Development of Atmospheric Cosmic-Ray Showers

Greg Thornton and Roger Clay
Physics Department, University of Adelaide, Adelaide, South Australia 5000, Australia
(Received 19 June 1979)

The depths of shower maximum of cosmic-ray showers have been determined in the sea-level size range $10^5 < N_e < 10^7$ with use of atmospheric Cherenkov techniques. The mean depth has been found to increase rapidly in the middle of this range, suggesting a change in the mean primary composition from heavy to light nuclei.

Studies of the longitudinal development of cosmic-ray extensive air showers can give information on the energy spectrum and composition of the primary particles and also enable us to investigate some of the basic parameters of particle interactions at energies not yet available at accelerators. Unfortunately, in interpreting the outcome of any experiment there is often uncertainty in separating out the effects of all the poorly known parameters. However, these difficulties are less critical near the shower maximum, and the most basic and useful shower measurements are then those which aim to determine and interpret the electron number at shower maximum and the atmospheric depth at which it occurs. We therefore wish to discuss the way in which interesting astrophysical and particle properties influence the depth of electron maximum observed in our experiments.

Early stages of air-shower development depend critically on the initial primary-particle interaction mean free path, the interaction inelasticity, and secondary-particle multiplicity. Also, the inelasticity and multiplicity of the secondary-pion (etc.) interactions and the development of the electromagnetic cascades[1] are important. Exceptionally early shower development can be caused by a short initial mean free path, a high inelasticity, or a high multiplicity. It can also be associated with a high-atomic-number primary particle which is expected to have a short mean free path and a relatively high initial multiplicity.[2] These early stages are difficult to observe and their interaction parameters are often studied by interpreting observations of the depth in the atmosphere of shower maximum as a function of shower size. Ideally, this is measured by the elongation rate (rate change in depth of shower maximum for a factor-of-e change in primary-particle energy) and the absolute depth of shower maximum for one given primary energy. Linsley[3] has shown that, with general arguments and few assumptions about particle physics, for a constant primary-particle composition the elongation rate (X_e) is bounded from above by the characteristic length of cascade theory, X_c

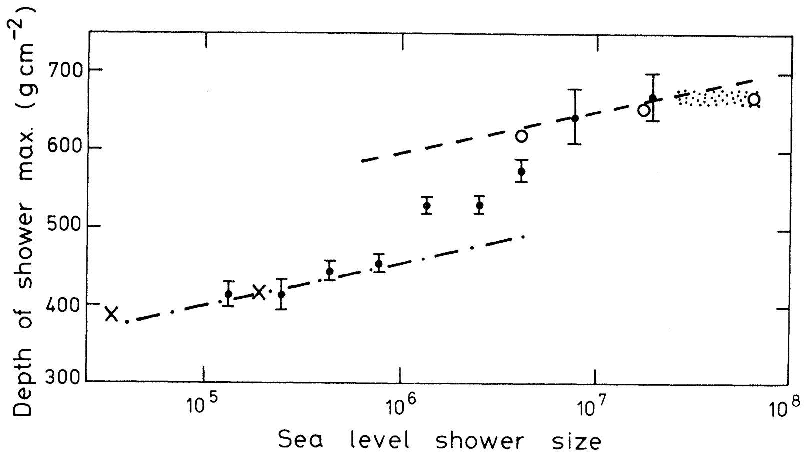

FIG. 1. The measured relationship between the depth of air-shower maximum and sea-level shower size. The filled circles are our data. Open circles are Cherenkov observations of Ref. 8. The stippled band is a Cherenkov result from Ref. 12. The crosses are direct airplane observations of Ref. 13. The lines correspond to simple model relationships for proton primaries (dashed line) and iron primaries (dot-dashed line) as described in the text.

($\sim$38 g cm^{-2} in air), and is most probably $\sim(1-B)X_c$, where B is the exponent of the pion multiplicity formula [multiplicity $\propto$ (energy)^B, with $B \lesssim 0.5$; scaling models predict multiplicity $\propto \ln E$, with a low effective value for B].

We have demonstrated[4,5] that the full width at half maximum (FWHM) of the atmospheric Cherenkov-light pulse from extensive air showers is strongly dependent on the sea-level size (N_e) for $N_e \sim 10^6$ showers. We have also shown[6,7] that calculations relating FWHM to the height of shower maximum indicate a rapid increase in depth of shower maximum [X_m (g cm^{-2})] with N_e's over our range of observation ($10^5 \lesssim N_e \lesssim 10^7$). The corresponding elongation rate is $\sim$60 g cm^{-2}. Because this is significantly greater than the maximum expected from any conventional shower model, we are led to examine the possibility of a change in chemical composition over our observed size range.

Let us consider in a simple way the shower developments for different primary nuclei using the cosmologically significant nuclei of iron and protons as two species to be compared. We wish to examine their variation of depths of shower maximum with observed sea-level size. We assume an increase in X_m of 75 g cm^{-2} (X_e) per decade of primary energy for both species (see, e.g., Kalmykov *et al.*)[8]. The mean free path of a 10^{16}-eV primary iron nucleus in air[9] is taken to be 14 g cm^{-2} and that of a 10^{16}-eV proton[8] is taken to be 55 g cm^{-2}. The shower attenuation length (λ) is assumed to be 200 g cm^{-2} (see, e.g., Ashton *et al.*[10]). With the understanding that the model is crude, we use the common approximation that the iron-induced shower develops at 56 independent showers after the first interaction. It is also assumed that, to a first approximation, shower size at maximum is proportional to the primary energy. For a 10^{16}-eV iron nucleus,

$$X_m = X_0 + 14 + 75\log_{10}(10^6/56)$$
$$= X_0 + 333 \text{ g cm}^{-2};$$

for a 10^{16}-eV proton,

$$X_m = X_0 + 55 + 75\log_{10}(10^6)$$
$$= X_0 + 505 \text{ g cm}^{-2}.$$

For the purposes of this calculation, X_0 is an arbitrary constant and will depend critically on interaction multiplicities, etc. The assumption of a common X_0 is similar to assuming independent nucleon interactions after the first nucleus interaction.

The proton shower has its maximum $\sim$170 g cm^{-2} closer to sea level than the iron shower, and hence will have a sea-level size greater by

$$\frac{N_e(10^{16}\,p)}{N_e(10^{16}\text{ Fe})} = \exp(170/200) \simeq 2.3.$$

Thus we know the relationship between the sea-level sizes and also between the depths of maximum for the two showers. It can be shown that the change of X_m with a factor of e in N_e for a particular primary species is

$$X_e' = \left(\frac{1}{X_e} + \frac{1}{\lambda}\right)^{-1}.$$

As with Linsley,[3] this should be $\lesssim 32$ g cm^{-2}/change in N_e by a factor of e. We will now compare these changes in X_m with N_e to those obtained when X_m is derived from the Cherenkov FWHM.

The data were recorded during 1978 and 1979 at the sea-level Buckland Park air-shower array[11] with use of a Mullard XP2040 photomultiplier and a Tektronix 7912 transient recorder in the non-store mode. The system FWHM of 5.3 ns was removed from the data under the assumption that the system FWHM and the signal FWHM add in quadrature.[7] A total of 317 events in the core distance range $150 < R < 350$ m, and with N_e from $\sim 10^5$ to $\sim 10^7$, were used. The FWHM at 300 m from the core [τ_{300}(ns)] was calculated for each shower with the assumption that[6] FWHM $\sim R^{1.4}$, and the distance of shower maximum from the observer (H_m) was derived with use of[8]

$$H_m = 17.05 - 19.17\log_{10}(\tau_{300}) \text{ km}.$$

The depth of shower maximum was calculated from H_m and the shower zenith angle for an exponential atmosphere of scale height 7.1 km and a vertical depth of 1000 g cm^{-2}. The results are shown in Fig. 1 along with three points from Cherenkov observations of Kalmykov *et al.*,[8] a stippled band corresponding to observations of Hammond *et al.*,[12] and direct airplane observations of Antonov and Ivanenko.[13] Near $N_e = 10^6$, we find $X_e' \sim 60$ g cm^{-2}, which is much greater than the 32 g cm^{-2}, derived above, implying[3] that more is probably needed than merely a change in the particle-interaction mechanism.

The two lines in Fig. 1 are from the above calculations with use of $X_0 = 100$ g cm^{-2} under the assumption and that for a 10^{16}-eV primary proton shower $N_e = 1.5\times10^6$. These are in reasonable agreement with calculations presented by Dixon and Turver.[14] It can be seen that the experimental data match the iron line at $N_e \sim 10^5$, but at $N_e \sim 10^7$ they fit the proton line much better. Although X_m is changing rapidly with N_e near $N_e \sim 10^6$, the data of Kalmykov *et al.*[8] indicate that this trend does not continue past a few times 10^6. For small shower sizes there is some suggestion that the rate again decreases and the direct airplane observations of Antonov and Ivanenko[13] tend to confirm this opinion. We therefore believe that the experimental results are consistent with a changing primary composition with increasing energy from "iron" to "protons" for showers with sea-level sizes $\sim 10^6$ particles.

Experiments by other workers[15] are in the main consistent with early development at $\sim 10^{15}$ eV primary energy. However, interpretations of the observations in terms of composition are not consistent. The observations usually cited as the strongest evidence of a nonheavy nuclear composition at the lower energies are those concerning fluctuations in the muon- to electron-shower size ratio at sea level.[16] These fluctuations should mirror large fluctuations in the depth of shower maximum such as those associated with large-interaction-mean-free-path proton primaries. However, these experimental observations are mainly for showers with sizes above $N_e \sim 10^6$ and the observations may be consistent with fluctuations due to a composition change in this sea-level size range. Vernov *et al.*[15] have demonstrated that the observed muon- to electron-shower size ratio at $N_e \sim 10^5$ is compatible with iron primaries in that size range even with the slowly developing showers derived with use of the scaling model of nuclear interactions but they also claim that complete agreement with experiment is not possible at any energy with a scaling model since high interaction multiplicities are needed if observations of high-energy hadrons are to be explained. Ouldridge and Hillas[1] have disputed the latter suggestion and shown that a development of a scaling model for shower development and a mainly proton composition with energy-dependent hadron cross sections can explain most observations above $\sim 10^{16}$ eV. The remaining problem has been that the observations of Antonov and Ivanenko[13] have not been fitted into an accepted scheme of shower development.

Our data, together with those of Antonov and Ivanenko,[13] strongly suggest that development is early for showers with sea-level sizes of $\sim 10^5$ and that the development becomes "normal" for showers above $\sim 5\times 10^6$ thus suggesting that a corresponding composition change occurs in this size region from predominantly heavy (iron) primaries to mainly proton primaries. This change occurs at the same sea-level size as the well-known break in the sea-level shower-size spectrum[17] which has speculatively been associated by Karakula, Osborne, and Wdowczyk[18] with an end to a primary component associated with pulsar acceleration.

This work was supported by the Australian Research Grants Committee.

---

[1] M. Ouldridge and A. M. Hillas, J. Phys. G $\underline{4}$, L35 (1978).

[2] P. Freier and C. J. Waddington, in *Proceedings of the the Thirteenth International Conference on Cosmic Rays, Denver, Colorado, 1973* (University of Denver, Denver, Colo., 1973), Vol. 4, p. 2449.

[3] J. Linsley, in *Proceedings of the Fifteenth International Conference on Cosmic Rays, Plovdiv, Bulgaria, 1977* (Bulgarian Academy of Sciences, Plovdiv, Bulgaria, 1977).

[4] G. J. Thornton and R. W. Clay, J. Phys. G $\underline{3}$, L193 (1978).

[5] G. J. Thornton and R. W. Clay, J. Phys. G $\underline{4}$, L251 (1978).

[6] G. J. Thornton and R. W. Clay, to be published.

[7] G. J. Thornton, J. D. Kuhlmann, D. F. Liebing, R. W. Clay, A. G. Gregory, J. R. Patterson, and J. R. Prescott, in Proceedings of the Sixteenth International Conference on Cosmic Rays, Kyoto, Japan, 1979 (University of Tokyo, Tokyo, Japan, to be published).

[8] N. N. Kalmykov, Yu. A. Nechin, V. V. Prosin, Yu A. Fomin, G. B. Khristiansen, I. A. Bereshko, V. M. Grigoryev, and N. N. Efimov, in Proceedings of the European Conference on Cosmic Rays, Kiel, 1978 (unpublished).

[9] R. R. Daniel and N. Durgaprasad, Nuovo Cimento Suppl. $\underline{23}$, 82 (1962).

[10] F. Ashton, A. Parvaresh, and A. J. Saleh, in *Proceedings of the Fourteenth International Conference on Cosmic Rays, Munich, West Germany, 1975* (Max-Planck-Institut für Extraterrestrische Physik, Garching, West Germany, 1975), Vol. 8, p. 2831.

[11] P. C. Crouch, J. D. Kuhlmann, R. W. Clay, A. G. Gregory, J. R. Patterson, and G. J. Thornton, in *Proceedings of the Fifteenth International Conference on Cosmic Rays, Plovdiv, Bulgaria, 1977* (Bulgarian Academy of Sciences, Plovdiv, Bulgaria, 1977).

[12] R. T. Hammond, R. J. Protheroe, K. J. Orford, J. A. L. Shearer, K. E. Turver, W. D. Waddup, and D. W. Wellby, in *Proceedings of the Fifteenth International Conference on Cosmic Rays, Plovdiv, Bulgaria, 1977* (Bulgarian Academy of Sciences, Plovdiv, Bulgaria, 1977), Vol. 8, p. 287.

[13] R. A. Antonov and I. P. Ivanenko, in *Proceedings of the Fourteenth International Conference on Cosmic Rays, Munich, West Germany, 1975* (Max-Planck-Institut für Extraterrestrische Physik, Garching, West Germany,

1975), Vol. 8, p. 2708.

[14] H. D. Dixon and K. E. Turver, Proc. Roy. Soc. London, Ser. A 339, 171 (1974).

[15] S. N. Vernov, G. B. Khristiansen, A. T. Abrosimov, N. N. Kalmykov, G. V. Kulikov, V. I. Solovieva, Yu. A. Fomin, and B. A. Khrenov, J. Phys. G 3, 1601 (1977).

[16] S. N. Vernov, G. B. Khristiansen, A. T. Abrosimov, V. B. Atrashkevitch, I. F. Belijaeva, G. V. Kulikov, K. V. Mandritskaya, V. I. Solovjeva, and B. A. Khrenov, Can. J. Phys. 46, S197 (1968).

[17] A. M. Hillas, Acta Phys. Acad. Sci. Hung. 29, Suppl. 3, 355 (1970).

[18] S. Karakula, J. L. Osborne, and J. Wdowczyk, J. Phys. A 7, 437 (1974).

ERRATA

INFLUENCE OF EXTRA NEUTRONS ADDED TO THE $^{12}C + ^{16}O$ SYSTEM: GROSS STRUCTURES IN γ-RAY YIELDS FOLLOWING THE $^{13}C + ^{16}O$ AND $^{12}C + ^{18}O$ REACTIONS. Y.-d. Chan, H. Bohn, R. Vandenbosch, R. Sielemann, J. G. Cramer, K. G. Bernhardt, H. C. Bhang, and D. T. C. Chiang [Phys. Rev. Lett. 42, 687 (1979)].

The scaling factor for the ^{25}Mg $\frac{1}{2}^+$-$\frac{5}{2}^+$ 585.1-keV transition ($^{13}C + ^{16}O$) in Fig. 2(a) should read (×10), instead of (×2).

EXCLUSIVE PROCESSES IN QUANTUM CHROMODYNAMICS: THE FORM FACTORS OF BARYONS AT LARGE MOMENTUM TRANSFER. G. Peter Lepage and Stanley J. Brodsky [Phys. Lett. 43, 545 (1979)].

The expression for T_1 in Eq. (6) is missing one term. The correct result is

$$T_1 = T_3(1 \leftrightarrow 3) = \frac{1}{x_2x_3(1-x_3)}\,\frac{1}{y_2y_3(1-y_1)} - \frac{1}{x_3(1-x_1)^2}\,\frac{1}{y_3(1-y_1)^2} - \frac{1}{x_2(1-x_1)^2y_2(1-y_1)^2}\,.$$

The lowest anomalous-dimension term in Eqs. (7) and (8) is then $-e_{-\parallel}$ (not $e_{\parallel} - e_{-\parallel}$). This correction only introduces minor modifications in the prediction for $G_M^p(Q^2)$ for typical initial wave-function conditions. The revised Fig. 2 given below, illustrates the predictions for $Q^4G_M^p(Q^2)$ if one assumes an initial wave-function condition $\varphi(x_i,\lambda) \propto \delta(x_1 - \frac{1}{3})\delta(x_2 - \frac{1}{3})$ with $\lambda^2 = 2$ GeV^2 and various quantum-chromodynamic scale parameters $\Lambda^2 = 1$, 0.1, 0.01, and 0.001 GeV^2.

The ratio $G_M^p(Q^2)/G_M^n(Q^2)$ is a sensitive measure of the nucleon wave function. For the initial condi-