Production of Strange Particles and Antiparticles in Nuclear Interactions of Very High Energy ($E \sim 10^{13}$ ev)*

E. LOHRMANN AND M. W. TEUCHER
Department of Physics, University of Chicago, Chicago, Illinois
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The production of strange particles, nucleons, and antibaryons (antinucleons and antihyperons) in nuclear collisions of an energy between 10^{12} and 10^{14} ev was studied by looking for high-energy interactions produced by the secondary particles. The ratio of secondary interactions initiated by neutral particles to those initiated by charged particles was found to be $Q=0.16\pm0.06$. Under reasonable assumptions, these data indicate that $9_{-6}^{+8}\%$ of the high-energy charged secondary particles are charged K-mesons or baryons and antibaryons. The average energy of the primary collisions used in our analysis is estimated to be of the order of 10^{13} ev.

TWO stacks of nuclear emulsions (Table I) were scanned for nuclear interactions produced by protons and alpha particles of energies $E>1$ Tev[1] per nucleon by tracing electron-photon cascades backwards. In such interactions we observe very well collimated bundles of minimum tracks ("jets" or "showers"). The study of secondary interactions of particles emitted from such events offers a possibility of estimating the percentage of particles which are not π mesons and which are created in the primary jet. If one explains such events in terms of nucleon-nucleon collisons, it is always possible to define in the center-of-mass system (c.m. system) a "forward" and a "backward" cone. The forward cone is then responsible for the highly collimated beam of tracks which we observe in the laboratory system. At primary energies above 1 Tev, the average energies of the particles in the forward cone are of the order of 0.1 Tev or more in the laboratory system. Hence, the interactions of those secondaries also give rise to high-energy events in which several fairly well collimated minimum tracks may be emitted. If strongly interacting neutral secondary particles of sufficiently long lifetimes are present in the beam, their interactions will be of high energy, too, and look like jets. Therefore, they can easily be recognized and differentiated from the background stars. From the number N_{ch} of interactions produced by charged secondary particles and the number N_{n} of interactions produced by neutral secondary particles, one gets the ratio $Q=N_{\mathrm{n}}/N_{\mathrm{ch}}$. The percentage of the particles which are not π mesons can then be calculated from Q if we make the following assumptions:

(1) The particles other than π mesons which are contained in the beam are nucleons, K mesons, hyperons, nucleon-antinucleon pairs and hyperon-antihyperon pairs.

(2) The isotopic spin assignment $I=\frac{1}{2}$ for K mesons, nucleons and antinucleons, leads to equal numbers of charged and neutral nucleons, antinucleons or K mesons, at energies of the order of 10 Tev. This would also be expected to be approximately true for hyperons and antihyperons.

(3) The mean free path for production of secondary interactions by these particles is the same as for π mesons.

Let us introduce the following notations:

n_s: total number of charged secondary particles (shower particles) in the primary jet which can be found in the scanned volume.

$n_{x^\pm}$: number of charged particles among n_s which are not π-mesons.

n_{x^0}: number of strongly interacting neutral particles in the angular region determined by n_s.

The lifetime of π^0 mesons is 10^{-15} second or less. Their contribution to the production of secondary interactions may, therefore, be neglected in the energy region we are dealing with in this paper. Then we have $n_{x^0}\approx n_{x^\pm}$ from assumptions (1) and (2) and $Q=N_{\mathrm{n}}/N_{\mathrm{ch}}=n_{x^0}/n_s$ from assumptions (1) and (3). Thus we can obtain $Q=n_{x^\pm}/n_s$, i.e., the percentage of particles among the shower particles which are not π mesons. To measure Q, the following procedure was used: The dense core of our jets was scanned carefully for secondary interactions. The half opening angle of this dense core is always smaller than the median angle $\theta_{\frac{1}{2}}$ given by $\theta_{\frac{1}{2}}=[2Mc^2/E_{\mathrm{pr}}]^{\frac{1}{2}}$, where E_{pr}/Mc^2 is the total energy of the primary particle in units of its rest mass. This is due to the fact that in the energy region under consideration, the particles created in nucleon-nucleon collisions are not emitted isotropically in the c.m. system, but rather collimated in the forward and backward direction. A secondary interaction found in the scanned region was accepted if it had five or more fairly collimated shower particles ejected in the direction of the beam, approximately. If a charged particle was seen to come in, but the density of the other

TABLE I. Emulsion data.

Size of emulsions	Number of emulsions	Flown at	Duration of flight	Altitude
40 cm×20 cm×600μ	100	Guam	7 hours	102 000 feet
30 cm×15 cm×600μ	100	Texas	8 hours	104 000 feet

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[1] 1 Tev$=10^{12}$ ev.

TABLE II. Results.

Primary jet		Number of secondary jets			
Type	Energy[a] (Tev/nucleon)[b]	Charged primary	Neutral primary	Left off	Stack
$30+110\alpha$	5	3	0	1	Guam
$16+63p$	15	4	0	0	Guam
$2+43\alpha$	1.5	1	1	0	Guam
$0+37\alpha$	2.5	8	2	0	Guam
$0+20p$	5	3	1	0	Texas
$0+20n$	1	3	1	0	Texas
$0+22p$	7	1	0	0	Texas
$3+52p$	30	14	2	0	Guam
$8+64\alpha$	100	8	1	3	Guam
$0+32p$	5	5	0	0	Guam
$25+96\alpha$	2	1	0	0	Guam
Total		51	8	4	

[a] Estimated from the angular distribution and the kinematics of the secondary interactions.
[b] 1 Tev $=10^{12}$ ev.

parallel tracks in the neighborhood indicated a possible chance coincidence, the event was left off completely. From the track densities in the neighborhood of secondary interactions which were accepted by us, we estimated the probability of a chance coincidence to be less than 2%. The contribution of neutral events lying accidentally in the scanned volume, but not connected with the primary event, is entirely negligible. The types of primary events investigated and the results can be seen in Table II. A total of 59 secondary interactions was used in our analysis. We obtain $Q=8/51=0.16\pm0.06$. This would mean that about 16% of the shower particles are not π mesons. This gives an upper limit to the number of strange particles and nucleon-antinucleon pairs produced, since we must allow for the presence of nucleons in the beam which were knocked out from the target nucleus, or could be the primary nucleon which may continue on after the collision as a proton or as a neutron. In the case of jets initiated by alpha particles, there exists also the possibility that some of the nucleons of the original alpha particle continue on without having interacted. At the high primary energies considered ($\sim$10 Tev), the primary nucleon is able to produce a secondary jet, even if, in the c.m. system, it has transferred all of its energy into production of π mesons, K mesons, etc. Our observations on the primary jets indicate, however, that at energies of the order of 10 Tev, collisions of this kind do not occur. Therefore, the primary nucleon goes on with still much higher energy and may be found among the particles which are able to produce jets. Thus, as a conservative estimate, we took the number of nucleons in the forward cone to be equal to the number of incident nucleons in the primary jet (i.e., 1 for a proton-initiated jet and 4 for an alpha-initiated jet). From the number of shower particles n_s which belong to the forward cone, we get, upon averaging over all events, the following ratio of nucleons to shower particles:

$$q=(n_p+n_n)/n_s=0.15,$$

where n_p and n_n refer to the number of protons and neutrons in the forward cone capable to produce secondary jets ($E>25$ Bev). Assuming $n_p=n_n$, we find that 7.5% of the n_s shower particles are protons. Hence, another 7.5% of n_s must be neutrons. The original value of Q can then be corrected for the presence of such nucleons among the shower particles.

Let $n_{K^\pm}$ be the total number of charged strange particles plus nucleons and antinucleons produced in the primary collision and n_{K^0} the corresponding number of neutral particles. By assumption (2) we have $n_{K^\pm}\approx n_{K^0}$. Therefore, using assumption (3), we obtain

$$n_{K^\pm}/n_s=Q-\tfrac{1}{2}q=9_{-6}^{+8}\%.$$

It is of interest to compare the total number of strange particles and nucleon-antinucleon pairs produced in high-energy collisions with the total number of all the particles produced. Assuming that the number of π^0-mesons is equal to one half of the number of the charged π mesons and denoting the number of all particles produced by n_{total}, we obtain

$$\frac{n_{K^\pm}+n_{K^0}}{n_{\text{total}}}=\frac{4(2Q-q)}{2Q-q+6}=11_{-7}^{+9}\%.$$

Dividing our primary collisions into two groups of equal statistical weight, according to their energy, we obtain the same results for both groups within the statistical error. There is, at present, no indication that the result might depend on the number of heavy prongs in the primary jet.

Our results may be compared with similar results obtained by the Bristol[2] and the Berne[3] groups. The Bristol group found, from a sample of 60 secondary interactions:

$$Q=0.25\pm0.08.$$

This agrees with our findings within the statistical limits of error. The Bristol group, however, included secondary events of lower multiplicity and made no estimate for the contribution of nucleons among the shower particles. The average energy of their primary jets was somewhat lower. Therefore, it is not, perhaps, too meaningful to combine both results. The Berne results may be added to our statistics. In conclusion, our results would indicate that not more than 20% of the shower particles could be strange particles and nucleon-antinucleon pairs, although the primary energy of the nuclear collisions which were investigated in this paper is of the order of 10 Tev. The present statistics are even in agreement

[2] Edwards, Lofty, Perkins, Pinkau, and Reynolds, Phil. Mag. 3, 327 (1958).
[3] Hänni, Lang, Teucher, Winzeler, and Lohrmann, Nuovo cimento 4, 1473 (1956).

with a proportion of these particles as low as a few percent. This result may be compared with several theoretical approaches to multiple particle production. It seems difficult to obtain agreement with some models using simple phase-space considerations at such high energies.

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Interplanetary Magnetic Field and Its Control of Cosmic-Ray Variations

J. H. PIDDINGTON
Radiophysics Laboratory, Commonwealth Scientific and Industrial Research Organization, Sydney, Australia
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A model interplanetary magnetic field is described which may explain some features of solar cosmic-ray increases and also fluctuations in the primary radiation. The main features are as follows:

(1) A chromospheric "explosion" occurs at the time of a flare in gas permeated by the sunspot field. The gas, linked with magnetic flux $\lesssim 10^{21}$ gauss cm^2, is ejected from the vicinity of the sun.

(2) The gas and field remain linked and the latter is so distorted that solar cosmic-rays are released $\sim\frac{1}{4}-1$ hour after the flare.

(3) The trailing radial field is drawn out past the earth's orbit to form a magnetic cone with closed ends. The life of the interplanetary field is at least a few months and a number of segments may be built up from different spot fields. The general field may contribute, being extended to largely radial form by a general outward movement of gas.

(4) Cosmic rays released after one flare may be influenced by the radial field resulting from a previous flare associated with the same, or perhaps a different, spot group.

(5) On February 23, 1956, the magnetic cone enclosing the earth contained irregularities separated by $\sim$0.5 astronomical unit, capable of deflecting 15-Bev protons up to $\sim 20°$ and completely scattering 1.5-Bev protons. Cosmic-ray diffusion was anisotropic, the rate being $\sim$65 times greater along the field than across the field. The main features of the solar increase may be explained by such a field.

(6) Some observed variations of primary cosmic radiation (Forbush-type decreases, 27-day and diurnal variations) may be qualitatively explained by the model.

(7) The model may explain auroras in terms of ions of intermediate energy ($\sim 10^5$ev) transported from the sun in the magnetic cone which reaches the earth in a day or two and may inclose it for many days or weeks.

1. INTRODUCTION

LARGE solar flares are occasionally followed by increases in cosmic radiation which originate near the sun and have a complex time-intensity distribution over the earth.[1,2] In addition, the primary radiation itself suffers intensity changes which are thought to be solarcontrolled.[3] Of particular interest were the variations of February, 1956, when a flare-associated increase of great intensity[4] occurred during a Forbush-type decrease.[1]

A number of attempts have been made to explain these data in terms of model interplanetary electromagnetic fields. There appear to be possible objections to each of these models, discussed briefly in Sec. 9 below.

In the present paper a new model is described. It is presented as a hypothetical interplanetary field which seems capable of explaining the cosmic-ray data and as such is described very briefly in the following section. An attempt is then made to show how this interplanetary field may be created from localized solar fields. The treatment is necessarily inadequate because our knowledge of the flare and associated phenomena is far from complete and also because of limitations of hydromagnetic theory. It does seem worth while, however, to attempt to show that the interplanetary magnetic field should be largely radial in form and that it would be formed mainly from *freshly created* magnetic field, the energy source being the kinetic energy of ejected gas clouds and the pressure of very hot gas behind these clouds.

In later sections the various cosmic-ray data are explained in terms of the model magnetic field.

2. COSMIC-RAY DATA AND NECESSARY MODEL FEATURES

The requirements which must be satisfied by an interplanetary magnetic field relate to the observed variations in solar and primary cosmic radiations. Many of the data relate to the events of February 23, 1956, and have been listed by Simpson and others[1,2,4] and by Gold.[5]

[1] Meyer, Parker, and Simpson, Phys. Rev. **104**, 768 (1956).
[2] R. Lüst and J. A. Simpson, Phys. Rev. **108**, 1563 (1957).
[3] J. A. Simpson, Proc. Natl. Acad. Sci. U. S. **43**, 42 (1957).
[4] H. Elliott and T. Gold, collection of data relating to the solar cosmic-ray outburst of 1956, February 23 (Royal Greenwich Observatory, 1956).
[5] T. Gold, Observatory **76**, 47 (1956).