{21} eV. Such showers would be observed at a rate of about 1/yr. Showers impacting within several hundred meters of the detector would require a size of about $N_e \simeq 10^7$ electrons or an energy of about $2 \cdot 10^{16}$ eV. Such showers would occur at a frequency of about 10^6/yr. Hence, it should be possible to map out the cosmic ray spectrum in the energy range $10^{16} \le E \le 10^{21}$ eV with significant data rates.

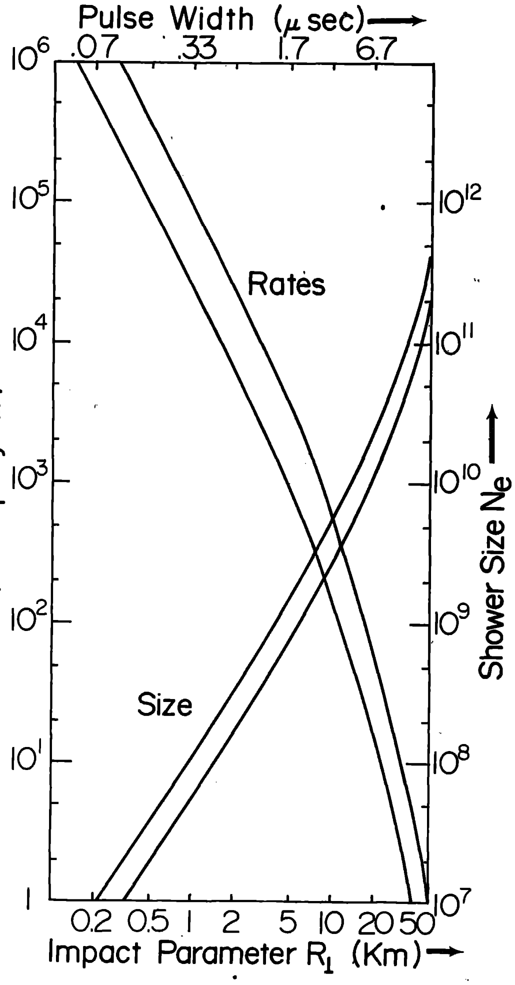

Fig. 1. Rates (left scale) and observed shower sizes N_e (right scale) vs shower impact parameter $R_\perp$ (lower scale) and corresponding pulse widths (upper scale).

3. Rates for Cross Section and Primary Separation Measurements. In order to carry out experiments (2) involving the cross section measurement and (3) the separation of protons from the heavy component, significant data cuts will have to be made. These two measurements each require that a reasonably precise location of the starting point of an EAS be determined. Obviously, the shower's starting point cannot be directly observed. However, the Fly's Eye can be expected to observe the 1/4 maximum point which typically occurs at an atmospheric depth roughly 300 g cm^{-2} beyond the depth of primary interaction. This occurs somewhere between 300-600 g cm^{-2}. The distribution of the 1/4 maximum points may be used as a measure of the distribution of interaction points. Unfortunately, many of the showers are seen early in their history traveling more or less towards the Fly's Eye. Hence, the optical emission angles are small and a sizable portion of the shower's trajectory may be contained in a single photomultiplier's field of view. For the purposes of estimating the rate of events acceptable for making the above two measurements we have accepted only Monte-Carlo events whose trajectories had no PMT fields of view containing slant depth bins greater than 120 g cm^{-2} at slant depths beyond 300 g cm^{-2}. This requirement allows the 1/4 maximum point for all selected events to be located with precision $\simeq \pm 25$ g cm^{-2}. The result of this selection process leaves us with about 10,000 events/yr in the energy range $10^{16} \le E \le 10^{19}$ eV useful for measuring the p-air cross section and separating protons from heavy primaries.

The method of separation is fairly straightforward. Essentially, it involves a multiparameter fit to the composite "interaction point distribution" obtained after making data cuts as outlined above. We have approximated such an analysis based upon a Monte-Carlo-generated sample of showers using standard composition at lower energies.[8,9] The primary nuclei were grouped into four regions of composition as shown in Table 1. The Monte-Carlo program sampled this composition, choosing nuclei at random with probabilities based on their abundance on an energy per particle basis. The nuclear groups [3-6] and [15-23] were ignored due to their low abundances. The relative weights of the four "included" nuclear groups, shown in Table 1, were obtained after conversion to an energy per particle basis by the factor $A^{\gamma-1}$ with $\gamma = 1.7$. The cross section for nucleus-air collisions are based on the results of Heckman et al. 1975.[10] However, the proton-air interaction length was taken to be 75 g cm^{-2} corresponding to a total inelastic cross section of 325 mb. The composite interaction lengths for the remaining nuclear groups are given in Table 1. The resultant distribution of depths of first interactions for 5,500 events generated by the Monte-Carlo program was collected into 50 bins of 10 g cm^{-2} width. This distribution is pictured in Fig. 2. (For the sake of clarity only the final fit to the distribution is shown.)

Table 1

Standard Composition of Low-Energy Cosmic Rays Weighted by $A^{\gamma-1}$

Z	Group	Interaction Length of cm^{-2}	Fraction of Nuclei at a Given Energy/Nucleon
1	H	75	0.395
2	He	49	0.175
6-14	CNO	26	0.179
>24	Fe	19	0.175

A very simple fitting procedure was employed in order to extract information from the Monte-Carlo-generated composite distribution. The He and the CNO groups were combined assuming that half of the resultant group had an interaction length of 49 g cm^{-2} and that the other half had an interaction length of 26 g cm^{-2}. The Monte-Carlo distribution was then assumed to be the sum of four exponentials of the form

$$f(x) = \frac{w_1}{\lambda_1} e^{-x/\lambda_1} + w_2 \left[\frac{e^{-x/\lambda_2}}{\lambda_2} + \frac{e^{-x/\lambda_3}}{\lambda_3} \right] + w_3 \frac{e^{-x/\lambda_4}}{\lambda_4} \qquad (2)$$

where the λ_i are the interaction lengths and the w_i are the relative weights of the relevant nuclear groups.

The above function was fit to three "centering points" for the distribution (X = 50, 100 and 250 g cm^{-2} indicated in Fig. 2) varying only the proton interaction length λ_1 while holding the others fixed. This particular procedure was carried out primarily for ease of calculation. However, these fits would not be expected to be nearly as sensitive to the interaction lengths of the heavier nuclei primarily for two reasons: (1) rather large centering depths were chosen to optimize sensitivity to the more penetrating particles and (2) the interaction lengths of the heavies do not scale linearly with the proton interaction lengths. A minimum χ^2 best fit (shown in Fig. 2) was obtained for $\lambda_1 = 78$ g cm^{-2} compared to an input value of 75 g cm^{-2}.

In order to evaluate the accuracy of determining the proton cross section with this method, ten independent Monte-Carlo runs were analyzed giving an average value of 73.4 g cm^{-2}. The r.m.s. error in a single test is 5.5 g cm^{-2}. The average weight w_1 obtained for proton showers was 0.42 compared to 0.395 in the input. The r.m.s. error in this quantity for a single test is 0.10. These results imply that a proton component in the presence of a "mixed" composition is indeed detectable and that the interaction length can be determined to order ~10%. In the real measurements, a full-blown multiparameter fitting routine will be used over the whole range of data. Moreover, the measured p-air cross sections could then be used to recalculate the cross sections of the heavier nuclei. Thus, some iteration should be possible which should lead to better accuracies in extracting the relative weights of the various nuclear components. It appears then that protons can be detected and their cross section measured if they make up 10-20% of the primaries in our accessible energy range. The possible absence of low mass primaries is also detectable and would be an interesting discovery in itself.

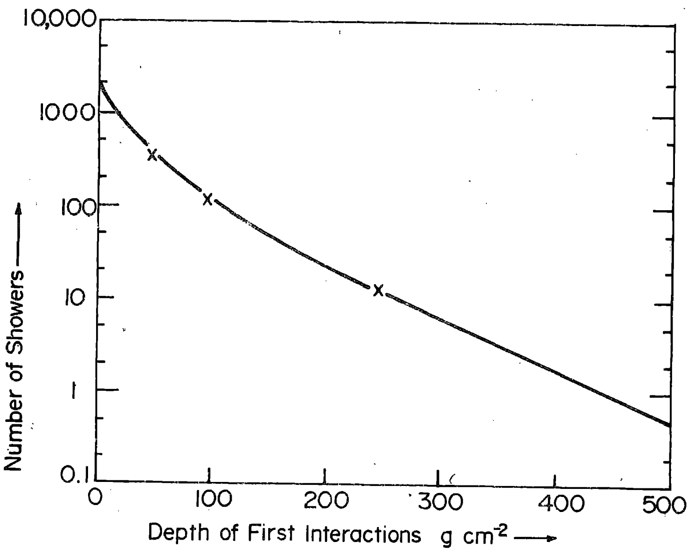

Fig. 2. Monte-Carlo generated distribution of shower starting points for 5,500 events. Primary constituents were selected from nuclear groups H, He, CNO, and Fe. The curve represents a four-component best fit to the Monte-Carlo generated distribution.

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