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High transverse momenta observed in air shower cores

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Abstract. Evidence is presented from many sources for the occurrence of very high transverse momenta at energies above 10^{14} eV. These very high transverse momenta indicate the operation of a super-strong force.

Detailed results are given of the last three years of operation of the Sydney 64-scintillator array and of our Monte Carlo simulations of air showers. These are compared with our earlier results and the results of other groups from 1953–70. It is shown that:

(i) Two main types of core exist which can conveniently be called single cores and multi cores. All groups observe both types. The two types can be distinguished objectively if the highest (Δ_1) and second highest (Δ_2) particle densities, observed over areas of 0·25 m^2, are compared. For showers at sea level, single-cored showers have $\Delta_1/\Delta_2 > 1{\cdot}5$; multi-cored showers have $\Delta_1/\Delta_2 < 1{\cdot}5$. There is a 90% agreement between this objective definition and subjective classification. At a given shower size single-cored showers (i.e. with $\Delta_1/\Delta_2 > 1{\cdot}5$) have a more marked radial symmetry, a much higher mean Δ_1, a steeper electron structure function within 3 metres of the core, a much higher mean hadron energy and many more high-energy hadrons in the core.

(ii) For simulated showers (of total primary energy 10^{15} eV) these characteristics are shared by the showers with proton primaries. Simulated showers with heavy primaries behave like real multi-cored showers.

(iii) The experimental distribution of Δ_1/Δ_2, at shower sizes around 10^5 particles, cannot be reproduced by a pure simulated beam of protons *or* a pure beam of heavy primaries. It can be reproduced by a beam of chemical composition similar to that of lower-energy cosmic radiation.

(iv) At shower sizes above 10^6 particles the Russian, Sydney and Kiel groups find an increase in the fraction of multi-cored showers ($\Delta_1/\Delta_2 < 1{\cdot}5$). It has been impossible to simulate these events, even assuming very heavy primaries, if only normal transverse momenta were used in the very high-energy interactions.

(v) We have investigated, in a number of experiments, the hypothesis that the high transverse momenta observed in scintillator experiments are due to fluctuations in the scintillators (either instrumental, or statistical, or both). We show the hypothesis to be untenable.

(vi) The effect of local hadronic interactions on core type is shown to be negligible.

1. Introduction

If a high-energy γ-ray of 10^6 GeV fell vertically upon our atmosphere it would produce a cascade of electrons and photons by the processes of bremsstrahlung and pair production. At its maximum of development, at about 3000 m above sea level, this cascade would contain approximately 6×10^5 electrons (Galbraith 1958).

Electrons tend to scatter away from the axis of the shower (defined as the line of flight of the original γ-ray) but at the maximum one finds by far the greatest density (that is, the number of electrons per unit area in the plane perpendicular to the axis) on the axis. The shower would be symmetric around this axis. If the shower fell on an array of detectors, each 0·5 m × 0·5 m, arrayed like a chessboard with the axis of the shower passing through the centre of one detector, then that detector would be traversed by 5·4 times more electrons than any of the four detectors adjacent to it. When this shower reached sea level, the total number of electrons would have fallen to 10^5. They would still show a strong radial structure but with a somewhat flatter central peak. The ratio of densities in the central detector and its nearest neighbour would have fallen from 5·4 to 3·3. At either altitude this shower could well be called a 'single-cored' shower. Showers with this sort of structure are sometimes observed and showers with radial structure and a somewhat flatter central peak are quite common. (There is ample other evidence, however, that they are not due to primary γ-rays.)

In 1953, showers with quite a different central structure were observed (Heinemann and Hazen 1953). These showers had either two or more well-separated peaks, or a region around the axis where the electron density was roughly constant. The original experiment used a large multiple-ionization chamber. Since then, this type of shower, often called a multiple-cored shower, has been seen with spark chambers (Matano *et al.* 1968), separate ionization chambers (Gorgunov *et al.* 1960), scintillators (Bray *et al.* 1964 a), neon hodoscopes (Bagge *et al.* 1965), large cloud chambers (Miyake *et al.* 1963) and a combination of scintillators, ionization calorimeter and x-ray film emulsion chamber (Nikolskii 1969).

This paper is mostly an account of the study and interpretation of this type of shower. We will show that the experimental and theoretical investigations of all Groups are in substantial agreement and conclude, firstly, that the core structure of a shower is considerably affected by the nature of the primary particle and, secondly, that at high primary energies (10^7 GeV and greater) it can only be explained by invoking transverse momenta in the elementary processes much greater than are seen at machine energies.

2. Methods of investigation

Experimentally, one covers as large an area as one can with some type of charged-particle detector. The detectors used have been multi-wire ionization chambers, scintillators, spark chambers, neon hodoscopes, large cloud chambers and emulsion chambers and ionization calorimeters. All have their advantages and disadvantages.

To get from the core structure observed by these methods to the nature of the primary particle and the characteristics of nuclear interactions at high energies one needs theoretical predictions with which the experiments can be compared. This is usually done by simulating air showers by the Monte Carlo technique using some particular primary particle, and reasonable assumptions as to the characteristics of nuclear interactions.

2.1. *Large cloud chambers*

A very large cloud chamber, $1{\cdot}3 \times 2 \times 0{\cdot}7$ m^3 with 21, 1 cm Pb plates, has been used by the Osaka group (Miyake *et al.* 1963). Very impressive photographs of both single- and multi-cored showers have been obtained. The large amount of lead makes the development of the hadronic component easily visible. The main drawback is the small surface area, $2 \times 0{\cdot}7$ m^2.

2.2. *Ionization chambers*

The original observations on multi-cored showers were made using multi-wire ionization chambers (Heinemann *et al.* 1953, Heinemann 1959). Again, this array had the disadvantage of covering only a small area (1·0 m^2). It had the additional disadvantage of only giving a one-dimensional picture of the distribution.

An elaborate arrangement of 60 cubic ionization chambers above 10 centimetres of lead and 75 centimetres of carbon and 64 chambers below this material was used by the Moscow group (Gorgunov *et al.* 1960) to study both the electron and hadron components of air showers. Figure 3 of the paper quoted shows a twin-cored shower having two electron 'peaks' of 2000 and 3000 particles per chamber respectively, separated by 1·6 m. The 'valley' between has six chambers each with less than 45 particles. The chambers underneath the carbon show matching hadronic peaks. The array, also, was somewhat limited by its fairly small surface area (4 m^2).

2.3. *Scintillators*

Close-packed arrays of scintillators have been used by the Osaka (12 m^2) and Sydney groups (16 m^2). More open arrays have been used by the Osaka group (25 m^2). Scintillators have the advantages of fast response, ease of operation and a response giving the number of particles passing through them. However, in order to take advantage of this last property one must know the proportionality factor and how it varies with particle density and distance from the shower core. Fortunately this has been investigated in detail (Bray *et al.* 1965) by comparing the response of scintillators with the response of cloud chambers and of Geiger counters at the same place, in the same shower. In this paper, details of further experiments on scintillator response are given.

2.4. *Spark chambers*

Glass faced spark chambers have been used effectively by the Tokyo group (Matano *et al.* 1968). Up to the density at which they begin to saturate, they are a device, like cloud chambers, which give a track for every ionizing particle. Unfortunately the density beyond which they are nonlinear is rather low, namely of the order of 1000 particles/m^2. Complete saturation is about a factor of 10 higher than this. They can be used to cover a considerable area (16·5 m^2). Excellent pictures of well-separated multiple cores have been obtained (Matano *et al.* 1968) and transverse momenta up to 50 GeV/c deduced. They suffer from a defect shared by the neon hodoscope. To determine a density of charged particles, all the sparks in a given predetermined area must be counted. For a shower of primary energy 10^6 GeV this may be as many as 20 000 on 16·5 m^2. If these have to be counted by hand it becomes impossible to produce numerical maps of electron density over the whole device for any but a small fraction of events.† This means that, in general, a subjective judgement of whether or not a core fell on the spark chambers must be made. If the judgement is positive a further subjective judgement must be made as to whether it is a single-cored or multi-cored shower. In the future, if should be possible to automate the scanning and make these judgements objective.

2.5. *Neon hodoscope*

These have been used by the Tokyo group (Oda and Tanaka 1962), who later discontinued their use in favour of spark chambers, and the Kiel group (Bagge *et al.* 1965). The Kiel group used 180 000 small (approximately 1 cm^2) glass pots, filled with neon, disposed over 32 m^2. Like Geiger counters, the neon pot is an 'on-off' device. The

† For a scintillator array this can easily be done automatically by computer; the Sydney group have 67 000 detailed numerical maps of events many of which have been published (Bray *et al.* 1964 b).

response is the same no matter how many particles traverse it. Hence only an estimate of the density of particles traversing a given area can be given. This is unlike the cloud chamber, the spark chamber in its linear region, or the scintillator (when the scintillator–cloud chamber ratio is known). To get a reasonably accurate estimate of the density a fairly large number of pots must be used. Hence the device is not, as is sometimes claimed for it, a high-resolution detector. At low densities the number of pots discharged in a given area is almost proportional to the number of particles passing through the area. For an area of 0·21 m^2 on the Kiel array this ceases to be even approximately true at densities of approximately 300 particles/0·21 m^2. The device is then, like the scintillator, nonlinear, but with a much lower saturation level than have scintillators. It also has a rather large amount of dead space. Only about 1/3 of the area is sensitive area.

Its worst defect, however, is that, so far, numerical maps of electron density in a given event can only be obtained if the response of all the pots is recorded. To do this by hand for the 180 000 pots of the Kiel array takes approximately 1 man-week. As a result very few such maps have been made. The Kiel group have published two (Bagge *et al.* 1965) and we are indebted to Dr J. Trümper who has provided us with another eight.† (This is to be contrasted with the 67 000 maps from the Sydney scintillator array). As a result of this the Kiel group have had to rely on subjective judgements from a visual inspection of the hodoscope photographs as to whether a core has hit the array or not, and if so what type it is.

2.6. *Theoretical treatment*

The Sydney group (McCusker *et al.* 1969) have carried out an extensive series of simulations of air showers using the Monte Carlo method. Cascades for primaries of atomic weight $A = 1, 4, 16$ and 64 were simulated. Various primary energies from 10^6 to 10^7 GeV were used. A variety of models of high-energy nuclear interactions were tried. All interactions were taken to be nucleon–nucleon or pion–nucleon interactions with the exception of the first interaction of a heavy primary. If we consider an incident proton, then the following procedure was adopted.

(a) The position of the first interaction was sampled by the Monte Carlo method assuming an exponential atmosphere and an interaction mean-free-path of 90 g cm^{-2}.

(b) For all hadron–nucleon interactions we assumed two 'fireballs' were produced. The multiplicity of the secondaries from these were sampled assuming a Poissonian distribution and mean multiplicity proportional to $\ln E$ or $E^{1/4}$ depending on the model.

(c) The type of secondary was chosen at random with a probability of 0·6 for charged pions, 0·3 for π^0 and 0·1 for nucleons.

(d) The direction of emission was random in the fireball frame.

(e) The momentum was selected from a $p\,e^{-p}$ distribution with a mean of 0·5 GeV/c for pions and 1·0 GeV/c for nucleons. The momentum of the last fireball secondary was chosen to make the total momentum zero. The backward fireball was the mirror image of the forward fireball.

(f) In some models the γ of the fireball in the centre-of-mass system was sampled from a $p\,e^{-p}$ distribution with a mean chosen to give a mean inelasticity of 0·5. In others the inelasticity was fixed and γ adjusted to balance energies.

† Dr J. Trümper also has provided us with 14 photographs of drawings of the response of the Kiel array to showers and we can attest to the difficulty of producing density maps from these.

(g) In one model (and this was in most ways the most successful) it was supposed that in nucleon–nucleon collisions two isobars were formed, rather than that the two original nucleons went on with lesser energy. The isobar mass was 1·5 GeV and the decay was to a nucleon and a single pion with a $\cos^2 \theta$ distribution in the isobar system. 25% of the total energy in this model went into the fireballs and, as a result, about 50% went into the proton from the forward moving isobar (in the laboratory system) and 25% into the decay pion.

(h) Secondary π^0 mesons were supposed to decay immediately into two γ-rays. The direction of one γ-ray in the π^0 system was chosen at random, thus determining the energy and direction of both photons. At this point the Monte Carlo process ceased. The number and distribution of the electrons from the resulting cascade was calculated at any subsequent depth from the Kamata–Nishimura theory and the known energy and direction of the γ-ray.

(i) All hadrons were followed until they decayed to muons (if they were pions) or reached sea level, or fell to an energy less than 50 GeV.

The program calculated the number of electrons striking each scintillator (each 50 cm × 50 cm) of a 9 × 9 grid at 5 different atmospheric depths (200, 400, 600, 800 and 1000 g cm^{-2}), the number and energy of the hadrons striking each scintillator, and the total numbers of electrons and of muons at each depth. The primary particle was 'aimed' at the centre of this grid. Over 1000 showers have been simulated. Each simulation took 15 minutes on an English Electric KDF9, which is about twice as fast as an IBM 7040 in this application.

A very similar Monte Carlo simulation has been made by the M.I.T. group (Bradt and Rappaport 1967). The main differences were that the M.I.T. group were more interested in simulating the response of the BASJE† array and that the number of simulations was very much less. Where the findings of the groups can be compared they are in excellent agreement (McCusker *et al.* 1969).

A simulation of air showers by a somewhat different method has been made by the Durham group (De Beer *et al.* 1966). They used the Monte Carlo method to follow the primary proton. However, when charged pions resulted from the interactions of the proton they were not followed by the Monte Carlo method. Instead the method of the diffusion equation was used to calculate the result of each pion-initiated cascade.

In the interactions of the primary:

(*a*) the points of interaction were chosen by the Monte Carlo method with an interaction mean free path of 80 g cm^{-2}.

(*b*) the primary proton was assumed to survive retaining 50% of its initial energy. All other secondaries were pions. The momentum distribution of the pions was chosen from a $p\,e^{-p}$ distribution with a mean transverse momentum of 0·4 GeV/c. The multiplicity of the pions was assumed to vary as $E^{1/4}$ (with two different constants in two different models) or as $E^{1/4}$ up to 2000 GeV and as $E^{1/2}$ at higher energies. No simulations with an isobar model have been made. The Durham group were mostly interested in the behaviour of muons and have not simulated electron distributions near the core. Where their results can be compared with the M.I.T. and Sydney results the agreement is good. Their correlation of primary energy and shower size at sea level have been used by the Kiel group in their studies of core structure.

The Kiel group have carried out two simulations of air showers. In the first of these (Böhm *et al.* 1968) a primary of atomic weight A and energy E_0 was presumed

† Bolivian Air Shower Joint Experiment

to fall on the atmosphere. The point of the first interaction (and only the first interaction) was selected by the Monte Carlo method. In this first interaction one nucleon only was presumed to interact, with an inelasticity k chosen from a distribution of mean 0·5, and a transverse momentum p_T chosen from the usual $p\,e^{-p}$ type of distribution with mean 1·0 GeV/c. This fixed the direction and energy of this nucleon. All the other nucleons were supposed to continue on without deflection and generate $A-1$ cascades which superimposed to give the main core of the shower. The separation of the sub-core formed by the first nucleon is determined solely by the height of the first interaction and the transverse momentum acquired in that interaction. The number of particles at sea level (N_i) in the ith cascade is obtained from the work of the Durham group. The central densities of the core (Δ_1) and the sub-core (Δ_2) are then obtained from the experimental ($\Delta-N$) distribution of the Kiel group. The results were then compared with the experimental findings of the Kiel group. In this work 10 000 showers were normally simulated in each run of an X-1 Electrologica computer.

In the second simulation (Thielheim and Beiersdorf 1969, 1970—private communication) many more details were subjected to the Monte Carlo process. The model used was a fairly close approximation to the Sydney isobar model. At a total primary energy of 4×10^{15} eV, 100 proton-, 25 α-, 6 oxygen- and 2 copper- ($A = 64$) induced showers were simulated. Later in this paper the results of these simulations will be compared in detail with the results of the Sydney Monte Carlo simulations (the agreement is good) and with the Kiel experimental results.

3. Evidence for high transverse momenta

If one studies the interactions in emulsions of protons and of heavy primaries of total energy between 10^{13} and 10^{14} eV one sees that the core structure of the resultant cascade at a given number of interaction lengths from the origin depends very strongly on the nature of the primary particle. It seems likely, therefore, that at energies 10 to 100 times higher, the same will be true for cascades in air. It also seems likely that, if there is a marked change in the mean transverse momentum as one goes to higher energies, the core structure will be affected. Thus these two quantities, namely, the composition of the primary beam and the mean transverse momentum, will both affect core structure and, in producing evidence of a change in the second, one needs to consider also the first. We hope to show by a consideration of the experimental work and Monte Carlo simulations of all the groups active in this field that the composition of the radiation at 10^{15} eV is much the same as at 10^{10} or 10^{13} eV; that it becomes richer in heavy primaries above 10^{16} eV and that at these higher energies transverse momenta occur which are much greater than those observed in the energy region 10^9 to 10^{14} eV.

3.1. *Description of the Sydney apparatus*

The Sydney 64-scintillator array consists of 64 plastic scintillators each $41\times41\times10$ cm^3. They are each viewed by a Philips 56 AVP phototube. The scintillators have been used in four different configurations. These were (i) 'unshielded', in which the 64 scintillators were arrayed in an 8×8 chessboard-like pattern with no material above them but the 1/16 inch sheet steel of their casings and a 4 g cm^{-2} light roof, (ii) 'shielded', a similar spatial arrangement but with 30 cm of Pb over all the scintillators and 5 cm Pb between them, (iii) 'sandwich', 32 out of the scintillators in 4×8 pattern beneath 30 cm of Pb and 32 scintillators vertically above the same lead and (iv) 'meatless sandwich', in which the lead in the last arrangement was removed and 32 of the scintillators were placed directly above the other 32 scintillators. Figure 1 shows a diagram of these arrangements. The array has a back-up system of Geiger counters at distances up to 50 m from the scintillators and at various times up to 4 Wilson cloud chambers have been placed over, under or close to the scintillators. The array is triggered by the coincidence of three Geiger–Müller counters, each of area 115 cm^2, placed at the corners of a 2 m triangle just under the light roof. When

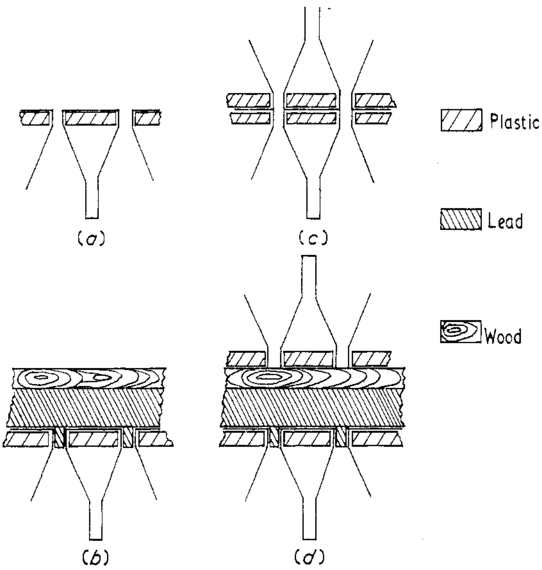

Figure 1. Side elevations of the four different arrangements of the Sydney 64-scintillator array. (*a*) The unshielded arrangement. (*b*) The shielded arrangement with the scintillators covered by 30 centimetres of lead. (*c*) The 'meatless' sandwich arrangement with one set of 32 scintillators placed directly over the other 32 scintillators. (*d*) The 'sandwich' arrangement with the two sets of scintillators separated by 30 centimetres of lead and 15 centimetres of wood. The wood is to prevent the back-scattering of electrons from the lead into the top scintillators.

the array is triggered the response of each photomultiplier is digitalized and recorded on paper tape. Using the regular tests before and after the event, a computer program converts this information into maps giving the number of particles passing through each scintillator. So far more than 67 000 such maps have been printed. Over 200 of these have been published (Bray *et al.* 1964 a, Bray *et al.* 1964 b, Winn *et al.* 1964, McCusker *et al.* 1969).

3.2. *Types of core*

Figure 2 shows two showers from the same 64-scintillator run. The showers have been chosen because they have approximately the same central density (Δ_1 = 539 and 524 particles per scintillator respectively) and this central density is about the middle of the (logarithmic) range of central densities observed during the experiment. Their difference in appearance is obvious and, subjectively, one could class one as a single-cored and the other as a multi-cored shower. However, a subjective classification is not desirable and fortunately one can substitute an objective criterion. If we call the largest density in the shower Δ_1, the second largest Δ_2 and so on, we can then divide showers into two classes, namely, those with $\Delta_1/\Delta_2 > 1{\cdot}5$ and those with $\Delta_1/\Delta_2 < 1{\cdot}5$. It turns out that almost all of the showers, both real and simulated, which had previously been classed as 'single'-cored, belong to the first of these classes and almost all of the multi-cored showers belong to the second class (McCusker *et al.* 1969). A similar system has recently been used by the Kiel group (Samorski *et al.* 1970) and, with the alteration of the critical ratio from 1·5 to 3 to allow for mountain altitude, by the Osaka group (Miyake *et al.* 1968). The efficacy of this system is shown in table 1.

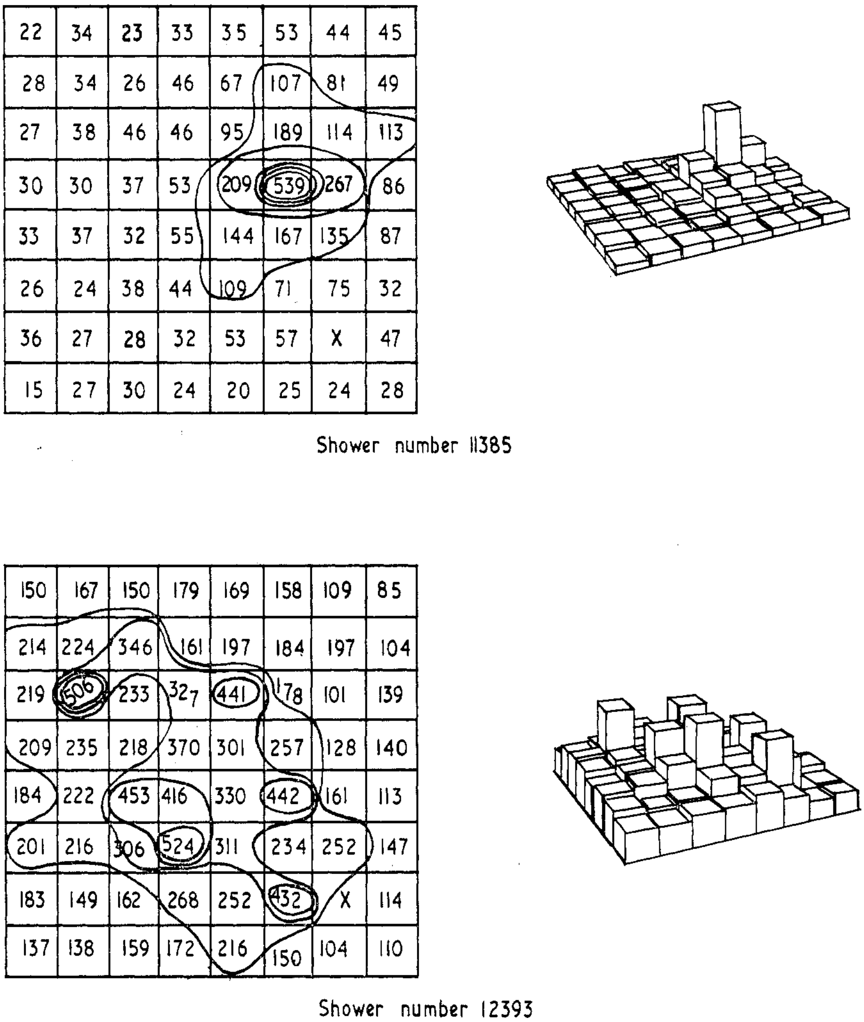

Figure 2. Electron density maps of a single-cored shower (event 11385) and a multi-cored shower (event 12393) on the Sydney array. Three-dimensional histograms of the electron density distributions are also represented.

Here we give the values of Δ_1/Δ_2 for showers from the first 44 000 Sydney events which had previously been subjectively judged to be single- or multi-cored showers. The effectiveness of the criterion is obvious. The table also shows the distribution of Δ_1/Δ_2 for simulated showers whose primaries were (*a*) protons of 10^{15} eV and (*b*)

Table 1. The number of showers with a given value of Δ_1/Δ_2 in steps of 0·1 from 1·0 to 3·2

Δ_1/Δ_2	Sydney simulated events		Sydney real events		Kiel real events
	proton	copper	single	multi-cored	$10^5 < N < 10^6$
1·0		9		23	3
1·1	1	11		77	5
1·2	2	11		44	4
1·3	2	5		20	1
1·4		5	1	8	1
1·5	1	1	2	6	
1·6	2	1	5	5	2
1·7	1	1	4	1	
1·8	1	2	5	2	
1·9	2		6		
2·0	4		5		
2·1	5		10		
2·2	2		5		
2·3	8	1	6		1
2·4	8		10		
2·5	6		13		
2·6	5	1	7		
2·7	4		9		
2·8	10		5		
2·9	6		12		
3·0	4		9		
3·1	5		7		
3·2	5		8		
>3·2	14		29		

The first two columns are for Sydney simulated showers where the primary particles were, respectively, protons and copper nuclei of total energy 10^{15} eV. The second two columns are for real showers on the Sydney array which had been classed as single- or multi-cored (including flat-topped showers) from their appearance. Note that the value $\Delta_1/\Delta_2 = 1·5$ effectively separates these two classes. The fifth column is for real showers observed at Kiel for which we had detailed maps of the particle distributions.

copper nuclei of 10^{15} eV. The comparison of experimental and simulated distributions will be made later. Table 1 also gave the values for real showers from the Kiel group of sizes between 10^5 and 10^6 particles.

If one looks at the distribution of all the Sydney experimental events one sees that it is impossible to reconcile this distribution with either a pure proton beam or with a pure beam of very heavy primaries. One can, however, reproduce the experimental distribution rather closely if one supposes that the primary beam at energies around 10^{15} eV has the same composition as at 10^{10} eV.

3.3. *Fraction of multiple-cored showers for different shower sizes*

Table 2 gives the fraction of showers with $\Delta_1/\Delta_2 < 1·5$ in runs from August 1966 to December 1968. In this selection only showers whose axis fell within the central 3 m × 3 m section of the array were considered.

Table 2. Fraction of showers with $\Delta_1/\Delta_2 < 1{\cdot}5$ for showers from SN 44000 to date for various shower sizes

Shower size	10^5 to 2×10^5	2×10^5 to 5×10^5	5×10^5 to 10^6	$>10^6$
% multiples	$37\pm7\%$	$38\pm7\%$	$53\pm17\%$	$71\pm17\%$
Numbers of events	86	87	17	14

For showers from SN 1 to SN 15 800 the proportions with $\Delta_1/\Delta_2 < 1{\cdot}5$ were $42\pm7\%$ for showers of size 10^5 to 10^6 and $91\pm8\%$ for showers greater than 10^6 (Bray *et al.* 1964).

3.4. *The hadrons in air shower cores*

Our 64-scintillator array ran from September 1963 to January 1965 with 32 of the scintillators directly beneath a 30 cm thick lead slab and the remaining 32 scintillators above the slab. This allowed us to observe the character of the electromagnetic core and, at the same time, the distributions of hadrons capable of producing more than 40 particles beneath the lead from an interaction in the lead. This required a mean hadron energy greater than 70 GeV and the hadron energy could be roughly determined from the scintillator response. The shielded scintillators were separated from each other by five centimetres of lead. As a result their responses were independent (Winn *et al.* 1964).

Table 3 shows the number of single-cored and also multi-cored ($\Delta_1/\Delta_2 < 1{\cdot}5$) showers in the size range $5\times10^4 < N < 5\times10^5$ which discharged a given number of shielded scintillators.

Table 3. The number of single-cored and multi-cored showers discharging a given number of shielded scintillators. The showers are of sizes 5×10^4 to 5×10^5 particles

Number of shielded scintillators hit		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Number of showers	Single	18	1	3	5	1	4	0	1	1	3	0	3	3	1	1	0	1
	Multi	57	29	25	9	8	3	5	5	2	3	1	0	0	0	0	0	0

Obviously the hadronic behaviour is very different for showers having different types of electronic core. We shall see later that the hadronic behaviour of single-cored showers is very similar to that of simulated showers with proton primaries whilst the multi-cored showers behave like simulated showers produced by heavy primaries. For the showers in table 3 the mean number of shielded scintillators discharged per shower is 4·3 for single-cored showers and 1·8 for multi-cored showers. If we consider the cases where one scintillator was hit by more than 1000 particles (corresponding to a hadron of energy greater than or of the order of 1600 GeV) the difference is even more striking. Only 1% of the multi-cored showers showed such a response as compared to 33% of the single-cored showers of the same size.

The gross difference in the hadronic behaviour of showers with Δ_1/Δ_2 less than or greater than 1·5 again shows that this criterion selects a real difference in showers. The same criterion applied to simulated showers selects the same difference in hadronic behaviour and also separates with 90% accuracy proton showers from showers having copper primaries.

3.5. *The calculation of transverse momentum*

If one has a shower with separated peaks in the electron distribution (e.g. figure 2(*b*) of this paper or figure 1 of Matano *et al.* 1968) then one can assume that the peaks are due to neutral pions from the same interaction and calculate the minimum value of $rp_L/h(=p_T)$ for these pions. Here r is the separation of a given core from the centroid of the distribution, p_L is the longitudinal momentum of the pion in the lab system and h the height of production. To get this value one uses the observed electron density of the peak and well-known theory of the electromagnetic cascade. In general, however, one knows that the pions will not have come from the one interaction and often not even from consecutive interactions of the same hadron. In general, the spread of the peaks will be due to many interactions of the nucleons from heavy primary particles. However, the quantity rp_L/h still gives an estimate of mean transverse momentum in the various interactions down through the atmosphere.

In calculating the quantity in our own experiment we corrected first for the known scintillator-to-cloud-chamber ratio and then for the background density due to overlap from the various cascades. Figure 3 shows a scatter diagram of this quantity rp_L/h against shower size for showers falling on our 64-scintillator array.

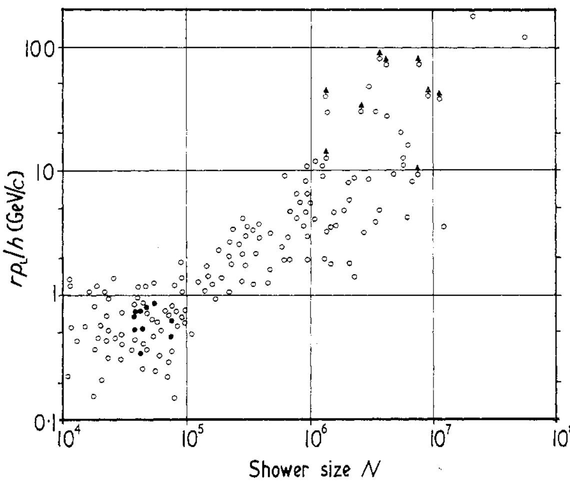

Figure 3. The value of rp_L/h in GeV/c plotted against the shower size N for some Sydney events. Open circles represent real showers. Full circles are simulated events using primaries of atomic weight 64 and a mean transverse momentum of 0·5 GeV/c.

In order to check that the method gives reasonable values, we have applied it also to the electron distributions produced by our simulations. When we apply exactly the same technique to electron maps resulting from simulated cascades, produced by copper primaries with a mean transverse momentum in all the interactions of 0·5 GeV/c, we get the points shown as full circles in figure 3. It can be seen that the values of rp_L/h come close to 0·5 GeV/c. However, the figure also shows that for the larger multi-cored real showers rp_L/h is often much greater than 0·5 GeV/c.

3.6. *Possible alternative explanations of multi-cored showers*

If the events giving high rp_L/h are real then obviously we are dealing with a new and important phenomenon. It becomes necessary to show that the multi-cored appearance could not have arisen from a 'normal' single-cored event by fluctuations, defects of the apparatus or local interactions of hadrons.

First we wish to know the distribution in a single-cored shower from which fluctuations or experimental deviations may arise. Table 4 shows the predicted values of Δ_1/Δ_2, Δ_3/Δ_2, Δ_4/Δ_2 and Δ_5/Δ_2 for the Sydney simulation using 10^{15} eV protons and the isobar model, also for the Kiel simulation using protons of 4×10^{15} eV and finally the experimental Sydney values for single-cored showers (Bray *et al.* 1964 a).

Table 4. The ratio of densities (Δ_1 to Δ_5) in the first five scintillators going outwards from the core, to the density Δ_2 in the second scintillator for the Kiel and Sydney simulated showers with proton primaries and real Sydney single-cored showers

Type of event	Δ_1/Δ_2	Δ_2/Δ_2	Δ_3/Δ_2	Δ_4/Δ_2	Δ_5/Δ_2
Simulated, Kiel, protons of 4×10^{15} eV	2·57	1	0·58	0·44	0·34
Simulated, Sydney, protons of 10^{15} eV	2·63	1	0·61	0·41	0·31
Real single-cored showers, Sydney	2·53	1	0·60	0·45	0·37

The agreement between the two simulations and the experimental single-cored showers is good. If all showers are produced by primary protons with 'normal' transverse momenta then it is by fluctuations from this distribution that we must produce many events like figure 2 of this paper, figure 1 of Matano *et al.* (1968) or figure 8 of Bagge *et al.* (1965).

3.7. *The effect of the response of plastic scintillators to air shower cores*

We have already carried out lengthy comparisons of the response of plastic scintillators, cloud chambers and Geiger counters to air shower cores (Bray *et al.*

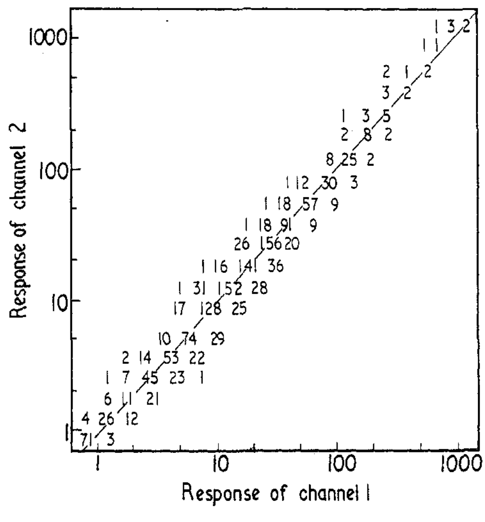

Figure 4. A scatter diagram of the response of two photomultipliers viewing the same scintillator. The figures represent the number of response pairs within given density ranges.

1965). Here we report two further experiments to examine the role that fluctuations, both in particle number and the response of the apparatus, can play in distorting the appearance of a core.

In the first experiment we modified the container of a scintillator so that four phototubes could look at the same scintillator. We then plotted the response from one phototube against each of the others. Figure 4 shows the scatter diagram from one pair of phototubes for densities varying from 1 to 1000 particles per scintillator. The very good agreement between the two is a check on the accuracy of the whole system with the exception of the scintillator itself. It rules out, for instance, any systematic errors due to possible after-pulsing.

The second experiment was designed to test all the system, including the scintillators. To do this 32 of the scintillators were left in the usual position, with scintillator above phototube. The other 32 were inverted and placed directly above the first 32 with only 1/8 inch steel and an air gap between the scintillators. The arrangement is shown in figure 1(*c*). The arrangement had two disadvantages. It was not possible to get the scintillators into contact and hence, since most showers are not vertical, the two scintillators of a pair did not 'see' exactly the same particles. This effect was enhanced by dense local electromagnetic cascades generated in the brass tubes surrounding the upper phototubes. Secondly, the material of the top scintillator affected the particles entering the bottom scintillator. However, both of these effects act to *increase* the difference in response and hence if we use this experiment to estimate errors due to scintillator response in our unshielded array, the estimate will be an overestimate.

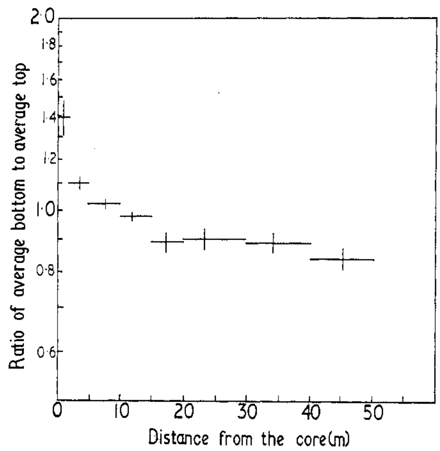

Figure 5. The average ratio of the response of the lower to the upper scintillator in the 'meatless sandwich' run against distance of the scintillator pairs from the shower core for showers of size $10^5 < N < 10^7$ particles.

Figure 5 shows the ratio of bottom to top response plotted against distance from the core. It can be seen that at distances of less than 5 m from the core, production of new particles predominates over absorption. At distances greater than 10 m the reverse is the case. This is to be expected and reflects the increasing average energy of particles as the core is approached.

Figure 6 shows a scatter diagram of the ratio of bottom to top response against the density in the top scintillator. Single-cored showers are shown as open circles and multi-cored showers as closed circles. It can be seen that the fluctuations in response are independent of density and of core type. Accordingly we have used all showers to plot the frequency histogram of the different values of top to bottom ratio and this is shown in figure 7. The mean of the distribution is 1·26 with a standard deviation of 0·50, hence a fractional standard deviation of 0·40.

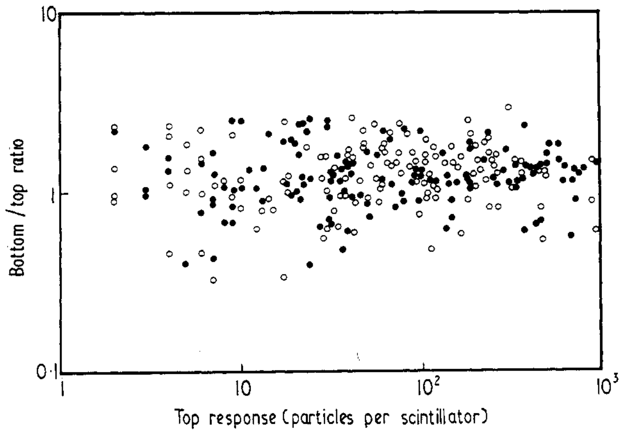

Figure 6. The ratio of bottom to top response for pairs of scintillators during the meatless sandwich run plotted against the response of the top scintillator. The events are random samples of both single-cored events (open circles and multi-cored events (full circles).

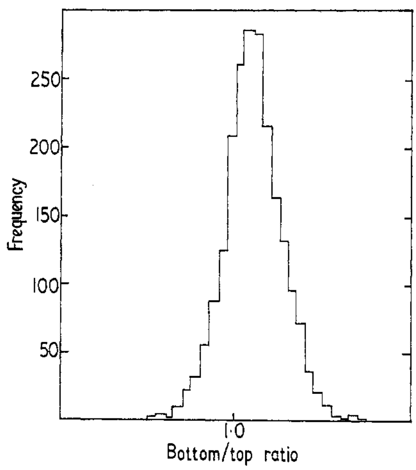

Figure 7. A frequency histogram of the ratios of the response of the upper scintillator to that of the lower scintillator for the 'meatless sandwich' run. The mean of the distribution is 1·26 and the fractional standard deviation is 0·40.

We now wish to enquire whether or not it is possible to produce apparently multi-cored events from real single-cored distributions or vice versa if we allow a fractional standard deviation such as given above in the response of each channel. To do this we used the Monte Carlo technique to generate fluctuations with the fractional standard deviation (0·4) on 100 showers from proton primaries and 30 with copper primaries (with energy 10^{15} eV). We have already seen that the mean structure function of the simulated proton showers is the same, within very small limits, as that of real single-cored showers. Table 5 shows the results. The only effect of any significance is a *decrease* in the fraction of *multi-cored showers* after fluctuation, in the case of

Table 5. The fraction of showers with $\Delta_1/\Delta_2 > 1{\cdot}5$ for two classes of showers before and after random fluctuation with a fractional standard deviation of 0·4

Type of event	Before fluctuation	After fluctuation
Proton 10^{15} eV	93 ±10%	88 ±10%
Copper 10^{15} eV	11 ±5%	25 ±6%

showers for copper primaries. The Kiel group have suggested that the 55% of Sydney showers (table 10) which are multi-cored are generated by fluctuations of real single-cored events. It is obviously rather difficult, in almost any circumstances, to explain 55% of a sample as due to fluctuations. In this case, after this experimental proof of the almost negligible effect of fluctuations on core type, it is impossible.

3.8. *The effect of local hadronic interactions*

The Kiel experimental group (Samorski *et al.* 1970) have suggested that the 84 events that they have found with shower size less than 10^5 particles and showing well-separated sub-cores are due to the local interactions of hadrons in the wooden beams (thickness 7 g cm^{-2}) which support the roof above their array. These sub-cores contain up to 100 particles, over and above the background level, in a circle of 20–30 cm diameter. We will now show

(i) that a multiplicity of 50 particles from 7 g cm^{-2} of material of low atomic number requires an extremely high energy,

(ii) that the number of even 1000 GeV hadrons in such small showers is about two orders of magnitude too small to produce the effect.

(iii) that a thicker producing layer, of material of higher average atomic number at the same height on the Sydney array, showed no such effect.

The multiplicity of charged particles coming from an interaction in light elements is well known and is very much less than 100 even for hadron energies of 1000 GeV. The mean multiplicity from lithium hydride at 300 GeV (Dobrotin and Slavatinsky 1960) is 8 ± 1. The mean multiplicity from carbon at 1000 GeV is $9{\cdot}9 \pm 1{\cdot}4$ (Hansen and Fretter 1960). This last experiment is particularly relevant. The cloud chamber was 40 cm wide (i.e. appreciably wider than the 25–30 cm diameter of the Kiel group sub-cores). The floor of the cloud chamber was 0·75 m from the bottom and 1·25 m from the top of the carbon layer. The carbon layer was appreciably thicker than the wooden beams in the Kiel experiment thus giving more opportunity for secondary cascading and the conversion of γ-rays to electron–positron pairs. It is well known that the mean multiplicity increases only slowly with primary energy (Yash Pal 1967, McCusker and Peak 1964). Even if $\langle n_s \rangle$ varies as rapidly as $E^{1/4}$ one needs an energy of the order of 100 000 GeV to get 100 particles. An event of approximately this energy has been seen in nuclear emulsion (Teucher *et al.* 1959). It had only 16 charged shower tracks. Even the interactions of 1000 GeV hadrons producing small sub-cores of 10 particles do not happen with anything like a high enough frequency to explain the Kiel results. As we have seen, the experimental probability of observing a hadron of energy greater than 1600 GeV per shower in the size range $5\times10^4 < N < 5\times10^5$ is about 0·2. (0·33 for single-cored events; 0·01 for multi-cored events, above, § 3.4). The probability of this hadron striking the beam is just the ratio of the beam area to the hodoscope area, i.e. 1/10. The probability of the hadron interacting in 7 g cm^{-2} is $\{1-\exp(-7/90)\}$. Thus the number of interactions of 1000 GeV hadrons expected in 1546 showers (of $N < 10^5$) is

$$1546\times0{\cdot}2\times0{\cdot}068\times0{\cdot}1 = 2.$$

Kiel report 84 sub-cores of size up to 100 particles in this sample.

Finally we have attempted to reproduce the Kiel result using our 64-scintillator array. In our case the light roof supported by two light girders is two metres above the scintillators and could not be expected to show any effect. However, at one end of the scintillator block we have two steel girders supporting the coaxial cables supplying EHT to and taking out the signals from the scintillators. This made a strip of a total of 12 g cm^{-2} (8 g cm^{-2} Fe, 1·5 g cm^{-2} Cu and 2·5 g cm^{-2} polystyrene) at a height of 95 cm above the array. Obviously this strip is a better producing layer and a more efficient γ-ray converter than 7 g cm^{-2} of wood. Figure 8 shows a cross section of

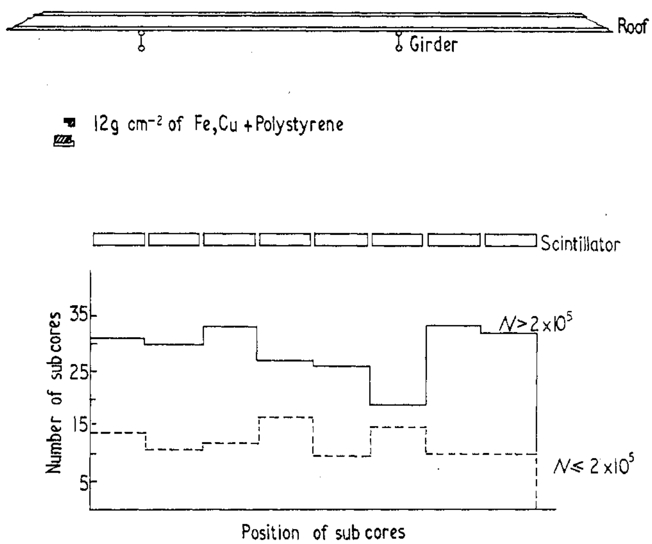

Figure 8. A side elevation of the Sydney 64-scintillator array showing the positions of the scintillators, the roof of the hut and the steel girders supporting coaxial cables going to the scintillators. The frequency of occurrence of sub-cores of multi-cored showers in the different scintillator rows is also shown for showers with $N \lesseqgtr 2\times10^5$ particles.

the array and a histogram of the number of sub-cores against distance from this beam. There is no enhancement in the rate of sub-cores near the beam, either for showers of size less than 2×10^5 or for showers of size greater than 2×10^5, which, having more energetic hadrons, might be expected to show a greater effect.

4. The Sydney Monte-Carlo simulations

4.1. *The electromagnetic component*

Both our Monte-Carlo program and the recent work of Thielheim and Beiersdorf allow the determination of the electron density in the central scintillator (Δ_1) and its neighbours (Δ_2, Δ_3, etc.) for various types of primary particle, with various primary energies and given mean transverse momentum in the interaction of the hadrons. In table 4 we give the ratios of these densities (Δ_1/Δ_2, etc.) for the Sydney and Kiel proton simulations ($\langle p_T \rangle = 0{\cdot}5$ GeV/c) and for the real, Sydney single-cored events. There is excellent agreement between the two simulations and the experimental results. This strongly suggests that many single-cored events are produced by primary protons.

Table 6. The electron structure function of various types of simulated showers given as the ratios of the densities in scintillators 1 to 5 going outwards from the core

Type of event	Δ_1/Δ_2	Δ_2/Δ_2	Δ_3/Δ_2	Δ_4/Δ_2	Δ_5/Δ_2	Number of showers used
Sydney, Cu, 10^{15} eV	1·37	1	0·73	0·60	0·53	30
Kiel, Cu, 4×10^{15} eV	1·22	1	0·83	0·69	0·58	2
Sydney, α, 10^{16} eV	3·36	1	0·51	0·34	0·25	20
Sydney, Cu, 10^{16} eV	2·77	1	0·50	0·34	0·26	7

In table 6 we give the same ratios for the Sydney simulations using copper primaries of energy 10^{15} eV, for the Kiel simulation for copper nuclei of energy 4×10^{15} eV, and for the Sydney simulation for α-particles and Cu nuclei of 10^{16} eV (each simulation in this last case took $1\frac{1}{2}$ hours computing time on a KDF9).

We see from a comparison of proton, α-particle and Cu simulations that the mean central structure of air showers at primary energies around 10^{15} eV is a sensitive function of the nature of the primary particle. Comparison of the real single-cored showers with simulated events shows that the majority of the single-cored showers are due to primary protons. Similarly since simulated showers with proton primaries only rarely produce events with $\Delta_1/\Delta_2 < 1{\cdot}5$, the majority of the multi-cored showers must be due to heavier primaries. At these energies the excellence of the fit shows that the mean transverse momentum must be close to 0·5 GeV/c.

At 10^{16} eV this is no longer the case. Even with the heaviest primaries all the simulated showers have Δ_1/Δ_2 not only greater than 1·5 but also greater than 2·5. Figure 9 shows the electron distribution maps of two showers with the highest and lowest value of Δ_1/Δ_2 in this simulation using α-particles of 10^{16} eV total energy.

On the other hand the observed real showers become *increasingly multi-cored* above sizes of 10^6 ($93\pm5\%$ of the Kiel (table 1, Samorski *et al.* 1970) showers, $85\pm12\%$ of the Sydney showers). It has proved impossible to simulate these large multi-cored showers using a mean transverse momentum of 0·5 GeV/c. We conclude that at these high energies the mean transverse momentum is much greater than at machine energies.

4.2. *The hadronic component*

Our Monte Carlo simulations also gave the distribution of hadrons, both in number and energy, on a 9×9 array of $0{\cdot}5\times0{\cdot}5$ m squares at the five atmospheric depths: 200, 400, 600, 800 and 1000 g cm^{-2}. Several of these maps have been reproduced elsewhere (McCusker *et al.* 1969) and we have shown that the strong correlation between real single-cored showers and simulated proton cascades and between real multi-cored showers and simulated heavy primary cascades also occurs in the hadronic component. In table 7 we give the mean number of hadrons greater than

50 GeV and greater than 1000 GeV falling on a 4·5 m × 4·5 m area around the shower core at sea level for showers generated by protons and copper nuclei each of total energy 10^{15} eV.

There is an obvious dependence on the atomic weight of the primary particle and an equally obvious relationship between the number of hadrons observed experimentally for single- and multi-cored showers of the same size (§ 3.4).

Number, HF 1/4

80	92	103	109	103	92	80	68
92	115	139	155	139	115	92	76
103	139	207	273	206	139	103	82
109	155	277	734	275	155	109	85
103	140	208	277	207	139	103	82
92	116	140	155	139	115	92	76
80	92	104	109	103	92	80	68
68	76	82	85	82	76	68	62

Number, HF 1/5

570	672	770	817	770	672	570	477
672	875	1096	1242	1097	876	672	537
770	1097	1757	2463	1758	1098	771	590
817	1245	2473	8196	2480	1246	818	612
771	1099	1765	2486	1766	1100	772	590
673	877	1100	1247	1101	878	673	537
571	673	771	819	772	673	571	477
477	537	590	612	591	537	477	424

Figure 9. The electron distribution maps of two simulated showers using α-particle primaries of 10^{16} eV and 'normal' transverse momentum. These are the showers with the lowest and highest values of the central electron density (Δ_1) in the sample.

Table 7. The mean number of hadrons on an area 4·5 × 4·5 m² around the core (> 50 and > 1000 GeV) in showers with proton and copper primaries of total energy 10^{15} eV

	p	Cu
Number of hadrons > 50 GeV	15·5	9·3
Number of hadrons > 1000 GeV	4·5	1·3

5. Comparison with other work

5.1. *The Tokyo air shower group*

The Tokyo air shower group (Matano *et al.* 1968), using a 20 m^2 spark-chamber array, has observed 15 multi-cored showers in which the sub-core had a transverse momentum greater than 5 GeV/*c*. These events formed 3% of all the shower cores observed for showers with sizes greater than 10^5 particles. The results can be compared directly with ours. In our larger sample we found 44 showers with $rp_L/h > 5$ GeV/*c* out of a sample of 1041 showers whose cores hit the 64-scintillator array, with $N > 10^5$. Thus our fraction is $4{\cdot}2 \pm 0{\cdot}4\%$ in good agreement with the Tokyo result within the statistical errors. Their values of rp_L/h ranged from 5 to 50 GeV/*c*; ours from 5 to 120 GeV/*c* in a larger sample.

5.2. *The Osaka group*

The Osaka group has observed multi-cored showers on Mt Norikura with a wide variety of detectors (Miyake *et al.* 1963, 1968). These include an array of 100, 0·25 m^2 scintillators on a square grid of spacing 2·5 m, the same array with a spacing of 5 m, a very large multiplate cloud chamber and an array of 96 scintillators closely packed into two 48-scintillator layers separated by two metres of water. It is the last of these arrays that is most closely comparable with our experiment. They use the criterion $\Delta_1/\Delta_2 > 3$ to define a single-cored shower (the higher ratio is necessary because of the mountain altitude). They find that 25% of the showers, using their criterion, are multi-cored.

We have used the results of our Monte-Carlo simulations together with an assumed charge spectrum of the primaries similar to that at low energies to predict the fraction of single-cored showers at mountain altitudes. Our predicted value (McCusker *et al.* 1969) is 65% compared with the observed value of the Osaka group of $75^{+10}_{-8}\%$.

The Osaka group have computed transverse momenta for their multi-cored showers in a manner similar to the Tokyo group and ourselves and find transverse momenta ranging from 'several GeV/*c* to several tens of GeV/*c*' (Miyake *et al.* 1968). That is to say there is good agreement between the findings of the Tokyo Group, the Osaka group and ourselves.

5.3. *The Kiel theoretical group*

The first simulations of the Kiel group (Böhm *et al.* 1968) were so simplified (as we have pointed out in § 2.6) and, in fact, had folded into them the experimental distribution with which they were later compared, that no solid conclusions could be drawn from them. Their later work was of quite a different character (Thielheim and Beiersdorf 1970—private communication) and can profitably be compared with the Sydney Monte-Carlo simulations and experimental results and also with the Kiel experimental results.

In table 8 we detail the numbers of showers simulated by the Kiel and Sydney groups for different types of primary and different energies ($> 10^{15}$ eV).

In general, the agreement between the two simulations is very good. For instance, taking the electromagnetic component first, the Kiel group get a range of maximum central densities (Δ_1) at any given shower size N for mixed primary beam, p, α, O and Cu of 50 to 1, in agreement with the Sydney simulations (figure 3, Thielheim and Beiersdorf 1970—private communication, and McCusker *et al.* 1969—figure 4). This

Table 8. The number of showers simulated for various types of primary particle and for various energies ($\geqslant 10^{15}$ eV) by the Kiel and Sydney groups

Group	Primary energy	p	α	O	Cu	Total
Kiel	10^{15}	100				233
	4×10^{15}	100	25	6	2	
Sydney	10^{15}	643	141	50	135	1028
	2×10^{15}	32				
	10^{16}		20		7	

range is also in agreement with the experimental results of the Sydney and Osaka groups (McCusker *et al.* 1969). However, the Kiel experiment gives a range of 10 to 1. We will discuss this later.

Thielheim and Beiersdorf also get a similar radial fall off in electron density as the Sydney Group for the various types of primary. The ratios Δ_1/Δ_2, Δ_3/Δ_2 etc. for the two proton simulations we compared in table 4. The same ratios (calculated from figure 2 of Thielheim and Beiersdorf 1970—private communication) for copper primaries are given in table 6. There is fairly good agreement between the simulations. The mean Kiel structure function for copper primaries is somewhat *flatter* than the Sydney function but it is based on only two showers.

Again, like the Sydney simulations, the Kiel results show the highest median central density for proton showers and the lowest for copper showers. The highest central density recorded by Kiel is 67 000 particles/m^2 for a proton shower; the highest recorded by Sydney (for showers of four times smaller primary energy) was 10 600 particles/m^2 also for a proton shower. Both groups find a wide range of central densities for proton showers and a small range for showers with copper primaries.

Thielheim and Beiersdorf use a quantity Γ_e to measure the flatness of the electronic structure function. This is the distance from the axis at which the electron density has fallen to $1/e$ ($= 0{\cdot}367$) of the central electron density. Their median values of Γ_e for different primaries are shown in table 9. The rapid change of this value as the atomic weight increases again shows the great influence of the nature of the primary on the core structure at sea level.

Table 9. $\langle\Gamma\rangle$ and $\langle\Gamma_s\rangle$ for simulated showers with different types of primary particle

Primary	p	α	O	Cu
Median Γ_e (m)	0·73	0·85	2·5	3·3
Γ_s (m)	0·76			2·5

Our central density is the number of electrons hitting one scintillator (Thielheim and Beiersdorf went down to 10 cm × 10 cm squares) so we cannot calculate the same quantity. However, if we calculate the radius at which the density is $\Delta_1/2{\cdot}718$, we have an analogous quantity (which we call Γ_s). This is given in the second line of table 9 for protons and copper nuclei.

The Kiel group find only a few multi-cored showers with well separated sub-cores. Their sample was taken at a primary energy of 4×10^{15} eV and included only six oxygen nuclei and two copper nuclei. In the Sydney sample taken at 10^{15} eV (with 50 oxygen nuclei and 135 copper nuclei) the proportion was appreciably greater. On the other hand the Sydney group found no separated sub-cores (and in fact no showers with $\Delta_1/\Delta_2 < 2{\cdot}5$) for α-particle or copper showers at 10^{16} eV with 'normal' transverse momentum. Thus these theoretical predictions seem in reasonable agreement.

This is true also for the hadronic component. Both groups find that, near the shower core, the number of hadrons above a given energy depends critically on the atomic weight of the primary particle. In particular the number of nucleons greater than 1000 GeV is much less for copper primaries than for proton primaries of the same total energy (table 7).

The main difference between Thielheim and Beiersdorf and the Sydney group lies not in the results of the simulations but in the conclusions drawn from their results by the Kiel workers. They have concluded that "there is no possibility to infer primary composition from multi-cored structures in the electromagnetic component". In fact, as we have already shown, the experimental distribution of Δ_1/Δ_2 values can not be simulated by either group using a pure proton beam or a pure copper beam. Neither group has been able to simulate showers with central densities of 20 000 particles/m^2 at a size of 10^6 particles, using oxygen and copper primaries. This in fact means that one can often say a great deal, not only about the chemical composition of the beam from a large sample of cores, but even about the primary of one particular shower. This is illustrated in figure 10 where we have

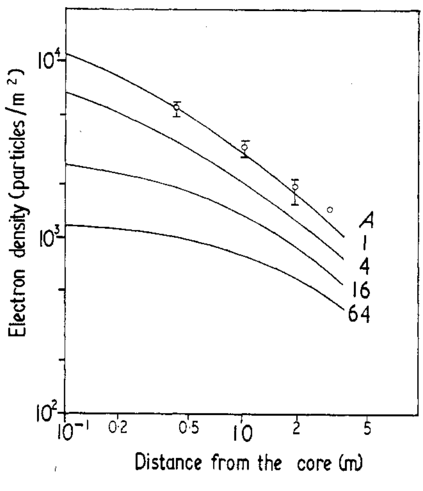

Figure 10. The mean electron structure function of showers with primaries of energy 4×10^{15} eV and of atomic weight 1, 4, 16 and 64 respectively from the Kiel Monte-Carlo simulation (Thielheim and Beiersdorf 1970). The experimental values for the Kiel event 7/471 (Bagge *et al.* 1965) are also shown.

superimposed the experimental structure function of Kiel shower 7/471 (figure 7(*b*) of Bagge *et al.* 1965) on the mean structure functions of showers produced by p, α, O and Cu primaries of 4×10^{15} eV (figure 2 Thielheim and Beiersdorf 1970—private communication). There has been no normalization of experimental points to the theoretical curve. It is obvious that this particular shower could not be due to an

91	120	140	145	144	97	112	63
95	120	190	439	224	149	88	71
96	131	185	209	143	119	76	73
94	80	117	140	121	110	91	94
63	91	88	77	89	69	69	62
50	74	67	73	55	49	47	58
54	60	71	72	65	51	48	46
47	52	52	58	49	34	45	35

Figure 11. The electron distribution for the real shower (event 118218) on the Kiel array. This event may be compared with the Sydney event 11385 in figure 2.

Kiel event 118171

56	61	38	60	53	56	46	53
41	52	63	79	80	82	53	31
63	49	72	98	92	119	85	61
60	64	88	120	153	126	82	78
61	71	93	129	143	131	69	63
59	73	64	86	109	113	80	71
48	73	65	61	96	100	86	59
45	46	56	69	59	50	54	53

Sydney event 5302

	52	87	136	123	144	126	
61	82	110	136	153	135	120	115
57	68		107	114	99	125	
49	46	60	87		90	117	57
51	37	58			74	53	59
36		43	38	33	40		47
34	64	37	44	27	37	22	42
	23	33	49		43	18	19

Figure 12. Two real flat-topped showers, Kiel event 118171 and Sydney event 5302. It has not been possible to simulate this type of event using proton primaries and normal transverse momentum.

oxygen or copper nucleus. Since Thielheim and Beiersdorf found no proton showers with multiple cores separated by more than 36 cm, it also follows that the Kiel experimental events 7/377 (figure 8 Bagge *et al.* 1965) or the event shown in figure 4 of Samorski *et al.* (1965) cannot be due to proton primaries.

5.4. *Kiel experiment*

There are very considerable similarities between the results of the Kiel experimental group and that of other groups. For instance figures 2(*a*) and 11 show two single-cored showers ($\Delta_1/\Delta_2 > 1{\cdot}5$) recorded respectively by the Sydney and Kiel groups. The Sydney event has a central density Δ_1 of 539 per scintillator; the Kiel event has a density of 439 particles on an equivalent area. The value of Δ_1/Δ_2 is 2·0 for the Sydney event, 2·0 for the Kiel event. The lowest densities on the arrays are 15 and 34 per scintillator respectively.

The pair of showers in figure 12 are obviously very different in character to the pair in figures 2(*a*) and 11. Both of the showers in figure 12 have $\Delta_1/\Delta_2 < 1{\cdot}1$. Both have central densities of 153 particles per scintillator. The Sydney event has 14 scintillators with $\Delta > 100$ particles per scintillator; the Kiel event has 10 equivalent areas with $\Delta > 100$ particles/area. We have simulated many showers like either of those in figures 2(*a*) and 11, using proton primaries; we have been unable to simulate multi-cored showers with moderately high Δ_1 such as that in figure 2(*b*) unless we used both a heavy primary, and a large transverse momenta.

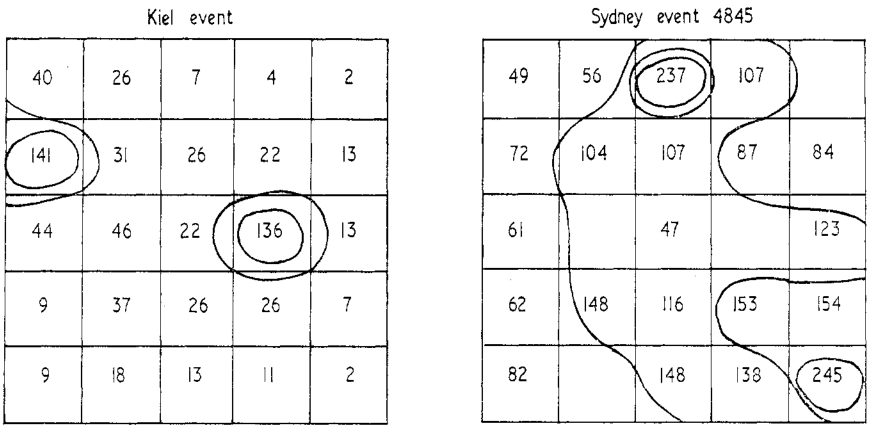

Figure 13. Two real double-cored showers. The Kiel event is reproduced in figure 4 (Samorski *et al.* 1965). The Sydney event is shower number 4845.

Figure 13 shows two showers each with two well-separated peaks. The Kiel event is taken from figure 4 of Samorski *et al.* (1965) . The Sydney shower is event 4845 from Bray *et al.* (1964 b). The Kiel group give a value of 20 GeV/c for the transverse momentum of their event.

The Kiel group also get a similar rate of occurrence of events with large values of rp_L/h to the Sydney group. Kiel report 11 events with $rp_L/h > 5$ GeV/c (figure 4 Samorski *et al.* 1970) in a total of 20 000 showers recorded. Sydney have 37 such events in 52 000 showers recorded to 31st December 1968. The respective fractions are $0{\cdot}5 \pm 0{\cdot}16\%$ and $0{\cdot}7 \pm 0{\cdot}11\%$. We have already seen that the Sydney rate is in agreement with the Tokyo rate. The highest value of rp_L/h quoted by the Kiel group is 20 GeV/*c* (Samorski *et al.* 1965) for the event shown in figure 13. The Tokyo and Sydney groups working with larger samples have higher maximum values.

Another point of agreement is on the effect of fluctuations on core type. We have seen in § 3.7 that the experimentally determined fluctuations (both Poissonian and instrumental) have a negligible effect on the fraction of showers with $\Delta_1/\Delta_2 > 1{\cdot}5$ in a representative sample of 100 single-cored showers (before fluctuations 93% of the sample had $\Delta_1/\Delta_2 > 1{\cdot}5$; after fluctuations the fraction was 88%). The Kiel group have made a similar calculation, but applied to smoothed distributions fitted to a sample of 30 real showers of which $80 \pm 7\%$ had Δ_1/Δ_2 *less* than 1·5. They used only Poissonian fluctuations. The effect of the fluctuations was to produce a sample of which $83 \pm 7\%$ had $\Delta_1/\Delta_2 < 1{\cdot}5$. That is to say, just as in the Sydney simulation, fluctuations had no effect outside the statistical error on the fraction of the sample which was single- or multi-cored.

There are some differences between the Kiel experimental results and those of other groups. In the Kiel experimental sample the range of values of the central density Δ_1 at a given shower size is only 10 to 1. Both the Osaka and Sydney experimental groups and the Kiel and Sydney theoretical groups get 50 to 1.

Also the fraction of multi-cored showers ($\Delta_1/\Delta_2 < 1{\cdot}5$) in the Kiel sample of showers with $10^5 < N < 10^6$ is much *greater* than that obtained by either Osaka or Sydney. The fractions are shown in table 10.

Table 10. Fraction of real showers which are multi-cored ($\Delta_1/\Delta_2 < 1{\cdot}5$) in two size ranges at sea level and one size range at mountain altitude

Observer \ Shower size	10^5 to 10^6 particles	$> 10^6$ particles
Kiel	$80 \pm 7\%$ (30 events)	$93 \pm 5\%$ (30 events)
Sydney	$55 \pm 3\%$ (473 events)	$85 \pm 12\%$ (59 events)
	4×10^5 to 4×10^6	
Osaka	25% (81 events)	

These discrepancies between the Kiel experimental results and those of other groups and also between the Kiel experimental and theoretical results can both be accounted for if the Kiel experiment underestimates the central density in real single-cored showers. This effect loses the high values of Δ_1 from their $\Delta_1 - N$ diagram and underestimates Δ_1/Δ_2 thus converting what should be single-cored showers to multi-cored showers. That this could well be so is shown by event 7/471 (Bagge *et al.* 1965). This has all the appearance of a single-cored shower except that its central area shows only 1641 particles passing through it. Since this area has only 1250 neon pots and since the Kiel group use a prompt pulse on the neon hodoscope for $N < 10^6$, the hodoscope, for this central area, is working in a very nonlinear region.

The Kiel experimental group have attempted to show that their own events ($N < 10^5$) with well-separated sub-cores are due to local hadronic interactions in 7 g cm^{-2} wooden beams above their array. We have shown in § 3.8 that this suggestion is not tenable.

The Kiel group have also attempted to show that the high transverse momenta determined by the Sydney group are due to fluctuations. We have determined these fluctuations by direct experiment and have shown (§ 3.7) that this cannot be so.

5.5. *The Tien Shan array*

The Tien Shan array consists of a considerable number of plastic scintillators, a large ionization calorimeter and an emulsion chamber. The scintillators permit accurate location of the air-shower core; the calorimeter allows estimation of the energy of very energetic hadrons and the emulsion chamber gives the direction, energy and a number of γ-rays in energetic γ-ray 'families'. The array is at 3300 m altitude. Recently an event has been reported (Nikolskii 1969) which was produced by a primary of energy of the order of 10^{15} eV. The ionization calorimeter detected a nucleon of 5×10^{13} eV. The emulsion chamber revealed a family of 20 γ-rays of total energy 5×10^{13} eV. 'Pairing' of the γ-rays and the stage of development of the accompanying electron cascade around them fixed the π^0 production height at 1 km above the array. The main electron core of the shower was approximately 25 cm from this sub-core and a similar distance from the high-energy hadron. The two transverse momenta are greater than 2 GeV/c and greater than 10 GeV/c respectively.

6. Conclusions

As a result of our own experiments and simulations extending over a period of eight years and the experiments and simulations for many other groups we conclude:

(*a*) The criterion Δ_1/Δ_2 less than or greater than 1·5 separates real showers of a given size into two classes with very different mean properties. As compared with the showers with $\Delta_1/\Delta_2 < 1{\cdot}5$, the showers with $\Delta_1/\Delta_2 > 1{\cdot}5$ have a marked radial symmetry, a higher mean central density, a steeper electron structure function, a higher mean hadron energy and a much higher fraction of high-energy hadrons per shower.

(*b*) All experimental groups, using a wide variety of detectors, observe both types of shower.

(*c*) In simulations at 10^{15} eV, proton primaries produce 93% single-cored showers ($\Delta_1/\Delta_2 > 1{\cdot}5$). Copper primaries of the same total energy produce 11% single-cored showers. The simulated single-cored showers, like the observed showers with $\Delta_1/\Delta_2 > 1{\cdot}5$, have a higher mean central electron density, a steeper electron structure function, a more marked radial symmetry, a higher mean hadron energy and a much greater fraction of very energetic hadrons. The mean structure functions of the Sydney and Kiel groups for each type of primary are in good agreement. At shower sizes between 5×10^4 and 5×10^5 both simulations can reproduce both the electron and hadron distributions of individual real showers with considerable accuracy.

(*d*) The experimental distribution of Δ_1/Δ_2 for showers of $5 \times 10^4 < N < 5 \times 10^5$ shows a strong peak between 1·0 and 1·5 and a very broad distribution between 1·5 and 5·0 with a diffuse maximum around $\Delta_1/\Delta_2 = 2{\cdot}7$. This two-peaked distribution cannot be simulated either by showers produced by protons only, or by showers produced by copper nuclei only. It can be simulated by a mixed beam with the same proportion of different nuclei as low-energy cosmic radiation. For some individual real showers the atomic weight of the primary can be specified within narrow limits. This can be done for showers from the Kiel array, using the Kiel Monte Carlo simulations (figure 10).

(*e*) At shower sizes above 10^6 both Kiel and Sydney groups find that more than 80% of the showers have $\Delta_1/\Delta_2 < 1{\cdot}5$. On the other hand, simulations using primaries (from protons through copper) of total energy 10^{16} eV and 'normal' mean transverse momentum produce only showers with $\Delta_1/\Delta_2 > 2{\cdot}5$.

(*f*) In an attempt to explain these large multi-cored events, we have determined experimentally the fluctuations of our array, both Poissonian and those due to the apparatus. We have applied these to a sample of 100 showers, 93% of which had $\Delta_1/\Delta_2 > 1\cdot5$ and find that the fluctuations have very little effect on this fraction, changing it to 88%. We conclude that fluctuations applied to a pure beam of single-cored events cannot change it to a beam with more than 80% multiple cores. The Kiel group have applied fluctuations to a largely multi-cored sample and find, likewise, that they have little effect on the core type.

(*g*) The effect of local hadronic interactions on core type has been shown to be negligible.

We are left then with an appreciable number of large showers ($N > 10^6$) observed by many groups, which have $\Delta_1/\Delta_2 < 1\cdot5$. Simulations, even using very heavy primaries and normal transverse momenta, predict the opposite situation, namely that all should have $\Delta_1/\Delta_2 \gg 1\cdot5$. We conclude that at high energies there are processes which involve much higher transverse momenta than those commonly occurring in the energy range 10^9 to 10^{14} eV. This in turn implies the existence of a super-strong force. This force could be either the quark–quark binding force, or a force associated with the X process of the Utah group (Keuffel *et al.* 1970) or possibly some as yet unpredicted effect. It is, perhaps, too early to decide which is responsible. However, there is already evidence for the existence in air shower cores of both fractionally charged particles (Cairns *et al.* 1969, McCusker and Cairns 1969 and Chu *et al.* 1970) and massive particles (Jones *et al.* 1967 and White and Prescott 1970).

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