OBSERVATIONS ON THE NUCLEAR INTERACTIONS OF COSMIC RAY PIONS AND NUCLEONS AT ENERGIES ≳ 20 GEV

Part II. The Extremely Collimated Nuclear Interactions

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Received September 9, 1970

ABSTRACT

Detailed features of extremely collimated nuclear interactions induced by cosmic ray particles in carbon and brass (belonging to group I as classified in Part I of this series of papers) are presented. These extremely collimated nuclear interactions seem to be preferentially induced by pions rather than by nucleons; also the relative frequency of these seems to be less when brass is used as target compared to the case with carbon as target. The distribution of multiplicities of secondary particles emitted in the forward direction show certain regularities in the case of interactions induced by charged primaries. Observations on the γ-rays associated with these events give support to the interpretation that in these inelastic collisions pions are produced in pairs in the forward direction with low transverse momentum. It is suggested that such a low energy di-pion system could be the same as found in the so-called ABC effect.

I. INTRODUCTION

IN Part I[1] of this series of papers (which shall be referred to as I hereafter), nuclear interactions observed in a multiplate cloud chamber operated in conjunction with an air Cerenkov counter and a total absorption spectrometer have been classified into different groups depending on the degree of angular collimation of the secondaries for a given energy of the primary. It was shown there that a group of nuclear interactions characterised by a high degree of angular collimation exists which cannot be explained as arising from simple fluctuations from isotropic emission of secondaries in the c.m. system.

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In this paper we report on the detailed features of this group of events in an attempt to understand the process involved in the production of these events. We shall henceforth refer to these events as "collimated". These events are defined to be those which lead to an estimate of primary energy from the angular distribution of the secondaries (at least 3 in all including neutral pions) by the method discussed in I in excess of 8 times the energy estimated from the response of the total absorption spectrometer.

II. (*a*) Effect of the Nature of the Primary and the Target Material on the Frequency of Occurrence of the Collimated Events

In Table I the relative frequencies of occurrence of collimated events is given for different primary particles in targets of carbon and brass. Pions were distinguished from protons upto an energy of 50 GeV† by using the air Cerenkov counter. Kaons are expected to be negligible compared to pions in the cosmic radiation. Uncharged primaries have been assumed to be neutrons. The median energy of the primaries was about 28 GeV with a cut-off at 15 GeV.

TABLE I

Frequency of collimated events

Target / Primaries	Carbon	Brass
Protons	0/43	0/57
Pions	5/21	0/21
Neutrons	5/123	5/200
All charged particles	25/700	5/350

Table I indicates that roughly 25%‡ of the pion induced interactions in carbon are collimated. However, if one considers the results given in the fourth row in Table I and makes use of the fact that the ratio of pions to protons among charged primaries is $0 \cdot 50 \pm 0 \cdot 07$,[2] one obtains a lower figure of 10% for the frequency of this kind of collisions among pion inter-

† Although the threshold energy for protons in the counter was 45 GeV, the effective threshold energy could be raised to 50 GeV due to poor efficiency of detection near the threshold.

‡ "However there seems to be a dependence of frequency of these events of the primary energy as indicated in Section III. Part of the higher frequency among the identified pion events may be due to the higher energy in the selection of events in the initial period of data collection. See Part I [(1)]",

actions. The latter figure is statistically more accurate and we take this as a better representative of the true frequency rather than the first estimate of 25%. In arriving at this estimate, it has been assumed that collisions produced by protons do not give rise to the collimated events which is consistent with the data in Table I.

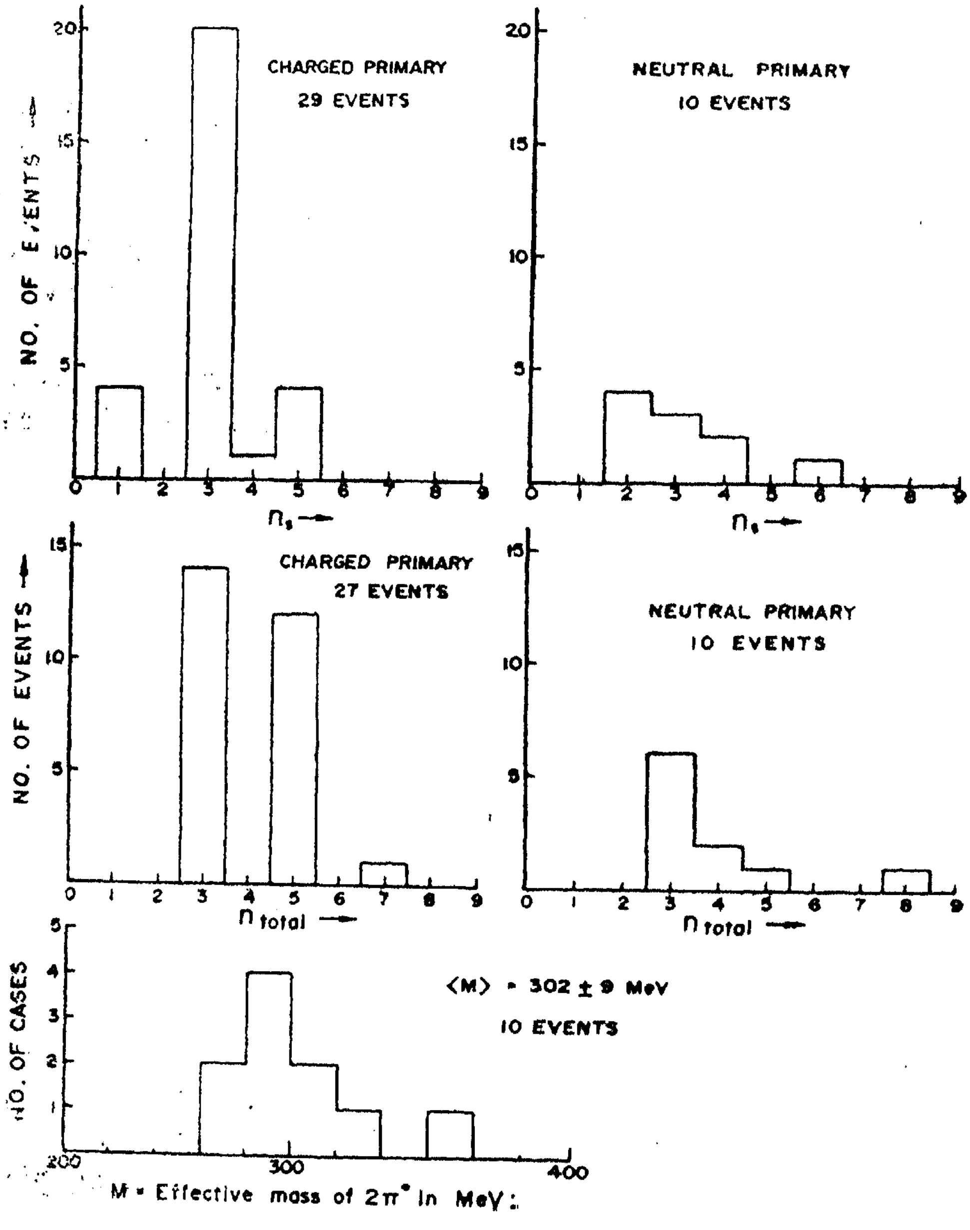

FIG. 1. The distribution of various quantities observed in the collimated events.

While protons seem not to produce these events, neutral primaries (neutrons) have been seen to be associated with some collimated events. However, this difference is not very significant statistically. If there is indeed such a difference between proton and neutron primaries, it would point to charge asymmetry, if any, of nuclear interactions. As discussed in Section III, the collimated nuclear interactions produced by neutral primaries do not exhibit certain features seen among the collimated events induced by charged primaries.

Finally, it is interesting to note that the relative frequency of these events is somewhat lower in brass than in carbon. The ratio of the frequencies in brass and carbon is $0{\cdot}4 \pm 0{\cdot}2$. It should be mentioned that the thickness of target plates in the two cases were $\lesssim 1/10$ of nuclear collision mean free path,[1] so that the above reduction is not attributable to secondary collisions taking place within the same target layer and masking the occurrence of collimated events.

(*b*) Special Features of the Collimated Events

Two important features of the collimated events are: (*a*) charged and total (including π^0) multiplicity distributions in the forward direction in the c.m. system of the incoming particle and a nucleon in the target material and (*b*) the transverse momentum distribution of γ-rays associated with the events. The former is shown in Fig. 1 and the latter in Fig. 2. The method used to estimate the number of π^0's in an event is to match the γ-rays into pairs from π^0's and count each of the unmatched ones as due to one neutral pion. It has been shown[3] that the detection efficiency for π^0 -mesons produced in the forward direction in the case of collimated events is close to unity.

The occurrence of odd multiplicities in both the charged and total multiplicity distributions is striking in the case of interactions induced by charged primaries. Another feature is the low mean energy of the neutral pions in comparison to the energy of the incident particle. The mean energy of π^0's in these events is $1{\cdot}7$ GeV whereas the mean energy of the primaries which gave rise to these π^0's is 50 GeV. The mean fraction of primary energy transferred to neutral pions, $\langle K_{\pi^0} \rangle = 0{\cdot}06$. This latter figure suggests that the incident particle which survives the collision retains most of the incident energy ($\sim 80\%$) since we can assume $\langle K_{\pi^\pm} \rangle = 3\,\langle K_{\pi^0} \rangle$. Based on these features it was suggested earlier[5] that a reaction of the following type would be applicable to the pion interactions:

$$\pi^{\pm} + N \rightarrow \pi^{\pm} + S_n + N \text{ or } N^*$$

where N stands for a nucleon in the target nucleus, N* an excited state of the target nucleon and S_n a system of n pions where n is even. The incident pion is assumed to retain its identity after the collision by losing only a small fraction of its energy. In some cases of collimated events, backward going relativistic secondaries were observed in the laboratory system which suggest the excitation of the target nucleon to an isobaric state.

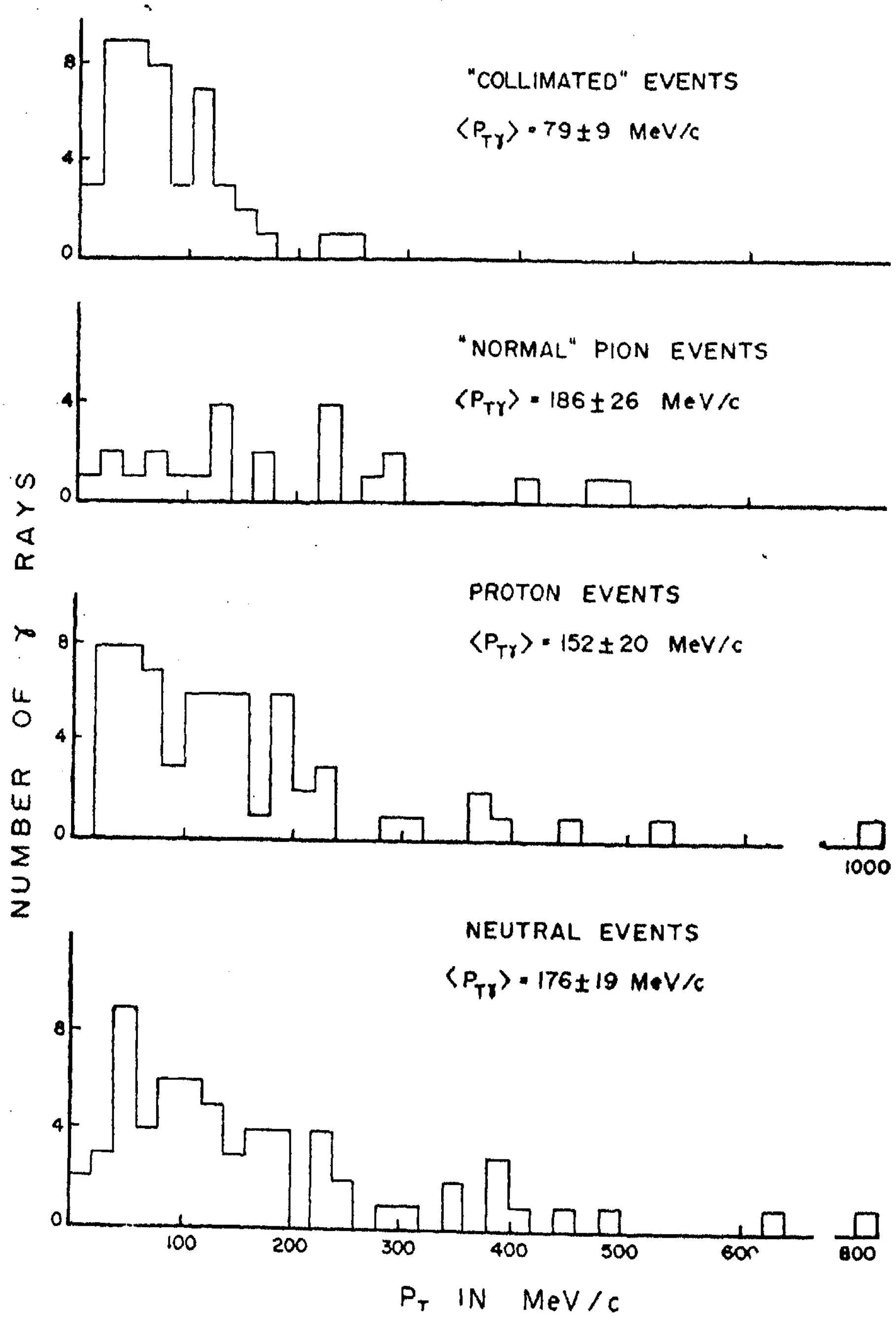

FIG. 2. The distribution of transverse momenta of γ-rays in different classes of events. The average value of the transverse momenta are given in the inset.

Further insight into the properties of S_n is gained by studying the transverse mometum distribution of γ-rays associated with the events (Fig. 2). The mean transverse momentum of γ-rays in the case of collimated events is significantly lower than in other events. This low value in turn points to a low value for the average of transverse momentum of neutral pions emitted from S_n. In fact the distribution of effective masses of two neutral pions from cases of S_2 and S_n given in Fig. 1 shows an average of 302 ± 9 MeV. This effective mass is close to the effective mass (317 ± 6 MeV) of di-pions in the ABC effect.[4] The ABC effect is an enhancement in the reaction cross-section $p + d \rightarrow He^3 + 2\pi$ corresponding to an effective mass of the 2π system at an energy of ~300 MeV. Since the enhancement is seen in only the neutral 2π system, the isospin attributed to the system is zero. A difficulty in the understanding of the ABC effect is the fact that it is seen in only the above reaction quoted. Searches for the ABC effect in other reactions like γp and πp have proved fruitless.[6] It may be, for some unknown reason, that the target has to be a nucleus for producing the ABC effect. The ratio of neutral to charged pions that are attributable to S_n is found to be 0·74 ± 0·18.* This and the earlier observations about the multiplicity distributions are consistent with an isospin assignment of zero to S_2.

III. Discussion of the Results

From the foregoing, it appears that collimated events induced by charged primaries are preferentially originated by pions and in these events additional pions produced in the "forward direction" occur in pairs of charged and neutral pions. The effective mass of these di-pions seems close to that observed in the ABC effect. The events appear more frequently in carbon than in brass. Although collimated events have been seen to be induced by neutral primaries, these do not seem to have the characteristic multiplicity distribution observed in the case of interactions induced by charged primaries (Fig. 1). Therefore we infer that the collimated events with the characteristic features elucidated above are induced by pions only.

Collimated events can in general be due to diffraction dissociation,[7] Coulomb dissociation[8] or due to "glancing collisions" involving one pion exchange.[9] However, none of these mechanisms seems to be involved in producing the events reported here. The argument against diffraction or Coulomb dissociation is the large disparity in energies of the outgoing particles in the forward direction, *viz.*, there is probably one outgoing charged secondary carrying away ~80% of the incident energy. In a dissociation

* The ratio of neutral to charged pions expected is 0·5 for the decay into two pions of a system with isospin zero; but corrected for phase space difference due to the different rest masses of charged and neutral pions this ratio is enhanced to 0·7 in the case of S_2 with the above quoted mass.

phenomenon, the incident pion, excited to a higher mass state and decaying into a number of pions, should have equipartition of the incident energy among the secondaries. In some events there appears to be a large energy transfer to the target nucleon as evidenced by the occurrence of a relativistic secondary at large angles. In a coherent dissociation phenomenon the target nucleus will not break up. Further, Coulomb dissociation is ruled out from the fall of the frequency of events in brass compared to carbon; it should be the reverse if Coulomb dissociation is involved because this has a Z^2 effect. One pion exchange is excluded from the fact that outgoing forward multiplicities are odd, whereas it should be even from conservation of G-parity. However, the relative ratio of collimated events in brass and carbon evaluated earlier in II (*a*), *i.e.* $0 \cdot 4 \pm 0 \cdot 2$ is consistent with the idea of peripheral nature of the collisions [only 20% of the incident energy is radiated as pointed out in II (*b*)]. The total inelastic cross-section would vary as $A^{2/3}$ where A is the mass number of a nucleus whereas the area of periphery of constant thickness of a nucleus would vary as $A^{1/3}$. Therefore, frequency of peripheral events to all events will vary as $A^{-1/3}$. Thus between brass and carbon one expects a relative ratio of $(12/64)^{1/3} = 0 \cdot 6$.

Phenomena similar to the one reported here have not been observed at accelerator energies so far. It appears that collimated events as per our definition based on the angular distribution of secondaries only, do seem to be induced by protons in emulsion at about 27 GeV/c at a frequency of about

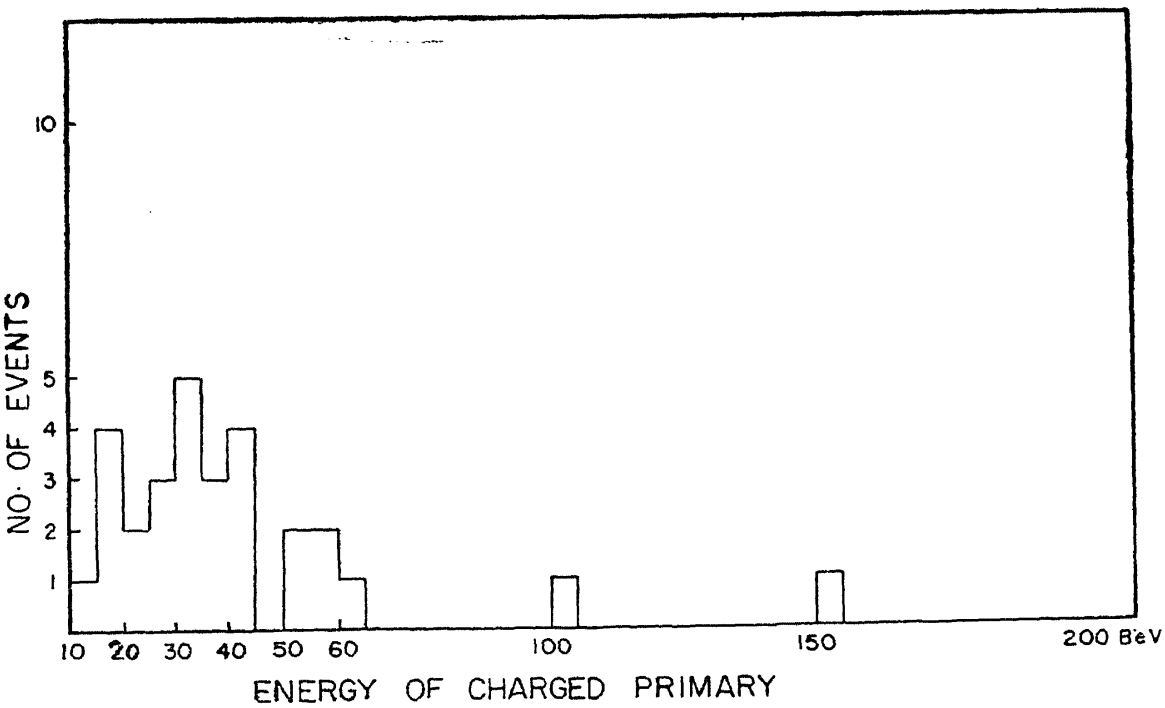

FIG. 3. The distribution in energy of the charged primaries producing the collimated event in carbon and brass as obtained with the aid of the total absorption spectrometer.[1]

… all interactions in emulsion and at a somewhat higher frequency … collisions against light nuclei of emulsion (C, N, O).* However, … features of these events are unknown so that we cannot say that … s have characteristics similar to the events reported here. Inter… pions have been studied upto 17 GeV/c[10] in heavy liquid bubble … vith no report of finding events similar to ours. The median … he events observed by us is 35 GeV. The distribution in energy of … primaries of these events is given in Fig. 3. There seems to be … dependence in the production of these events. For collisions in … iced by charged primaries the ratio of collimated events to all is … 1 at energies < 30 GeV whereas the corresponding figure for … 30 GeV is $0 \cdot 09 \pm 0 \cdot 03$. Further investigations on the interactions … carbon at energies 30–60 GeV from the 70 GeV proton Serpukov … will be interesting. A study on the role of the target (proton … could throw further light on the phenomena reported here.

IV. Conclusion

… of nuclear interactions, characterised by extreme collimation of … ries in the forward direction in the laboratory system, seem to be … eferentially by pions. These events appear to be relatively more … carbon than in brass. An energy dependence in the frequency … on of these events is indicated. It is possible to explain these … n terms of peripheral production of pions in pairs, the di-pion … g similar to that observed in the ABC effect. In these collisions, … t primary surviving the collision appears to retain $\sim 80\%$ of its … is not possible to invoke diffraction dissociation, Coulomb dissocia… pion exchange mechanisms to explain the events.

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…grateful to Professor Y. K. Lim for communicating these results to us.

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