J. Phys. G: Nucl. Phys., Vol. 3, No. 5, 1977. Printed in Great Britain. © 1977

Observed multiplicity distributions from 200 GeV neutrons on thick carbon targets; application to multi-core observations in air showers

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Received 13 September 1976, in final form 16 November 1976

Abstract. The multiplicity distributions of charged particles produced in carbon targets up to $10\,\mathrm{g\,cm^{-2}}$ by the M3 neutron beam at FNAL (~ 210 GeV median energy) have been measured in forward cones. The value of $\langle n \rangle$ increases only slowly with target thickness but the tail of the distribution $\langle n \geqslant 15 \rangle$ triples with an increase in thickness from 2·5 to $10\,\mathrm{g\,cm^{-2}}$.

The above is used to predict the contribution of local hadron interactions to the sub-cores in air showers observed at Kiel. We conclude that one-third or more of the sub-cores (about 30) are not due to local hadron interactions.

1. Introduction

In § 2 we describe the multiplicity distributions of charged particles produced by interactions of accelerator hadrons in thick carbon targets. In § 3 the above results will be used to calculate the expected contribution by hadron interactions in the laboratory roof to the sub-cores in air showers at Kiel (Samorski *et al* 1970). We will then deduce the rate of sub-cores incident from the air and compare it with other experiments.

2. Acceleration observations

As part of a search for multi-photon evidence of magnetic monopoles produced by ~ 200 GeV neutrons (Longo *et al* 1974, Burke *et al* 1975), test runs were made with carbon targets and no lead converters. Optical, wide-gap spark chambers were used, see figure 1, with 90° side photographs of all four chambers and an end-on photograph of the last chamber. Measured values of neutrons per pulse, pulse length and spark chamber sensitive time lead to a probability of $\sim 0{\cdot}01$ for superposition of two interactions. No correction was made since the effect on our results would be negligible.

The trigger required (see caption to figure 1) the emission of at least one particle within a forward pyramidal cone of 1·5 sr. The resulting bias in our sampling of multiplicities in a 0·07 sr forward cone would be negligible. Interactions in material other than the target were easily identified by vertex coordinates obtained from re-projections.

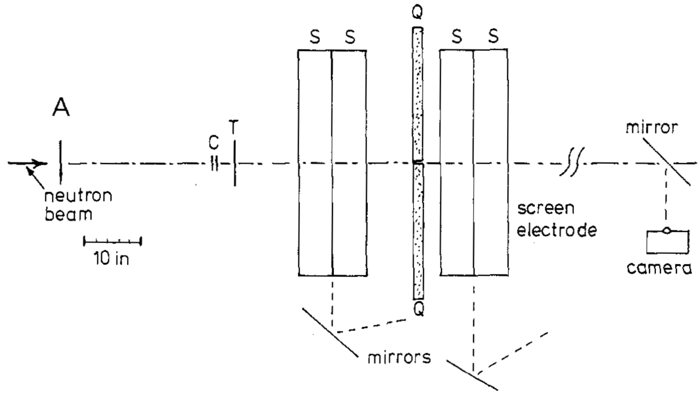

Figure 1. The experimental arrangement of spark chambers (S) at FNAL. The target is at C. The trigger was a pulse from any one of the four 'quad scintillators' Q in coincidence with T and anticoincidence with A.

The multiplicities for two primary target thicknesses, 1·5 and 6·1 g cm^{-2}, were read from re-projections of the films. Data were obtained for the maximum solid angle of 0·86 sr defined by the last spark chamber, and for the forward solid cone of 0·07 sr that corresponds to the Kiel sub-cores (Bohm *et al* 1968), a disc of 30 cm

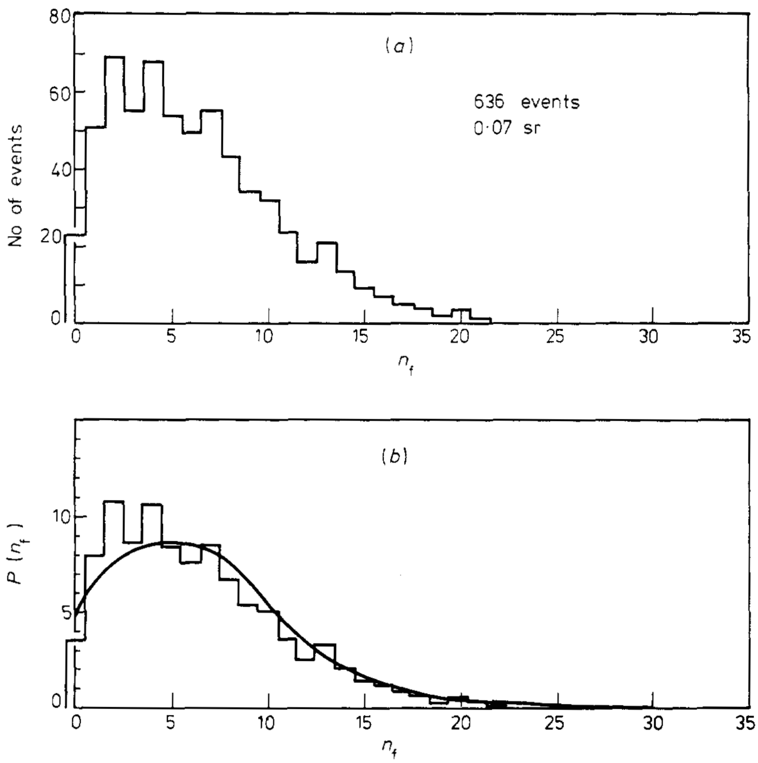

Figure 2. (*a*) The multiplicity distribution for the composite 'target' C + Q. The requirement that the initial interaction occurs in C will slightly favour higher multiplicities. (*b*) The probability $P(n_f)$, in %, of n_f particles. The curve is a Poisson fit to the data.

diameter at a distance of 100 cm. In addition, multiplicities including secondary interactions in the Q scintillators were obtained, a total thickness of $10\,\mathrm{g\,cm^{-2}}$. In this case data were taken for a solid angle of 0·07 sr for both target and secondary interactions in Q. These latter data constitute an approximation to $10\,\mathrm{g\,cm^{-2}}$ target data (the Kiel upper roof beams). A second set, for particles within a 30 cm diameter circle, approximates Kiel events with secondary interactions in the lower roof beams.

The resulting frequency distribution for the multiplicity from $10\,\mathrm{g\,cm^{-2}}$ (1 in graphite target plus the quad scintillators) within a 30 cm circle is shown in figure 2. This is the case of principal interest for our application to the Kiel data. The mean multiplicity, $\langle n_f \rangle$, is 5·4. Figure 2(*b*) has the ordinates transformed to probability, $P(n_f)$. The curve is a Poisson distribution, fitted to the data, which fits as well as expected for a thick target and narrow cone. At any rate, the curve is a good representation for $n_f \geqslant \langle n_f \rangle$, which is the region of present interest.

Figure 3(*a*) shows the observed dependence of $\langle n \rangle$ and σ on thickness and figure 3(*b*) shows the dependence of the height of the tail of the distribution on thickness.

3. Interpretation of the Kiel sub-core data

A $32\,\mathrm{m}^2$ neon-bulb hodoscope array has been used at Kiel (Samorski *et al* 1970) to study the lateral distribution of particles in cosmic-ray air showers near sea level.

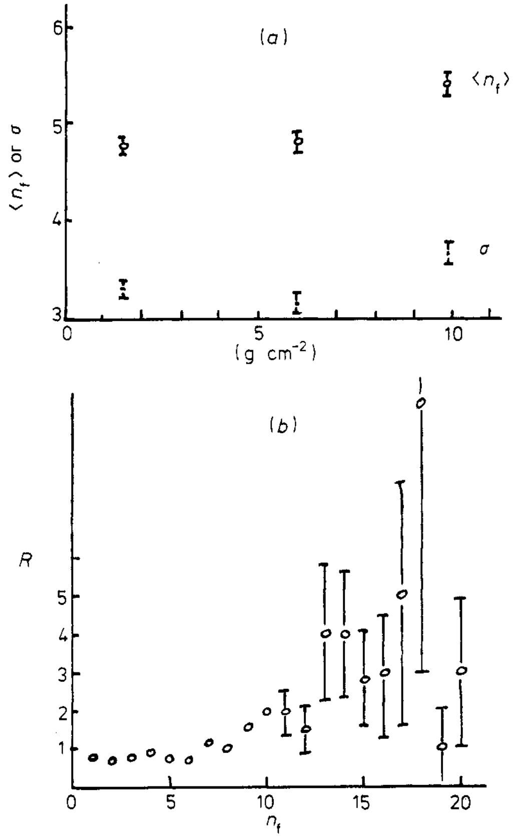

Figure 3. (*a*) The open circles are the mean multiplicities in the 0·07 sr forward cone and the full circles are the standard deviations. (*b*) The ratio R of the heights of the tails of the distributions for $10\,\mathrm{g\,cm^{-2}}$ compared with $2{\cdot}5\,\mathrm{g\,cm^{-2}}$.

Results from a sample of 2400 showers whose axes struck within the array have been described in some detail. In about 100 cases, sub-cores consisting of 20 or more particles (above the background of the main core) within a circle of about 30 cm diameter were observed. The Kiel roof (2·5 g cm^{-2}) and significant roof beams (7 g cm^{-2}) are $\sim$ 100 cm above the hodoscope. The 30 cm circle used for defining sub-cores subtends the solid angle 0·07 sr (hence our choice of 0·07 sr for the scan of accelerator data in § 2).

Most of the sub-cores of fewer than 130 particles have been attributed by the Kiel group to local interactions, by the hadron component of the showers, in the roof beams above the hodoscope. We will use the results of § 2 to calculate the expected local interaction rate, and the expected division of local interactions between the roof and the beams.

The absolute intensity of the low-energy hadron component of air showers has been measured by Kameda *et al* (1965). Their results and those of other groups are summarized in figures 4 and 5. Figure 4 gives the integral energy distribution of hadrons, I, as a function of E in a shower of size $N = 10^5$ particles. Below 10^3 GeV we have only the results of Kameda *et al* (1965). Above 10^3 GeV, the slope of the Kiel results agrees with that of Kameda *et al* (the absolute value is not significant since the Kiel group used the results of Kameda *et al* to determine their conversion factor from burst size to hadron energy). All results are converted to shower size 10^5 by using the fact that the number of hadrons is found to depend linearly on shower size (figure 5).

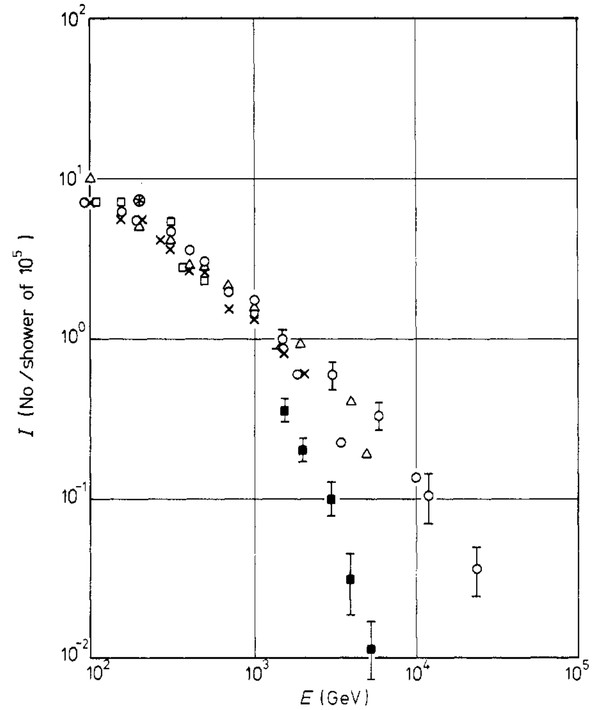

Figure 4. Integral energy spectrum of hadrons in air showers at sea level. ○, 5·6 × 10^4; ×, 1·8 × 10^5; △, 5·7 × 10^5; □, 3·2 × 10^6 (all data normalized to 10^5 (Kameda *et al* 1965)); ■, Matano *et al* (1968); ⊛, Kiel plus present data; ○, Kiel data 'renormalized' to data of Kameda *et al* (1965) (Fritze *et al* 1970).

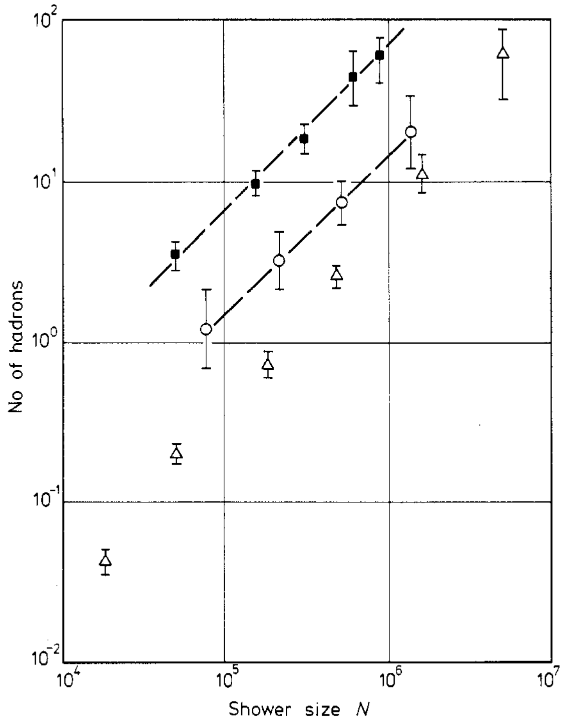

Figure 5. Number of hadrons in air showers at sea level as a function of shower size. ○, Fritze *et al* 1969 ($E \geqslant 800$ GeV) normalized to the data of Kameda *et al* (1965); ■, Kameda *et al* (1965) ($E \geqslant 100$ GeV); △, Matano *et al* (1969) ($E \geqslant 1700$ GeV).

From § 2, the probability that an interaction by a 200 GeV hadron in a 10 g cm^{-2} target will produce 20 or more particles in a 0·07 sr forward cone, $P(20,200)$, is obtained by integrating the Poisson fit of figure 2. The result is $P(20,200) = 0{\cdot}010$. In order to obtain $P(20,E)$ we have scaled $P(n_f,200)$ to $P(n_f,E)$ by expanding the abscissae (and contracting the ordinates) by the ratio of mean multiplicities in the forward cone of 0·07 sr. This ratio was obtained from the ratio of experimental mean total multiplicities (Whitmore 1974) multiplied by a factor for the increase in contraction into a forward cone with increase in E. The latter was calculated for a uniform centre-of-mass distribution of the secondaries in a proton–proton collision, which is an overestimate since it is observed that much of the increase in produced particles, for heavy nuclear targets, is in the backward hemisphere in the centre-of-mass frame (Busza *et al* 1975, Viswanath *et al* 1975).

The function $P(20,E)$ obtained by the above method was multiplied by $\mathrm{d}I/\mathrm{d}E$ as obtained from figure 4. The resulting product integrated from 200 GeV to infinity gives 1·4 for the average number of local bursts per shower having $n_f \geqslant 20$ particles in a forward cone of 0·07 sr if all the hadrons interacted. The additional contribution by hadrons of $E < 200$ GeV is estimated to be 0·1, giving a total of 1·5.

The above is for showers of size $\bar{N} = 10^5$ whereas the Kiel showers that produced most of the events were smaller than 10^5 (Samorski *et al* 1970). Thus, in view of the linear dependence of hadron number on $\bar{N}$ mentioned earlier, 1·5 is an upper limit. For an upper limit on the *probability* of a beam event per shower, we then have 1·5 $(a/A)((t/\lambda) = 1{\cdot}5)(8/80)$ $(9{\cdot}5/80) = 0{\cdot}018$, where (a/A) is the fraction of the area covered by beams, t is the thickness at the beams and λ is the interaction length in wood. The observed rate was about 84/2400 = 0·033, a factor of two higher than we have calculated.

However, we now show that the expected contribution by the main expanse of roof (of thickness 2·5 $\mathrm{g\,cm^{-2}}$) is significant. From our figure 3(*b*) we see that the tail of the frequency distribution falls by about a factor three when the 'target' thickness is reduced from that of the beam plus the roof to that of the roof alone. Thus, the probability of a roof event per shower is (1·5/3)(72/80)(2·5/80) = 0·014, where (72/80) is the relative roof area and (2·5/80) is the probability of interaction. This result indicates that we would expect about equal numbers of interactions from beams and roof, 0·018 per shower compared with 0·014.

Let us look at the experimental results in detail. In figure 6, we reproduce the Kiel frequency distribution of events with $n_f = 20$ to 130 relative to lateral position projected to the roof level (Samorski *et al* 1970).

Our calculated probability of 0·018 for beam events gives about 43 events out of the 2400 observed showers. These events would be peaked under the beams (projected). The width of the distribution would be about 20 cm, 10 cm from the effective beam width plus 12 cm for the angular resolution of the projection from the hodoscope to the beam plane. The latter is based on the time resolution of about 2 ns (Bagge *et al* 1965) for the timing scintillators, whose separation was ~ 10 m. The predicted number of roof events is about 30. They would be uniformly distributed. The broken line represents our predicted lateral distribution, that is the sum of the predicted beam and roof events.

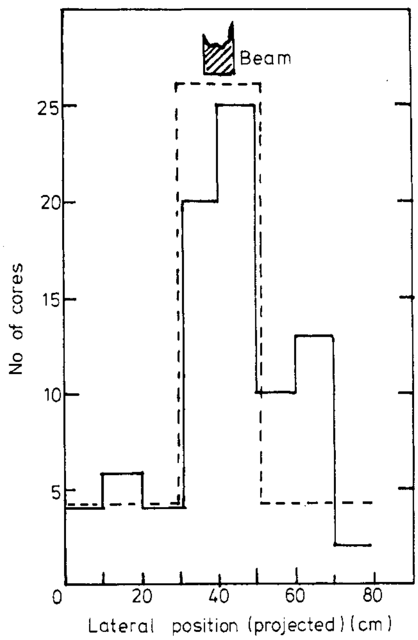

Figure 6. Full line, lateral position of sub-cores (projected into the upper beam plane) observed by Kiel; broken line, number of locally produced sub-cores predicted in this paper.

Since the lateral distribution observed at Kiel is indistinguishable from our predicted distribution, the initial conclusion would be that all of the Kiel sub-cores for $n_f = 20$ to 130 are due to local interactions of hadrons. However, the uncertainties are much greater than the apparent statistical errors of about 10%. Our predicted distribution depends (*a*) on the data of Kameda *et al* (1965), which involve the usual, rather large, uncertainties deriving from multiplate cloud-chamber identification of events and estimates of energy, and (*b*) on the rather uncertain numbers derived from our analysis of our FNAL data. The Kiel data are obtained from the number of neon bulbs that light up, which is $\frac{1}{3}$ the number of incident particles (Samorski, private communication).

Consequently, we estimate that about 20 events could be subtracted from the Kiel observations (figure 6) without making the apparent agreement significantly improbable. In addition, the systematic error due to scanner miss of smaller cores at Kiel is probably appreciable (a 20-particle core lights only seven bulbs). Thus, the above results are at least consistent with an appreciable admixture of true double-core showers (about 20) incident on the Kiel array.

We now turn to another method for deducing the rate of double cores from the Kiel data. Buscher (1968) presents the Kiel frequency–size distribution of their cores (figure 7). They separated the sub-cores into steep cores (I) and ordinary cores (II), according to the rapidity of the radial decrease in particle density. It happens that I and II are also separated by size (figure 7), which leads to the likelihood that the steepness criterion is not very definitive. Indeed, the statistical uncertainty in the measurement of the steepness of sub-cores I, for which fewer than 40 neon bulbs were lit, must be very high. Consequently, we believe that a first-order estimate of the true double-core rate can be made by disregarding the steepness criterion.

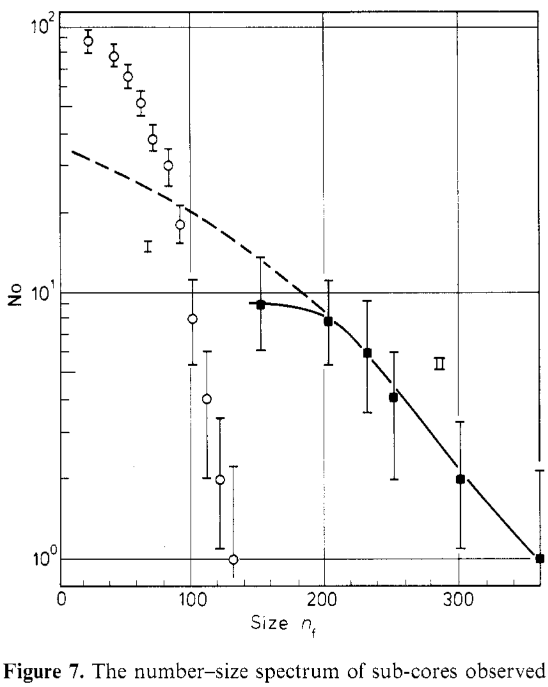

Figure 7. The number–size spectrum of sub-cores observed by Kiel. See text for interpretation.

If we do this, we can extrapolate the II distribution in order to estimate the number of II sub-cores that are included in the I category. A linear extrapolation gives ~ 70 with $n_f \geqslant 20$. A curve drawn through the points gives ~ 10. A reasonable (intermediate) extrapolation leads to ~ 30, as shown in figure 7. Of these 30 with $n_f \geqslant 20$ particles, about 20 will have n_f between 20 and 130 particles. Our earlier analysis of the lateral distribution data indicated that they are compatible with about 20 double-core showers with n_f between 20 and 130.

In summary, our interpretation of the Kiel data leads to a double-core rate $\geqslant (30/2400) = 1{\cdot}2\%$. This is in reasonable agreement with the other sea-level measurements that detected individual particles—Matano *et al* (1968), who state a 'few per cent', and Hazen *et al* (1975), who also find a few per cent.

In view of the possibility of getting information on the large transverse momentum cross section at high energies and/or the heavy primary component of cosmic rays, it is worthwhile to make additional observations that have less uncertainty of interpretation.

Acknowledgment

This work was supported in part by NSF and by ERDA.

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