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The dispersion energy relation for ultra-high energy nuclear reactions in emulsion

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Abstract. When a large volume of data from cosmic ray emulsion reactions is analysed it is found that the variation of the mean dispersion s in the log tan theta plot of the charged secondaries, at each energy, follows a linear characteristic when plotted against the log energy of the incident particle. The slope of the characteristic is peculiar to the type of incident particle, and is higher for nucleon–nucleon collisions than for pion–nucleon events.

1. Introduction

One of the most fundamental parameters that can be calculated from high energy reaction data in the cosmic ray field is the dispersion s of the tracks in the log tan theta plot:

$$s^2 = \sum_{i=1,n} \frac{(x_i - x_{\mathrm{m}})^2}{n-1}$$

where x_i = lg of polar angle of track (i), $x_{\mathrm{m}} = x_{\mathrm{mean}}$ of all tracks in an event and n = number of charged tracks in an event.

It has been known for a long time that there is a tendency for the value of s to increase with the energy of the incident particle; the interpretation of this empirical fact depends on the model adopted. The Cocconi (1958) form gets it from the greater Lorentz factor of the fireballs in the centre of mass system (cms) of the reaction with increase in available energy. As each of the fireballs is emitted with greater velocity with increasing energy, it is separated more widely from the centre of the distribution in the log tan theta plot, which is thus more spread out, leading to a higher value for the dispersion.

2. The slope parameter g

To investigate this phenomenon, the scatter diagrams of s against the log energy of the incident particle were drawn by computer methods for over five hundred events. The energy of the reaction was estimated by the Castagnoli (1953) method, which is based on the relativistic angle transformation formula and assumes that the emission is reasonably symmetric, with equal numbers of particles emitted in the forward and backward hemispheres in the reaction cms.

It is possible to divide these types of data for events in the range 100 to 10^6 GeV into four main classes: primary (nucleonic) and secondary (pionic) with each of these selected into charge = 1 and neutral. The nature of the neutral incident particles in secondary reactions is an interesting question, since they cannot be neutral pions because of the short lifetime. Identification is not often possible by measurements at these energies, of course.

In figure 1, the mean value of the dispersion s is shown for each log energy bin, for all data taken together. The slope g of the linear fit to the graph can be found:

$$\mathrm{d}(s)/\mathrm{d}(\lg E) = g = 0{\cdot}16 \qquad \text{for this set.}$$

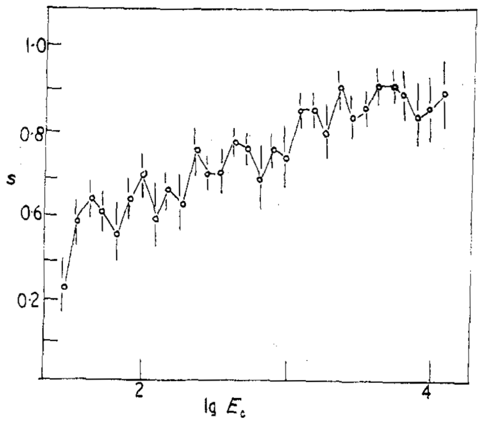

Figure 1. Variation of dispersion s with lg E for all events.

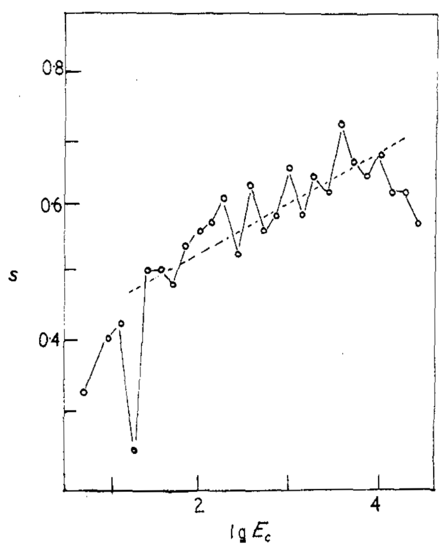

Figure 2. Variation of dispersion s with lg E for secondary reactions.

Figure 2 shows the same plot for all secondary events. The value of g is now 0·06, over the same range of energy, from 100 to 10^4 GeV. Figure 3 shows the variation of s with lg E for primary events; the value of g is here 0·28 from 100 to 10^4 GeV. The value of g for a mixture appears to be simply related to the value of g for the constituents A and B:

$$g_{\mathrm{mix}} = \frac{(g_A \times \text{number in } A) + (g_B \times \text{number in } B)}{\text{number in } A + \text{number in } B}.$$

It is interesting that the characteristic is linear for all mixtures that we are able to form, using the four basic sets already mentioned, and with further divisions into sets from different laboratories. This appears to indicate that there is a dispersion/log energy relation that is fairly linear for all reactions in this energy range (100 to 10^4 GeV) or that the constituents fit together in a mixture so as to allow this linearity.

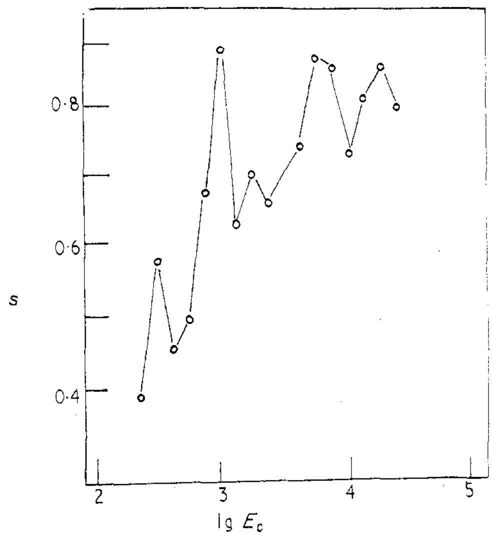

Figure 3. Variation of dispersion s with lg E for primary events.

The latter appears unlikely. For a specific class of interactions, the g value is about the same using data from different sources in separate groups. It must be noted that the dispersion of any reaction can vary over a wide range; we are considering the mean dispersion/log energy of incident particle here.

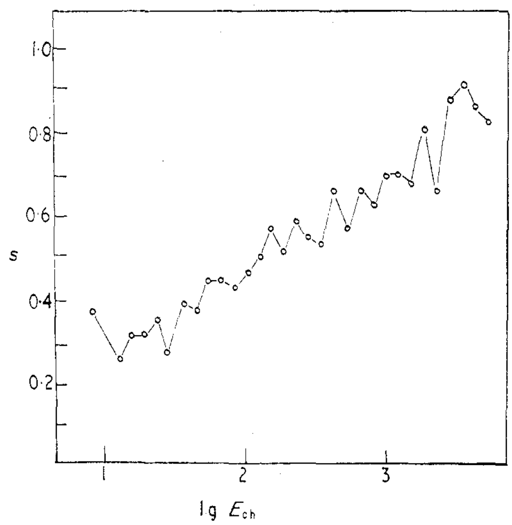

Figure 4. Variation of dispersion s with lg E_{ch}.

In figure 4 we show the variation of s with the charged particle energy E_{ch} of the reaction:

$$E_{ch} = \sum_{i=1,n} P_t \operatorname{cosec} \theta_i \times 1{\cdot}5$$

where we take P_t to be 0·4, the measured mean transverse momentum (GeV) for these reactions, and θ_i is the angle of emission of track i relative to the axis of the collision, defined by the momentum vector of the incident particle. The number of charged particle tracks in an event is n, and the factor 1·5 takes into account the 50% extra neutral particles that are present on average. This energy estimate does not suffer from some of the disadvantages of the Castagnoli estimate E_c used earlier. If E_{ch} is on average about one third of the total energy, as has been found then the likely energy is $3E_{ch}$, for the incident particle.

It is therefore interesting that s is also linear with lg E_{ch}, as shown in figure 4. There appears to be some variation about $s = 0{\cdot}4$ near the lower energy end of the plot, but the value of s goes up steadily from $E_{ch} \simeq 50$ GeV (Curran 1969).

It is known that the s value indicates the character of the emission in the cms of the reaction; isotropic emission from one centre at rest in the cms will give $s = 0{\cdot}39$, and higher values of s indicate that the emission is from two centres moving in opposite directions in the cms, or nonisotropic emission from one centre at rest, to take but two cases. We can see therefore that both using E_c and E_{ch} the s values show that there is nonisotropic emission at higher energies than about 50–100 GeV for the incident primary. Perhaps we have here a clear indication of the threshold energy for fireball production, and a clue that it is not a dominant mechanism at lower energies.

We could also take the scatter diagram for a class of events and fit a polynomial to the points in the usual fashion. This would give us curves which intersect near $s = 0{\cdot}4$ and $E = 100$ GeV. We have used a four-degree polynomial fitted by least squares. An alternative definition of a slope parameter would be the gradient of each of these fitted curves, at a fixed energy which could be 1000 GeV. It is clear again that this parameter would be different for the various classes. Here also there is an apparent threshold at about 100 GeV, where the different fitted curves seem to intersect. Reaction models should be possible that would allow the prediction of these slopes for each class at different energy levels.

3. Frequency distribution of the dispersion

If we plot the frequency distribution of all reactions we obtain the plot shown in figure 5. Here we can see that the peak is at about $s = 0{\cdot}6$ or so. This is far from

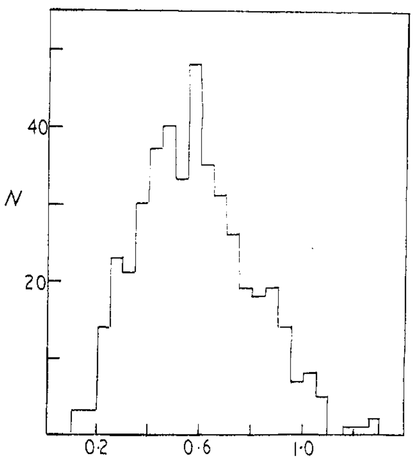

Figure 5. Frequency distribution of dispersion s for all reactions.

the value of 0·39 accepted for isotropic emission. Peaking is at about the same value of $s = 0\cdot6$ for both primary and secondary reactions taken separately. The shape of the distribution, as can be seen, is not quite gaussian.

It has been noted by Gierula (1969) that if we consider the Lorentz factor of the fireball emitting system in the cms $= \gamma_f$ and the Lorentz factor of the cms in the laboratory frame $= \gamma_c$ then we can use the relation

$$\gamma_f = \gamma_c{}^r$$

which will give a linear variation of the dispersion with log energy. There is a relation noted by Imaeda (1963) for the dispersion and the Lorentz factor of the fireball:

$$\gamma_f = \cosh k(\sigma^2 - 0\cdot39^2)^{1/2} \qquad k = \text{integer}, \ s = \sigma.$$

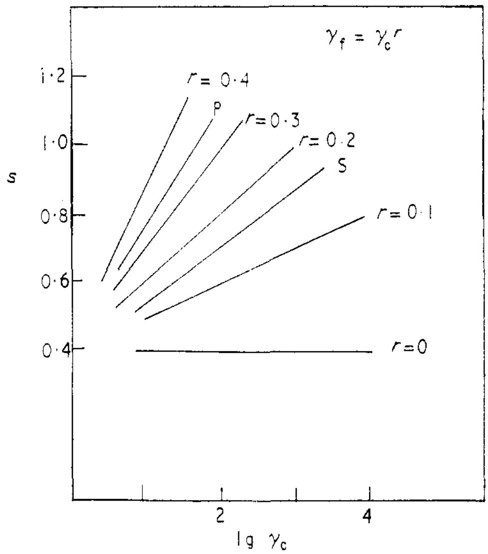

Figure 6. Variation of dispersion s with the Lorentz factor of the reaction cms for computer simulated reactions.

From this we see that there is a higher value of γ_f for higher values of the dispersion s. In fact, from our figures the mean value of s at 10^4 GeV shows that at this energy the mean Lorentz factor of the fireball in the cms is

$$\begin{aligned} &\text{primary reactions} &&= 4\cdot0 \\ &\text{secondary reactions} &&= 1\cdot8\,. \end{aligned}$$

The much lower value of γ_f for the secondary reactions has to follow from the lower dispersion at the same energy. We must remember here that this is in the context of the collinear two-fireball model of Cocconi. The s/log energy effect is independent of the model.

4. Nature of the incident particles

The direct identification of the incident particles by mass measurements is seldom possible at these energies. From the ionization, we can however estimate the charge; if $Z = 1$, and the particle did not visibly originate in another 'star' in the emulsion, it came from the primary cosmic radiation, since these detectors are flown at the top of the atmosphere. Hence it is almost certainly a proton. If a particle of $Z = 1$ can be seen to originate in a previous reaction 'star' in the emulsion block, and goes on to cause another interaction, it is classed as a secondary: some of these however may decay or pass out of the emulsion. These secondaries are nearly all charged pions, as neutral pions have too short a lifetime to be observed directly; there is a small fraction of kaons and hyperons.

These incident particles, primary or secondary, interact with an emulsion nucleus. When a small number of heavy prongs due to evaporation of the struck nucleus are present, the target cannot be either silver or bromine: less than five heavy prongs is usually taken to indicate a nucleon target, as noted in Perkins (1960). Hence

$$\begin{aligned} &\text{primary } (Z = 1) \text{ reactions} &&= \text{mostly proton–nucleon} \\ &\text{secondary } (Z = 1) \text{ reactions} &&= \text{mostly pion–nucleon.} \end{aligned}$$

The g values we give are thus for proton–nucleon and pion–nucleon reactions with a small contamination of kaon and hyperon events.

5. Error bounds on s and g

Statistical errors on the values of s are shown in figure 1. The errors in figures 2 and 3 are similar. Several hundred events have to be used in these diagrams to allow the linear trend in s to appear through the 'noise level'. For the statistical errors on g, we obtain

$$\begin{aligned} &\text{primary } (Z = 1) \text{ events (proton–nucleon)} && g = 0{\cdot}28 \pm 0{\cdot}06 \\ &\text{secondary } (Z = 1) \text{ events (pion–nucleon)} && g = 0{\cdot}06 \pm 0{\cdot}02 \\ &\text{all events } (Z = 1) && g = 0{\cdot}16 \pm 0{\cdot}04. \end{aligned}$$

6. Nature of the neutral secondaries

When we plot the mean dispersion against log energy for primary and secondary of $Z = 1$, as we have seen, there is a great difference between the two. But if we take the neutral primary and neutral secondary events, there seems to be little difference, according to our data. This is somewhat puzzling. If the value of g (secondaries, $Z = 1$) were equal to g (secondaries, neutral) or close to it, we might conclude that both were of a mesonic nature; that the neutral secondaries were kaons, and that the value of g was a function of the mass. But the most we can say here is that if the primary neutral particles are neutrons, then so are many of the neutral secondaries. This would argue a far greater cross section for nucleon–antinucleon pair production at these energies than would be expected.

7. Conclusions

By plotting the mean value of the dispersion s of the log tan theta plot at each energy for different incident particles, the slope g over the range from $E = 100$ GeV to 10 000 GeV is obtained using cosmic ray emulsion data. The value of g is found to be a characteristic of the incident particle. The slope for neutral primary and neutral secondary particles is similar; this would appear to indicate that both are mostly neutrons.

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