Angular distributions of secondary charged particles in showers initiated by gammas and protons

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We investigate the possibility of finding the direction of the primary of an extensive air shower from the directions of the secondary charged particles measured at Earth's surface. The Monte Carlo calculations of the showers initiated by γ's and protons indicate that the direction of the primaries can be estimated with an accuracy of $\frac{1}{4}°$ for 100 detected tracks. However, the experimental angular distributions should be properly corrected for systematic effects.

The discovery of gamma radiation from Cygnus X-3 by the Kiel group[1] has stimulated great experimental and theoretical activity in γ-ray astronomy in the ultrahigh-energy (UHE) domain (above 10^{14} eV). There are several operating or proposed experiments using extensive-air-shower (EAS) arrays in order to clear up the experimental situation and to search for new UHE-γ sources.[2] In this new field of γ-ray astronomy the direction of the primary γ ray is a crucial parameter. It is therefore interesting to find new techniques and methods for determining the arrival directions of showers with good precision. In this report we investigate the angular distributions of the individual charged particles at sea level in showers initiated by protons and γ rays. The purpose is to find out how accurately the directions of the primary photons can be estimated from measurements of the directions of cascade secondaries carried out at Earth's surface.

In the Monte Carlo calculation of the showers we exploit the strength of two existing simulation codes: SHOWERSIM (Refs. 3 and 4) and EGS (Ref. 5). SHOWERSIM is a modular software system developed for the Monte Carlo simulation of cascades initiated by ultrahigh-energy cosmic rays in the atmosphere. It is fast and efficient by making use of approximations which are very good at high energies. The EGS system is a package of computer programs that precisely simulates the development of lower-energy electromagnetic cascade showers. The simulations were performed in the two steps in order to take advantage of the strengths of both programs. We started with the SHOWERSIM code to simulate the early stages of the cascade development; any electron created in SHOWERSIM with an energy below 10 GeV was replaced by a shower from the EGS library created by using the EGS program.

The SHOWERSIM simulation of the showers was performed for vertical protons or photons at the top of the atmosphere with the detection level at 1034 g/cm^2. We choose a typical primary energy of 100 TeV; preliminary work at 1000 TeV shows similar angular distributions. The density distribution is that of the U.S. Standard Atmosphere. Pair creation, bremsstrahlung, and multiple Coulomb scattering are included in the electromagnetic part of the simulation. The radiation length of air was taken to be 37 g/cm^2. The total energy threshold is 170 MeV for photons and electrons, 0.5 GeV for pions, 1 GeV for kaons, and 2 GeV for nucleons. The details of the hadron-hadron interaction model are presented elsewhere.[4,6]

The EGS subshower library contains the electromagnetic showers initiated by the vertical electrons with energies from 0.1 to 10 GeV (in steps of 0.1 GeV). There is a 10-MeV energy threshold imposed on the secondary electrons. The initial heights of the production in the atmosphere vary from 100 to 6600 m (in steps of 100 m) from detection level. The subshower is rotated by a random azimuthal angle each time it is used. For each energy and height we have simulated one unrotated subshower, so the total number of unrotated subshowers in the EGS library is 6600.

We have simulated 50 γ-initiated showers and 50 proton-initiated showers. Results are presented for different radial distances from the shower axis with 10-

TABLE I. The mean value and standard deviation of the angular distributions. $\langle \theta_R \rangle$ is the mean value of the radial angle; the mean value of the transverse angle is 0. σ_R and σ_T are the standard deviations of the radial and transverse angles, respectively. The first three columns are for secondary electrons at sea level from an average γ shower and the next three are the results for all the charged secondary particles from an average proton shower.

Range of R (m)	γ shower (electrons)			p shower (all charged)		
	$\langle \theta_R \rangle$ (mrad)	σ_R (mrad)	σ_T (mrad)	$\langle \theta_R \rangle$ (mrad)	σ_R (mrad)	σ_T (mrad)
0–12	32	117	108	30	112	103
12–25	70	161	145	68	160	139
25–50	100	188	174	89	181	160
50–100	108	202	194	92	180	167

MeV energy threshold for electrons at the detection level. As the two variables for the angular distributions we choose θ_R and θ_T. We define θ_R as the track angle at the detection level projected unto the Z-R plane, where Z is the vertical direction and R the radial direction; θ_T is an angle projected onto a plane orthogonal (transverse) to the Z-R plane.

The mean value $\langle \theta \rangle$ and standard deviation (calculated from $\sigma^2 = \langle \theta^2 \rangle - \langle \theta \rangle^2$) of the radial and transverse angles are shown in Table I. The average value of the transverse angle is zero within errors. However, the mean value of the radial angle is not zero. As expected, there is an outward flow in the R direction; the secondary particles undergo outward diffusion from the axis. Table I shows that both σ_R and σ_T increase with increasing distance from the axis. As well, the mean values of the radial angle $\langle \theta_R \rangle$ increase with increasing distance from the axis.

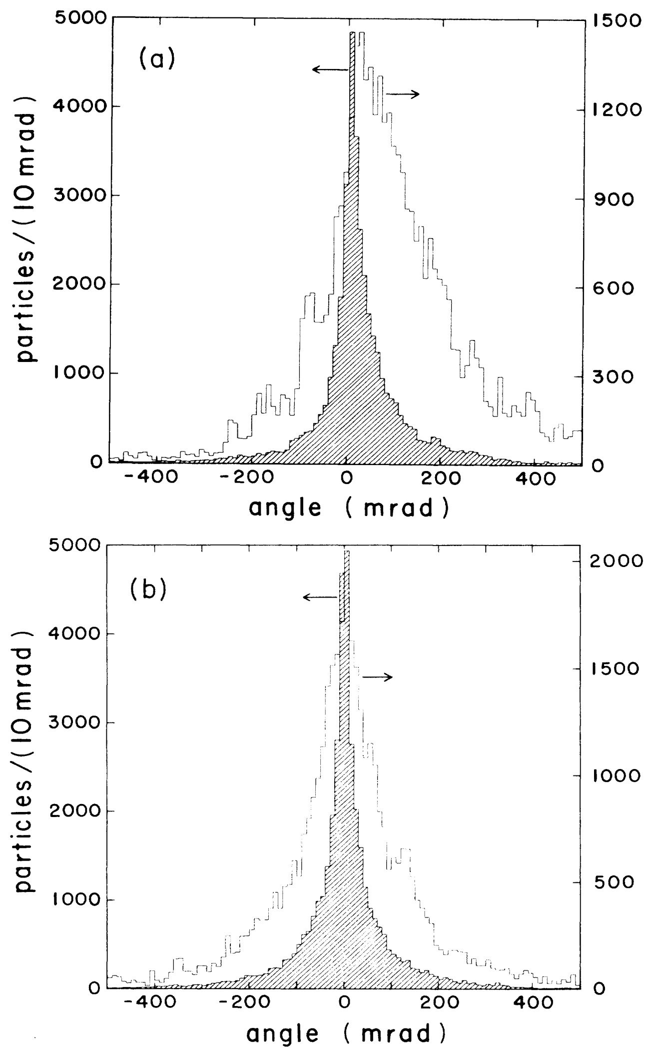

FIG. 1. (a) Data for γ-initiated showers. Radial angle (in mrad) distributions of secondary electrons for radial distances: 0–12.5 m (shaded histogram), and 25–50 m (open histogram). (b) Data for γ-initiated showers. Transverse angle (in mrad) distributions of secondary electrons for radial distances: 0–12.5 m (shaded histogram) and 25–50 m (open histogram).

We note that these distributions are non-Gaussian with long tails; there exists a central peak which is narrower than the values that σ would indicate.

The angular distributions are plotted in Figs. 1 and 2 for proton and γ showers for two examples of radial distances from the shower core, $0 < R < 12.5$ m and $25 < R < 50$ m. The heights have been arbitrarily normalized so their peaks are the same for easier comparison by eye. The different scales are given for each distribution. At close distances from the shower axis we notice the general trend that the transverse angle distributions, Fig. 1(b), are symmetric around zero and wider at larger distances. The radial angle distributions are similarly widened at larger distances; in addition, the maxima of the distributions are shifted to greater angles reflecting the fact that the mean value of the angles is increasing outward as the radial distance increases.

These results suggest that the angles of the charged particles in the shower at sea level are large enough to be easily measured but small enough to be a good estimator of the shower direction. The best estimation of the direction of the showers is provided by the particles close to the shower axis, where the corrections are small and the angular distributions are narrow. To use all of the detected particles in order to find the original direction of the primary of the shower, the experimental angular distributions should be properly corrected for the nonzero mean value of the radial angle; as well, they should be properly weighted since the standard deviations grow as the radial distance from the shower increases. We notice that these corrections and weights are different for the γ- and proton-initiated showers.

One notices that the angular distributions of the electrons at sea level have a central narrow peak with long tails. The long tails dominate the calculation of the rms width σ; by discarding 50% of the angles which deviate the most from the peak, it is possible to obtain significantly smaller σ values. For example, using the data from Fig. 1 and discarding that 50% which deviates

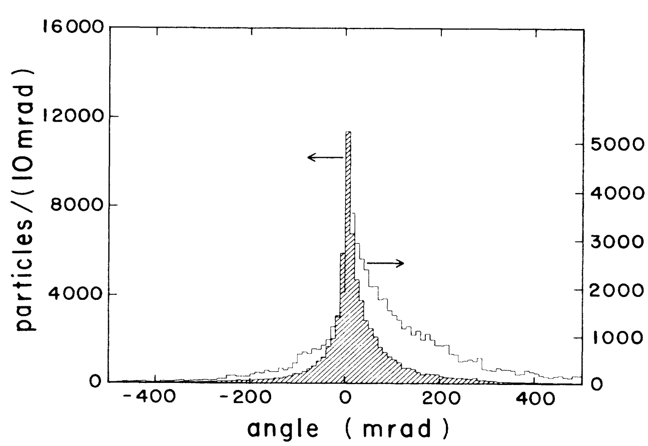

FIG. 2. Data for proton-initiated showers. Radial angle (in mrad) distributions of all charged secondary particles for radial distances: 0–12.5 m (shaded histogram), and 25–50 m (open histogram).

the most from the peak, we obtain the $\sigma_{0.5}$ values listed in Table II. A weighted average of the numbers in Table II yields 31 mrad as a typical number for a γ shower, significantly better than the nontruncated values listed in Table I. By using many multiple tracks, the center angle can be found much more accurately than these σ values (which refer to the rms deviation of a single track). One can simply take an average of the angles, or an average of the center 50% of the data after throwing away 25% of the data on the low side and 25% on the high side. More precision is obtained, however, by assuming a shape for the observed distribution and fitting the data to find the best centroid position. Using Monte Carlo simulation we find that the rms scatter of this fitted centroid from the true centroid is 4.0 mrad (0.23°) for the case of 100 detected tracks within 12.5 m of the shower center. Systematic corrections must be made for the centroid angles as a function of R, $\langle \theta_R \rangle$, listed in Table I. There will be residual uncertainties due to this correction because of the uncertainty in the location of the center of the shower. For example, the error in this systematic correction will be $\frac{1}{4}°$ in projected angle if the core location is uncertain to 2 m.

In summary, the results of the Monte Carlo calculation of EAS's initiated by primary protons and γ rays indicate that it is possible to find the direction of the primary photon and proton from the measurements of the directions of the charged secondaries at sea level. By fitting the measured angles it is possible to determine the direction of the shower primary with a statistical precision of $\frac{1}{4}°$ with 100 detected tracks. It is necessary to make corrections for systematic effects. These angle-measurement techniques are currently becoming feasible and economically competitive.[7,8]

TABLE II. The rms deviations $\sigma_{0.5}$ obtained after discarding that 50% of the data which deviates the most from the mean and after correcting for the systematic angular deviation, $\langle \theta_R \rangle$.

Range of R (m)	γ shower (electrons) σ_R (mrad)	σ_T (mrad)
0–12	17	15
12–25	34	29
25–50	51	39
50–100	53	44

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