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Extremely High Energy Nuclear Interactions^{*}

by

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By utilizing the technique of an "emulsion cloud chamber" to select high energy events¹ we have studied the angular distribution, multiplicity of penetrating particles and ratio of neutral mesons to charged particles produced by collisions of cosmic ray nucleons and α -particles with nuclei of copper. The techniques involved are described in ref. 1. The energy per nucleon of the primary causing the event is usually estimated by the kinematical considerations of ref. 1. Despite the energy being estimated on the single nucleon-nucleon assumptions, in those cases where an accurate check is available by the energy balance method of ref. 1, the two methods give agreement within statistical limits.

Table I summarizes the relevant data on the events completely or partially analyzed thus far. Column 1 designates the shower and the incident particle causing the shower (it is not possible in every instance to uniquely determine the primary but we can be certain that it has either a charge of 0 or 1, or its charge is definitely > 1). Column 2 gives the observed charged particle multiplicity per incident nucleon in the initial interaction and column 3 the ratio of neutral π mesons to charged particles². Column 4 gives the energy per nucleon in the laboratory system (γ) of the primary in units of the nucleon rest mass. Column 5 gives the observed value of the quantity $X = \frac{\bar{x}}{\bar{x}_I}$, where $x = \frac{O_{3/4}}{O_{1/4}}$ is the ratio of the laboratory angles containing a fraction 3/4 and 1/4 of the charged particles; $\bar{x}_I$ is the same ratio for a theoretical multiple process with an isotropic distribution in the center of mass system (c.m.)

of 2 nucleons. Column 6 gives the impact parameter $\frac{r}{R}$ for the shower corresponding to the Fermi theory³ and column 7 gives the charged meson multiplicity as determined from Fermi's theory⁴ for a single nucleon-nucleon collision corresponding to an energy of the incident nucleon $E = \gamma mc^2$ and the impact parameter given in column 7.

TABLE I

An examination of column 5 reveals a distribution in values for the quantity X . In a nucleon-nucleon collision isotropic in the c.m. system one should find $X = 1$, whereas for non-isotropic distributions in the c.m. system (e.g. such as predicted by the Fermi theory) X should show large deviations from the value 1. As the interactions occur in brass the showers we observe must in most cases result from successive collisions inside the nuclei.

Such showers resulting from several collisions, each with different impact parameters, would be expected to show on the average similar angular distributions characterized by some average impact parameter. This behavior is not observed for single nucleon produced showers but is observed for α -particle showers which from their multiplicities appear to involve the interaction of four separate nucleons. The three α -particle showers observed all have similar angular distributions characteristic of some average impact parameter.

We believe this is an indication that at high energies a nucleon-nucleus collision exhibits similar properties to a nucleon-nucleon collision. Multiple production of particles results from the first nucleon-nucleon interaction. These particles then all interact together in any successive collisions inside the nucleus⁵. This is consistent with the Fermi picture and results from the view that at extremely high energies a nucleon interacts in a similar manner whether it is accompanied by a real or virtual group of particles. If this is

TABLE I

(1) Shower and Primary	(2) Number of Charged Particles (N_{ch})	(3) N_{π^0}/N_{ch} [†]	(4) $\gamma \times 10^{-3}$	(5) X	(6) $\frac{F}{R}$	(7) $N_{ch}(\text{Fermi})^4$
A (a)	21(84)	$.6 \pm .2$	3	1.17	.18	15
178 (a)	23(92)	$.72 \pm .15$	6	2	.46	14
R ⁶ (a)	14(56)	$.75 \pm .25$	.48	2.33	.57	6.6
77 (P)	24		4	1.17	.18	16.5
104 (P)	20	$.5 \pm .3$	1.3	1.33	.23	11.7
67 (P,N)	9	$1.2 \pm .5$	4.5	1.33	.23	16
60 (P,N)	26		19.5	1.33	.23	23
91 (P,N)	16	$.6 \pm .35$	1.3	1.7	.34	10.8
17 (P)	24	$1.1 \pm .3$	5.1	3.7	.76	7.9
59 (P)	24	$.5 \pm .3$	8.9	4	.78	8.8
66 (P,N)	11	$.75 \pm .4$	.64	6.67	.87	2.7
1 (P)	36	$.6 \pm .2$	19.4	6.67	.87	6.3
2 (P,N)	15	$.5 \pm .25$	50	24	~ 1	≤ 3.4
8 ⁶ (P)	15		32		~ 1	≤ 6
G-L ⁷ (P)	18		23	≥ 9	~ 1	≤ 6

Av. $.71 \pm .3$

[†] This ratio is not corrected for secondary nuclear interactions. An approximate estimate for this indicates that the observed ratio can be lowered by as much as 30%. The correction will vary for each individual shower.

correct a characteristic impact parameter for a nucleon-nucleus collision is defined by the last target nucleon struck in the nucleus; the multiplicity should be near to that of a pure nucleon-nucleon collision.

On the basis of the above assumptions the observed charged particle multiplicity is compared with that calculated from the Fermi theory (column 7). We note that the agreement is best for low impact parameters but worsens at high impact parameters. It would appear that the idea of impact parameter has meaning in describing the angular distributions in these interactions but that the multiplicity is not a strong function of impact parameter. Independent evidence for the view that a single nucleon-nucleon collision and a nucleon-nucleus collision give the same results at high energy is provided by the similarity of the S-star⁶ (which resulted from a nucleon-nucleon collision), the Gerosa and Levi-Setti star⁷ (formed in AgBr) and our stars of high impact parameters.

The observed large ratio of neutral π mesons to charged particles implies within the context of the Fermi theory a relatively small contribution of nucleon-antinucleon pair production as compared to π meson production in this energy band.

We have also made approximate kinematical estimates of the energy of the showers given by Pickup and Voyvodic¹⁰ (energies of the order of 10^{11} ev) and by comparing their median energy and multiplicity with that derived from our data find that the multiplicity of meson production varies as $\gamma^{1/4}$, which is in agreement with the predictions of the Fermi theory.

Footnotes

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- 1 Kaplan et al, "Emulsion Cloud Chamber Study of a High Energy Interaction",
Phys. Rev., in press.
- 2 We assume that the soft component of mixed showers in its early stages arise
exclusively from the 2 photon decay of the neutral π meson. See Marshak,
Phys. Rev. 74, 1735 (1949).
- 3 E. Fermi, Phys. Rev. 81, 683 (1951).
- 4 The charged particle multiplicity is calculated on the basis of Fermi's theory
assuming only π mesons are produced. If one also allows for the production of
nucleon-antinucleon pairs, the calculated charge multiplicity is changed by
the same factor (.985) for each shower independent of the impact parameter.
- 5 Kaplan et al, Phys. Rev. 76, 1735 (1949).
- 6 Lord et al, Phys. Rev. 80, 970 (1950).
- 7 Gerosa and Levi-Setti, Nuovo Cim. 8, 601 (1951).
- 8 One can easily show that the c.m. system defined by an assemblage of particles
produced by a nucleon of energy $E = \gamma mc^2$ with a nucleon at rest is identical
to that formed by the incident nucleon ($E = \gamma mc^2$) and a nucleon at rest.
- 9 A further test of this hypothesis is possible with observations on energetic
showers made in a very heavy nucleus such as Pb. Such an experiment is now
being planned.
- 10 Pickup and Voyvodic, Phys. Rev. 82, 265 (1951).