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INTERNATIONAL CONFERENCE ON COSMIC RAYS AND THE EARTH STORM Part III

III-4-33. Extensive Air Shower Work in Australia

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§1. Introduction

The work reported here has been carried out by a group of thirty or so physicists, working mostly in the School of Physics in the University of Sydney. Important contributions, however, have been made by two small groups working respectively in Dublin (Dublin Institute for Advanced Studies) and Jamaica (Physics Department, University College of the West Indies). In addition reference will be made to two important experiments carried out some time ago at the University of Melbourne.

Some work has been (and is being) carried out on the astrophysical aspects of EAS, that is on direction finding and on the nature of the primary particles, but most of the work which has been completed in the last two years refers rather to the behaviour of high energy particles in nuclear interactions. This has been studied not only by using extensive air shower arrays, but also by using large emulsion stacks flown to high altitudes. Results from both will be referred to but with the emphasis on the former. The work has been supported by the Nuclear Research Foundation within the University of Sydney and by the Air Research and Development Command of the USAF under Contract AF 49 (638)-842.

§2. Air Shower Arrays

Two air shower arrays have been used at Sydney. The first was based on nine liquid scintillators and has been described in detail elsewhere[1]. The second is a Geiger counter array. The basic unit is a group of three small (18.3 cm^2) G. M. counters set 20 cm apart. Ninety-two of these units are arranged on a rectangular grid of 3 metre spacing. In addition there is at each corner a group of 48 Geiger counters (133 cm^2 each). Included within the array are two Wilson cloud chambers and four penetrating shower sets. At the moment a further addition is being made to this array which is expected to greatly increase its usefulness. This consists of sixty-four 40 cm$\times$40 cm$\times$10 cm plastic scintillators forming a compact 4 m$\times$4 m area which can be covered with up to 300 tons of lead.

The Dublin and Jamaican arrays each consist of 12 of the basic units, 2 penetrating shower sets and 2 Wilson cloud chambers.

§3. Cerenkov Radiation from EAS

The first work I wish to report was carried out with the old Sydney Array by J. Malos, D. D. Millar and C. S. Wallace. Narrow angle detectors were used to examine Cerenkov light from air showers where size, core location and direction of incidence was found by scintillator array. It was found that the angular distribution of light is broad and is determined by the Coulomb scattering of the emitted electrons. The light pulse received is proportional to the integrated mean particle density over the acceptance cone along the axis of the detector and, for a detector close to the shower axis, the maximum contribution is most frequently generated within 1 km of the apparatus.

§4. The Density Spectrum of EAS at High Densities

The density spectrum of EAS in the region of densities less than 1000 particles per square metre has been investigated by a great many physicists since the early days of air shower studies. It has been found that over fairly wide regions the differential spectrum can be well represented by a power law[2] and that[3] from 1 to 500 particles per square metre the experiment changes but little, being -2.31 at the lower end and -2.53 at the higher end.

In the present experiment[4] the density determination was made with Wilson Cloud Chambers. This enables the actual number of particles crossing a given area to be counted and, using suitable cloud chambers, can give a reasonably accurate determination of density (estimated as $\pm 15\%$ at the high end) up to about 10,000 particles per square metre. To obtain the slope of the spectrum the experimental results have been compared (using a χ^2 test) with the expected numbers using a variety of exponents (varied in steps of 0.1 from -2.0 to -5.0). This has been done:

a) making no allowance for Poissonian fluctuations or triggering probabilities,

b) allowing for the triggering probability of the counter arrangement, and

c) allowing both for this probability and the Poissonian fluctuations of the number of particles in the chamber, that is, the expected numbers were computed from

$$R_n = K\int_0^\infty (1-e^{-s\Delta})^3 \frac{e^{-A\Delta}(A\Delta)^n}{n!} \frac{d\Delta}{\Delta^\gamma}$$

where R_n is the rate for n particles in the chamber; S is the area of the Geiger counters; A the area of the cloud chamber, and γ the exponent of the density spectrum.

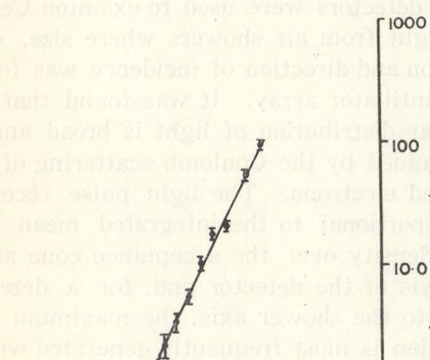

Fig. 1. The differential density spectrum of EAS obtained at Dublin. The points are uncorrected for the Poissonian fluctuations in the chamber on the triggering probabilities. The lines represent power laws of exponent–2.1 and–3.6 respectively. The effect of the corrections is to increase both exponents somewhat. It is not suggested that the change in slope happens abruptly.

The method has been used in two density regions and the experiment carried out at three stations (which all gave consistent results). For the region 50 to 500 particles per square metre the slope obtained was $-2.6\pm .2$ (correcting for triggering probabilities and Poissonian fluctuation) in good agreement with many previous experiments. However, the same method gave for the region from 1100 to 5000 particles per square metre a value of $-3.9\pm.5$*. This remarkable change in slope is also obtained if one uses no Poissonian corrections and is thus independent of assumptions regarding these. Fig. 1 shows the uncorrected spectrum from the Dublin station.

At this point reference must be made to the work of Norman[5] and Prescott[6] at the University of Melbourne. Both of these authors, one using proportional counters, the other using ionization chambers, obtained slopes a) in the region of lower densities in good agreement with previous G. M. counter and cloud chamber work, and b) at and above 1000 particles per square metre in good agreement with our own.

§ 5. Theory of Air Showers

This interesting result, together with results obtained by other groups[7),8),9),10),11)] on γ-ray, nucleon and μ-meson energy spectra, number spectra and other aspects of air shower work prompted us to try to make a theory of air showers which would embrace all the aspects. Two explanations of the γ-ray and density spectra leap to mind. The first is that the primary energy spectrum has a pronounced knee (as suggested by Norman)[5]. The other is that there is a marked change in some characteristics of nuclear interactions at some energy around 10^{14} ev. A comparison of the Bristol and Japanese γ-ray energy spectra given at the Moscow Conference with our density spectrum favours the latter of these hypotheses. Accordingly, we have used the cascade theory of Ueda, Ogita and Fukuda[12], together with the following basic hypotheses:

1) All interaction cross sections are geo-

* The errors give the 5% points.

metric.

2) The primary particles are protons with an $E^{-1.7}$ integral spectrum.

3) The number of secondaries produced by the collision of a particle of energy E_0 (Bev) with an air nucleus is given by[13]

$$n = 2E_0^{1/4}.$$

4) Of these particles a fraction $f_\pi n$ are pions and $f_X n$ are other particles

$$f_\pi + f_X = 1.$$

5) The X particles are divided into three classes $X^{(1)}$, $X^{(2)}$ and $X^{(3)}$. $X^{(1)}$ particles decay to pions or muons; $X^{(2)}$ particles contribute to the soft component by rapid decay times; $X^{(3)}$ particles are X particles other than the first two categories.* The respective fractions are f_{X1}, f_{X2}, and f_{X3}, and

$$f_{X1}+f_{X2}+f_{X3}=f_X.$$

6) A fraction η of the energy in the CMS is transferred to the secondary particles, $g_\pi\eta$ going to pions and $g_X\eta$ going to X particles. The variation of g_π and g_X with energy for two cases (A and B) investigated is given in Fig. 2.

7) The energy distribution of secondary pions and X particles in the CMS is given by power functions of the energy, *but in the*

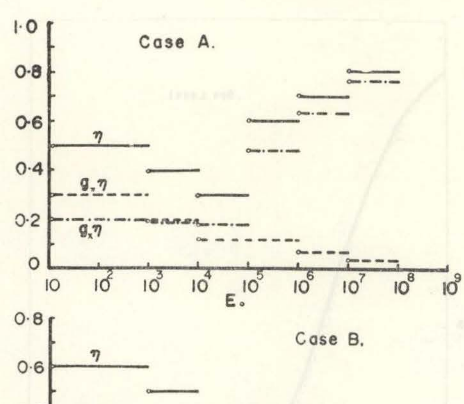

Fig. 2. The hypothesised variation in η, g_π and g_X for cases A and B with primary energy (expressed in Bev).

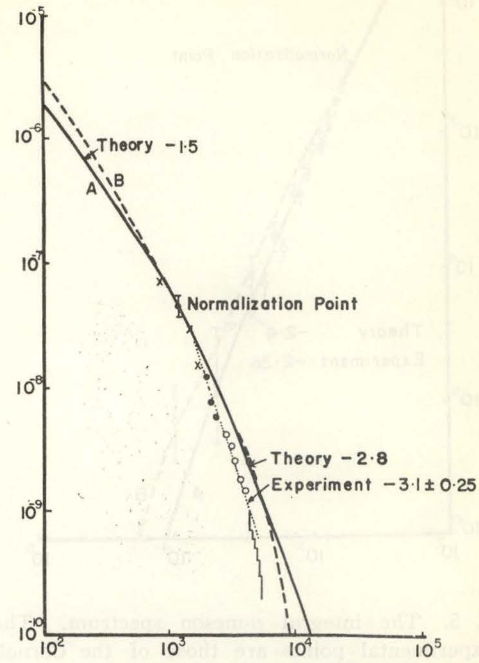

Fig. 3. The integral γ-ray energy spectrum at 220 g/cm². The experimental valus are those of the Bristol group (ref. 8).

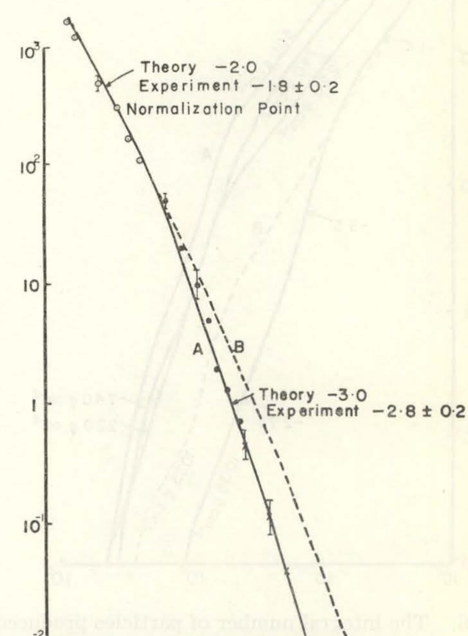

Fig. 4. The integral γ-ray spectrum at 740g/cm². The experimental points are those of the Japanese group (ref. 7).

* Thus allowance has been made in the theory both for the Σ^0 hyperon and other, long lived hyperons and K-mesons.

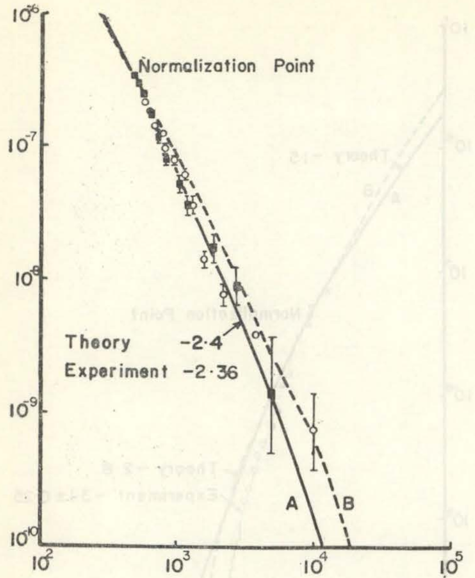

Fig. 5. The integral μ-meson spectrum. The experimental points are those of the Cornell group (ref. 10).

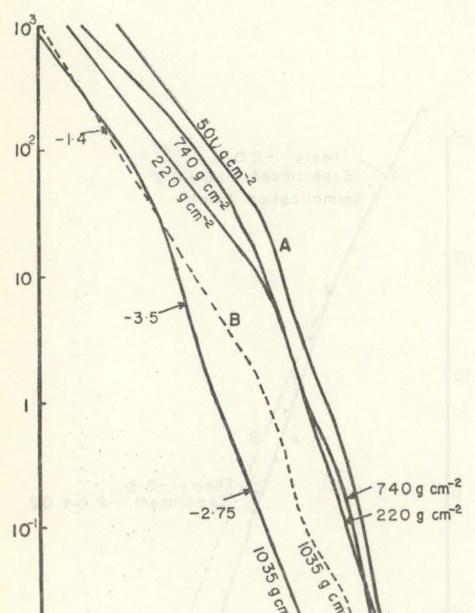

Fig. 6. The integral number of particles produced above a given observation level which initiate soft showers and give rise to more than n particles at sea level against n. The changes of slope are to be compared with the changes in slope of the density spectrum of EAS.

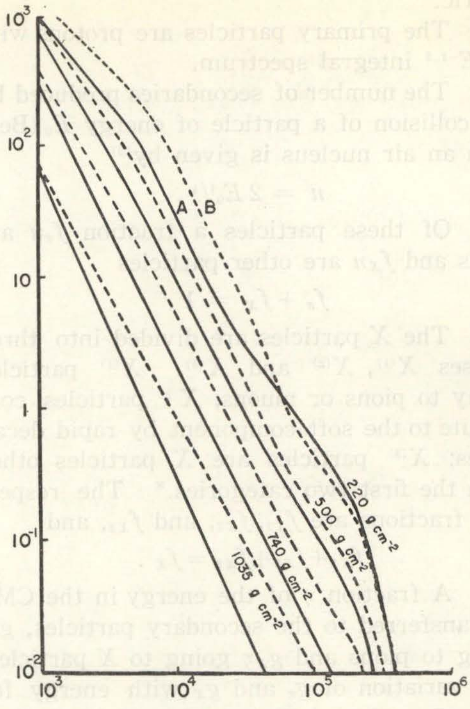

Fig. 7. The integral energy spectrum of the nucleonic component at different altitudes. The ordinate gives relative numbers and the abscissa the energy in units of the proton rest mass.

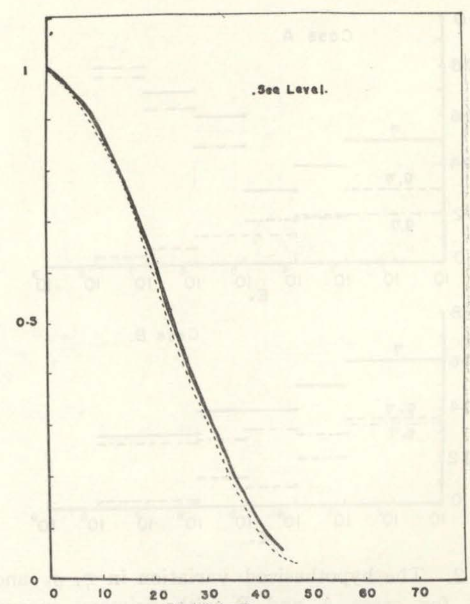

Fig. 8. The zenith angle dependence of EAS of size 10^5 at sea level. The dotted curve is Greisen's experimental result for EAS of greater than 50 particles per square metre.

case of the pions a maximum allowed momentum 25 Bev/c is imposed.

The solution of the resulting diffusion equations* was carried out on the digital computer SILLIAC. The results[14),15)] are shown in Figs. 3 to 11. Fig. 3 gives the γ-ray spectrum at 220 g/cm^2 from the top of the atmosphere and the theoretical curves are compared with the results of the Bristol group. Fig. 4 similarly compares the theoretical results with Japanese work at 740 g/cm^2. Fig. 5 gives the μ-meson spectrum at sea level, together with the experimental results of Greisen. Fig. 6 is to be compared with the density spectrum of EAS at different altitudes and Fig. 7 gives the energy spectrum of the nucleonic component. The zenith angle distributions for showers of 10^5 particles at sea level and mountain altitudes are compared with Greisen's results for showers of greater than 50 particles/m^2 in Figs. 8 and 9. The size dependence of nuclear active particles above various minimum energies are given in Figs. 10 and 11 for sea level and mountain altitudes. In addition, the number spectrum at sea level has been

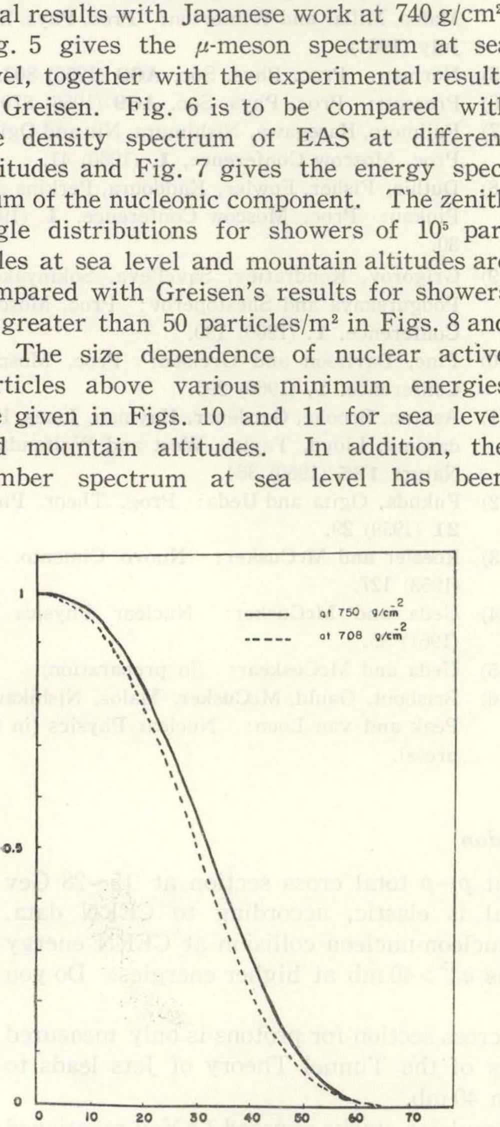

Fig. 9. The zenith angle dependence of EAS of 10^5 particles at 750 g/cm^2. The dotted curve is Greisen's experimental result at 708 g/cm^2.

* Allowing for the fluctuations in the depths of the first interaction.

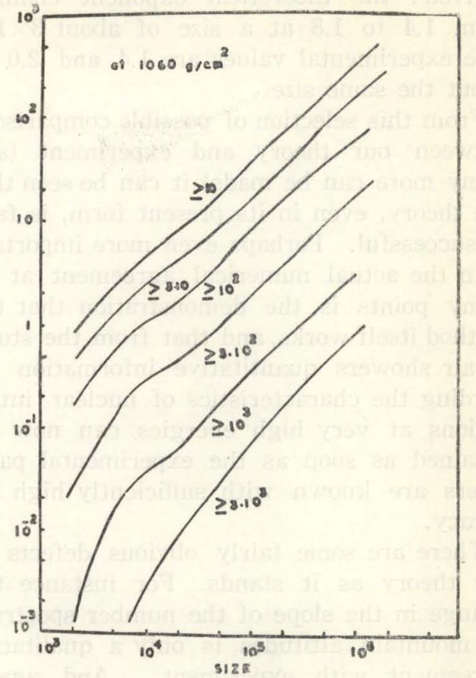

Fig. 10. The size dependence of nuclear active particles of various minimum energies at sea level.

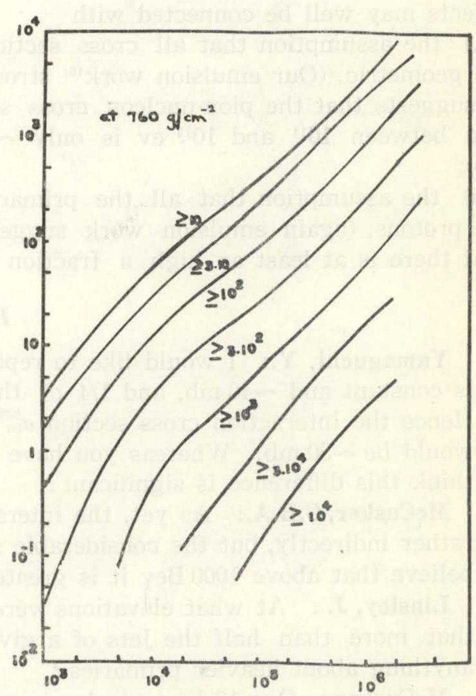

Fig. 11. The size dependence of nuclear active particles of various minimum energies at 760 g/cm^2.

derived: the theoretical exponent changes from 1.4 to 1.8 at a size of about 3×10^5. The experimental values are 1.4 and 2.0 at about the same size.

From this selection of possible comparisons between our theory and experiment (and many more can be made) it can be seen that the theory, even in its present form, is fairly successful. Perhaps even more important than the actual numerical agreement at so many points is the demonstration that the method itself works, and that from the study of air showers quantitative information regarding the characteristics of nuclear interactions at very high energies can now be obtained as soon as the experimental paramters are known with sufficiently high accuracy.

There are some fairly obvious defects in the theory as it stands. For instance the change in the slope of the number spectrum at mountain altitudes is only a qualitative agreement with experiment. And again, while the near independence of the attenuation length with shower size is predicted, the actual values are rather higher than those found experimentally. These and other defects may well be connected with

a) the assumption that all cross sections are geometric, (Our emulsion work[16] strongly suggests that the pion-nucleon cross section between 10^{11} and 10^{13} ev is only $\sim$20 mb);

b) the assumption that all the primaries are protons, (again emulsion work suggests that there is at least as high a fraction of α-particles and heavier nuclei as at lower energies).

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Discussion

Yamaguchi, Y.: I would like to report that $p-p$ total cross section at 15$\sim$28 Gev is constant and $\sim$40 mb, and 1/4 of the total is elastic, according to CERN data. Hence the interaction cross section $\sigma_{\text{in}}^{\text{NN}}$ for nucleon-nucleon collision at CERN energy would be $\sim$30 mb. Whereas you have told us $\sigma_{\text{in}}^{\text{NN}}>40$ mb at higher energies. Do you think this difference is significant?

McCusker, C.B.A.: As yet, the interaction cross section for protons is only measured rather indirectly, but the considerable success of the Tunnel Theory of Jets leads to believe that above 1000 Bev it is greater than 40 mb.

Linsley, J.: At what elevations were the emulsion stacks exposed? You mentioned that more than half the Jets of a given size had α-particle primaries. Can you say anything about heavier primaries?

McCusker: Our 10 litre stack was exposed at 126,000 feet; the Chicago stack somewhat higher than this and the Bristol stack at about 100,100 feet. We saw several heavy primary produced Jets; probably between 5 and 10% of all events.

Yamaguchi: Do you have information on secondary interactions due to neutrals?

What is the difference between neutral-nucleon, and proton-nucleon interaction cross sections?

McCusker: We cannot measure the interaction mean free path of neutral secondaries directly. From the distributions in n_s I would infer that the K and π interaction cross sections are not very different. The number of events, however, is not very big as yet. The ICEF results should greatly improve the position.

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III-4-34. The Conclusion Speech

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All speakers of this plenary session have made such good jobs and prepared such complete and fruitful reports that it is quite unnecessary for me to make my conclusion long. Besides, during ordinary sessions, such a wide range of problems concerning extensive air showers was discussed that it is impossible even to enumerate them in a short speech. Really at our sessions much was said both about details of interactions of most and even on the methods of future experiments on observations of non-atmospheric showers on the moon.

The only thing I want to do is to emphasize the progress achieved in the study of extensive air showers after the Moscow Conference.

One has to admit that in this field no extraordinary discoveries have been made, which could astound a layman.

But from a specialistic point of view very much has been done. A lot of data were obtained on the anisotropy of primaries at superhigh energies, on the energy spectrum in this region and on its upper limit; the systematic work was started on primary γ-rays of very great energies and on local sources; very great attention was paid to μ-meson component and to μ-meson beams in extensive air showers.

Very many data were accumulated on spatial and energy distribution of different components of showers, on their altitude dependence, on the core structure and so on.

In other words a great and fruitful work is being done in accumulating experimental materials and on its interpretation and, what is especially important, on obtaining fully reliable and indisputable data.

I think that we can strongly believe that this work will give its fruits, that the obtained data will lead us to a new stage in our knowledge of processes at the greatest energies occurring in nature (that is some joules per one individual particle) and will help us understand the phenomena in our and other galaxies, in bursts of supernova in interstellar space.