Pramāṇa, Vol. 17, No. 1, July 1981, pp. 111–120. © Printed in India.

An analysis of energetic cosmic ray interactions in graphite

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MS received 25 March 1981; revised 9 June 1981

Abstract. Fifty two high energy cosmic ray interactions in graphite have been analysed. The analysis strongly suggests that some of the characteristics of high energy interactions are dependent on the total transverse momentum, Σp_t, of all γ-rays in an interaction. Out of the 52 events analysed, 29 have $\Sigma p_t \leqslant 2{\cdot}5$ GeV/c and the rest have $\Sigma p_t > 2{\cdot}5$ GeV/c; the former are called small p_t events while the latter are designated as large p_t events. For these two types of events, the characterstics investigated are: (a) fractional energy distribution of γ-rays, (b) the invariant mass of γ-rays and (c) the energy distribution of γ-rays in the emission system.

Keywords. Cosmic ray interactions; fireball model; fractional energy distribution; invariant mass; emission system; transverse momentum; graphite.

1. Introduction

The transverse momentum of most of the particles produced in high energy interactions is small; the average value of p_t is $\sim 0{\cdot}35$ GeV/c. The low p_t data can well be represented by a distribution of the type, $\exp(-6p_t)$. However, the data of large p_t (> 1 GeV/c) values cannot adequately be represented by the above distribution (Alper *et al* 1973; Banner *et al* 1973; Carey *et al* 1974; Cronin *et al* 1973). For instance, the number of pions with $p_t \geqslant 4$ GeV/c is about four times larger than the number expected from the extrapolation of low p_t data (Busser *et al* 1973).

Experimentally it is well established that the average p_t of neutral pions increases with primary energy of interaction (Agrawal *et al* 1979; Sato *et al* 1976; Feinberg 1972). The investigation of Sato and Sugimoto (1977) has shown that p_t distribution of γ-rays in high energy interactions follows the same trend as pion p_t distribution and the production cross-section of interactions with large total p_t increases with increase in the energy of the primary particle. The results of Lattes *et al* (1971) also indicate different characteristics for interactions with large and small total p_t values.

These observations motivated us to investigate the different characteristics of high energy interactions with large and small Σp_t values, produced in the graphite units of emulsion chambers exposed to cosmic rays in balloon flights conducted at Hyderabad, India (Hasan *et al* 1979; Malhotra *et al* 1965). Details of balloon flights, selection criteria for events, detection efficiency of γ-ray cascades, methods of cascade energy estimation, etc. are given in the above references. The above experimental data have been recast in a form suitable for the analysis given in this paper. Only events with $N_\gamma \geqslant 4$ are accepted for analysis and the detection efficiency of all γ-ray cascades with energy $\Sigma E_\gamma \geqslant 500$ GeV is close to unity.

The data of the above references yielded 52 high energy interactions induced by primary cosmic rays in the graphite producing units of the emulsion chambers. The average energy of the primary is $\sim 2 \times 10^4$ GeV. For convenience, the interactions are divided into two groups according to the total transverse momentum Σp_t of all γ-rays observed in each interaction. The interaction with $\Sigma p_t \leqslant 2{\cdot}5$ GeV/c are classified as small p_t events while those with $\Sigma p_t > 2{\cdot}5$ GeV/c are termed as large p_t events. For these two groups of events, the transverse momentum distribution of γ-rays, the fractional energy distribution of γ-rays, the invariant mass of γ-rays and the energy distribution of γ-rays in the emission system are investigated and presented.

2. Experimental data

The data on γ-ray multiplicity N_γ, the total γ-ray energy ΣE_γ, the total γ-ray transverse momentum Σp_t, the invariant mass M_γ of γ-rays and the average energy of γ-rays in the emission system for each event are given in tables 1 and 2. Tables 1 and 2

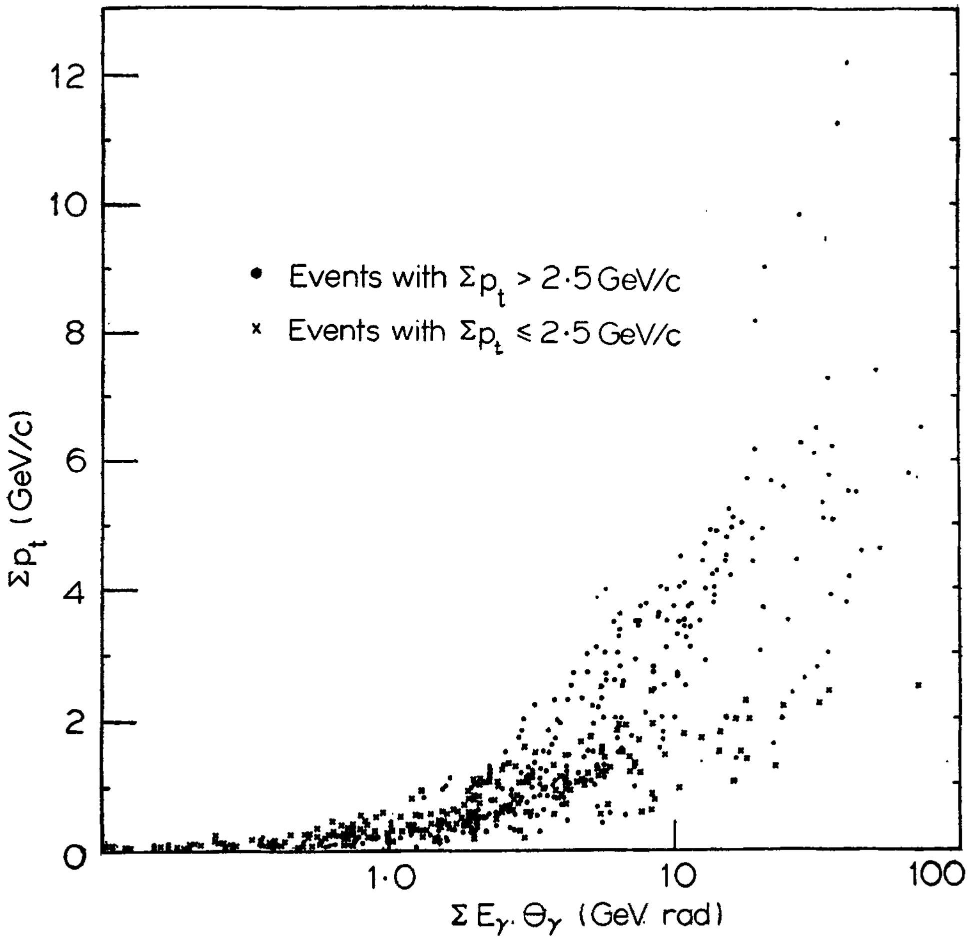

Figure 1. Transverse momentum flow diagram for large and small p_t events.

respectively refer to small and large p_t events. Table 3 summarizes the percentage of γ-rays in different ranges of normalized emission angle, $\theta_\gamma \Sigma E_\gamma$ for small and large p_t events. In table 4 are given the numbers of small and large p_t events in different energy ranges.

2.1 *Transverse momentum distribution of γ-rays*

The transverse momentum flow diagram *i.e.*, the sum of p_t of all γ-rays with emission angle less than θ_γ versus the energy normalized emission angle $\theta_\gamma \Sigma E_\gamma$ is shown in figure 1 where the crosses and dots respectively refer to small and large p_t events. As is evident from the figure, the transverse momentum flow is different for the two types of events in $\theta_\gamma \Sigma E_\gamma$ range (10-100) rad. GeV. This feature of the transverse momentum flow diagram can be used to distinguish between the two types of events. The integral transverse momentum distributions of γ-rays for small and large p_t events are separately shown in figure 2. The detection threshold of 50 GeV results in a detection bias against small p_t γ-rays. Therefore, γ-rays of $p_t \geqslant 0{\cdot}2$ GeV/c are used to

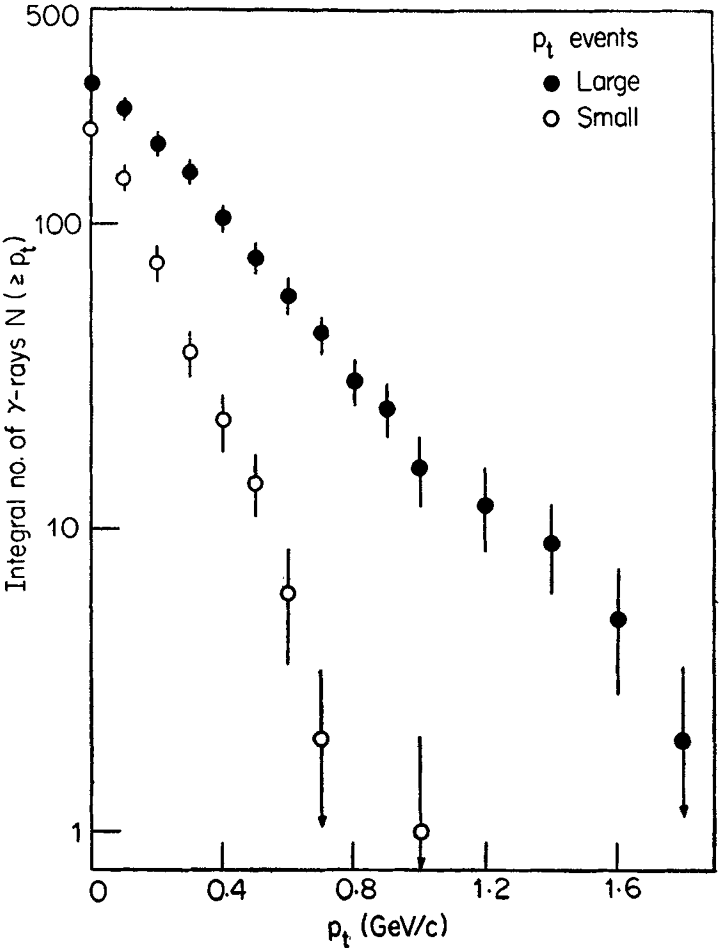

Figure 2. Integral transverse momentum distribution of γ-rays for large and small p_t events.

calculate the distribution function for the two groups of events. The distributions are consistent with the expression

$$\frac{dN}{dp_t} \propto \exp\left(-\frac{pt}{\langle p_t \rangle}\right), \tag{1}$$

where $\langle p_t \rangle$ is the average transverse momentum of γ-rays. The values of $\langle p_t \rangle$ are (0·166 ± 0·016) GeV/c and (0·375 ± 0·027) GeV/c for small and large p_t events respectively. Thus the combined p_t distribution is consistent with the expression

$$\frac{dN}{dp_t} = A \exp(-6p_t) + B \exp\left(-\frac{p_t}{0{\cdot}375}\right), \tag{2}$$

where A and B are constants.

2.2 *Fractional energy distribution of γ-rays*

The fractional energy, $f = E_\gamma/\Sigma E_\gamma$, distributions for small and large p_t events are separately shown in figure 3. The events with $f \geqslant 0{\cdot}05$ are free from detection bias.

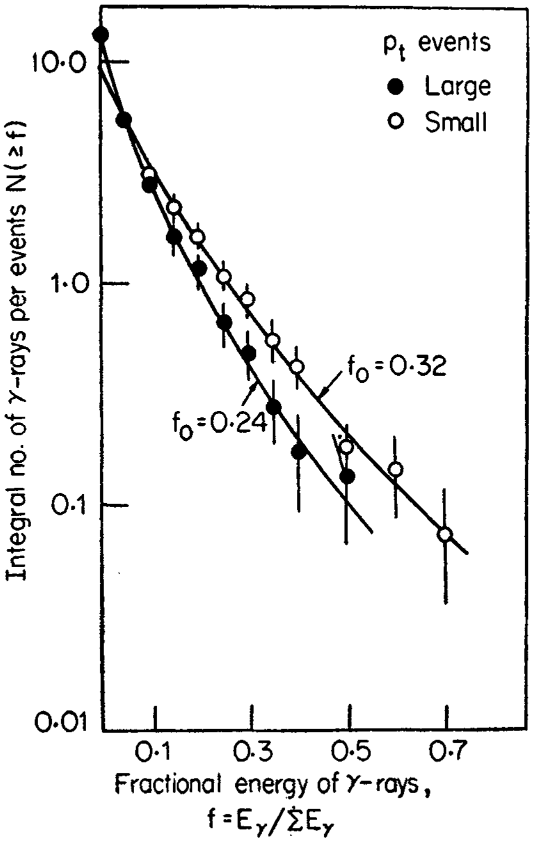

Figure 3. Fractional energy distribution of γ-rays for large and small p_t events. The solid curves represent equation (4) for f_0 = 0·32 and 0·24.

It can be seen that the distribution cannot be fitted with a single exponential function. The distribution decreases more rapidly than a single exponential distribution at low values of f. Therefore, the expected fractional energy distribution of γ-rays is calculated on the assumption that the fractional energy distribution of the parent π° -mesons is given by the expression

$$f\frac{dN}{df} \propto \exp\left(-f/f_0\right). \tag{3}$$

Neglecting the rest mass of π° -mesons, the fractional energy distribution of γ-rays from the above expression is of the form (Kopylov 1973),

$$N(\geqslant f) = \text{Const} \int_f^1 dy \int_y^1 \frac{\exp\left(-z/f_0\right)}{z^2}\, dz.$$

The above expression can be reduced to the following form (Sato *et al* 1976)

$$N(\geqslant f) \simeq E_1\left(f/f_0\right) - E_2\left(f/f_0\right), \tag{4}$$

where E_1 and E_2 are the exponential integrals. The fractional energy distribution was plotted using equation (4) for different values of f_0 for small and large p_t events. To find out the best fit distribution, ψ^2-test was done and it was observed that the distribution with $f_0 = 0{\cdot}32$ for small p_t events and $f_0 = 0{\cdot}24$ for large p_t events give the least value of ψ^2 per point. The least value of ψ^2 per point is 0·13 for small p_t events and 0·19 for large p_t events.

2.3 *Invariant mass of* γ-rays

The invariant mass of γ-rays in an interaction is defined as the sum of energies of all γ-rays in the emission system. The emission system is the system in which the total energy of γ-rays in an interaction is minimum. Mathematically, it can be represented by the following relation.

$$M_\gamma = \left[(\Sigma E_\gamma)^2 - (\Sigma P_\gamma)^2\right]^{1/2}, \tag{5}$$

where the summation covers all γ-rays in an interaction. For the purpose of computation, the above relation can be expressed in terms of the observed quantities as

$$M_\gamma = \left[(\Sigma E_\gamma) \cdot \Sigma (E_\gamma \cdot \theta_\gamma^2)\right]^{1/2}. \tag{6}$$

Histograms of the calculated values of the invariant mass M_γ are constructed for small and large p_t events. These are shown in figure 4. The average values of M_γ for the two types of events are

$$\langle M_\gamma \rangle = (2{\cdot}41 \pm 0{\cdot}48)\ \text{GeV for small } p_t \text{ events,}$$

$$\langle M_\gamma \rangle = (7{\cdot}93 \pm 1{\cdot}58)\ \text{GeV for large } p_t \text{ events.}$$

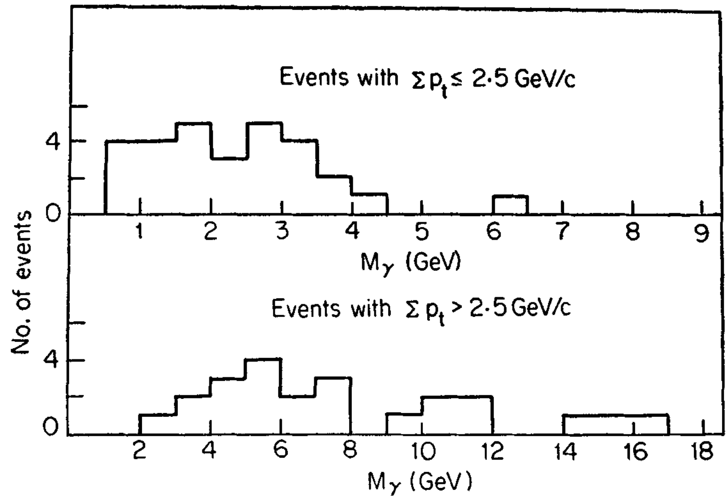

Figure 4. Histograms of the invariant mass M_γ.

2.4 *Energy of γ-rays in the emission system*

The energy of γ-rays in the emission system is estimated using the relation

$$E_{\gamma e} = \tfrac{1}{2}\left[\gamma_e (E_\gamma \cdot \theta_\gamma^2) + E_\gamma/\gamma_e\right], \tag{7}$$

where γ_e is the Lorentz factor of the emission system, E_γ is the γ-ray energy and θ_γ is the angle of emission of the γ-ray with respect to the energy weighted centre of the interaction (Agrawal *et al* 1979). The values of γ_e are calculated using the following relation

$$\gamma_e = \left[\frac{\Sigma E_\gamma}{\Sigma (E_\gamma \cdot \theta_\gamma^2)}\right]^{1/2}, \tag{8}$$

where the summation covers all γ-rays in an interaction. The value of $E_{\gamma e}$ for each γ-ray in an interaction is estimated using the above relations. These values are listed in tables 1 and 2. In figure 5, we plot the average energy of γ-rays in the emission system versus the total transverse momentum of γ-rays, Σp_t, in an interaction. It can be seen from the figure that $\langle E_{\gamma e} \rangle$ is larger for large p_t events. For large p_t events, the average value of $E_{\gamma e}$ is found to be (0·599 ± 0·069) GeV while it is (0·344 ± 0·038) GeV for small p_t events.

3. Discussion of the results

The transverse momentum distributions of small and large p_t events are shown in figure 2. The average values of p_t for small and large p_t events are (0·166 ± 0·016) GeV/c and (0·375 ± 0·027) GeV/c, respectively. The fractional energy distributions for the two types of events are shown in figure 3. These spectra cannot be

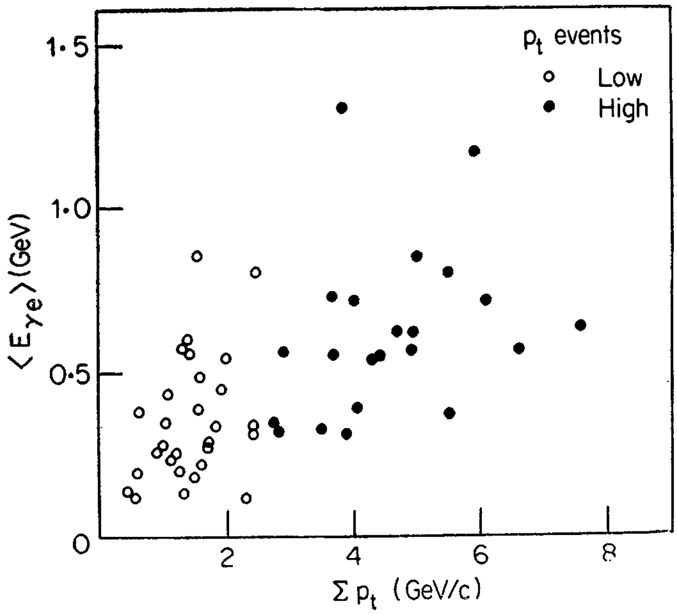

Figure 5. Average energy of γ-rays, $\langle E\gamma_e \rangle$, in the emission system for each event versus that total transverse momentum of γ-rays, Σp_t.

Table 1. Data on small p_t events ($\Sigma p_t \leqslant$ 2·5 GeV/c).

Event No.	ΣE_γ (GeV)	Σp_t (GeV/c)	N_γ	M_γ (GeV)	$\langle E_{\gamma_e} \rangle$ (GeV)
Al-B7	1005	1·69	9	2·6	0·29
Al-E67	1100	1·81	9	3·0	0·34
Al-E6	1230	1·5	11	2·3	0·19
Al-B25	1260	0·55	7	0·8	0·12
Al-B67	1275	1·13	7	1·6	0·23
Br-H180	1300	1·18	7	1·8	0·26
Br-K123	1390	1·54	9	3·5	0·39
Bo-169	1405	1·93	6	2·7	0·45
Al-C11	1450	1·69	8	2·5	0·28
Al-43	1520	0·92	6	1.5	0.26
Al-G14	1540	1.45	6	3.7	0.56
Br-L74	1550	0.99	6	1.7	0.28
Al-F29	1585	2·03	3	4.2	0.54
Bo-436	1840	1.07	4	1.4	0.35
Br-H181	1840	1.55	4	3.5	0.86
Bo-238	1990	1.64	10	2·2	0·22
Bo-468	2000	1·24	7	1·4	0·20
Al-A20	2020	1·64	4	1·9	0·48
Br-H11	2120	1·38	6	3·6	0·60
Bo-597	2130	2·37	8	2·7	0·34
Br-G62	2220	0·62	4	1·5	0·38
Bo-581	3220	2·40	11	3·4	0·31
Br-B34	3410	0·58	4	0·7	0·18
Br-E13	3780	2·28	14	1·7	0·12
Bo-467	3780	1·10	6	2·6	0·43
Br-I4	4960	0·40	5	0·68	0·14
Br-F2	5150	2·25	8	6·4	0·80
Br-E39	5250	1·29	9	0·91	0·13
Br-K45	6700	1·27	7	3·8	0·54

Al-Aligarh Data; Bo-Bombay Data; Br-Bristol Data

Table 2. Data on large p_t events (Σp_t > 2·5 GeV/c)

Event No.	ΣE_γ (GeV)	Σp_t (GeV/c)	N_γ	M_γ (GeV)	$\langle E_{\gamma_e} \rangle$ (GeV)
Bo-97	1385	4·06	12	4·7	0·39
Al-F35	1395	3·88	18	5·6	0·21
Br-I49	1500	4·03	7	5·0	0·71
Bo-1172	1500	3·68	8	4·4	0·55
Bo-278	1570	4·40	10	5·4	0·54
Bo-471	1590	2·81	10	3·2	0·32
Bo-713	1650	4·96	10	6·2	0·62
Bo-500	1770	3·63	7	5·1	0·73
Al-F2	1815	5·25	14	7·2	0·37
Br-F75	1960	2·73	8	2·8	0·35
Bo-675	2010	3·49	12	3·9	0·33
Bo-494	2460	4·94	12	6·7	0·56
Al-E22	2815	4·33	11	5·9	0·54
Br-C50	3840	6·13	11	7·8	0·71
Bo-589	3850	5·89	10	11·7	1·17
Bo-620	4720	12·23	19	15·7	0·83
Bo-607	5680	5·58	12	9·6	0·80
Bo-67	5760	3·84	11	14·3	1·30
Br-G2	8510	2·86	13	7·2	0·56
Br-K168	9190	4·62	18	10·9	0·61
Br-K16	10460	6·60	21	11·7	0·56
Br-K48	13420	4.96	12	10·2	0·85
Br-K14	14810	7·58	27	17·1	0·63

Al-Aligarh Data; Bo-Bombay Data; Br-Bristol Data

represented by a single exponential function, but are well approximated by a function of type

$$N(\geqslant f) \simeq E_1(f/f_0) - E_2(f/f_0),$$

where the values of f_0 for small and large p_t events are 0·32 and 0·24 respectively. This suggests that the fractional energy distribution of the parent π° -mesons is of the following form

$$f\frac{dN}{df} = \text{Const. exp } (-f/0{\cdot}32) \text{ for small } p_t \text{ events,} \tag{9}$$

$$f\frac{dN}{df} = \text{Const. exp } (-f/0{\cdot}24) \text{ for large } p_t \text{ events.} \tag{10}$$

Thus f distribution of the parent π° -mesons is steeper for large p_t events.

These results suggest that high energy interactions have a two-component structure; one characterized by small and the other by large $\Sigma\, p_t$ values. A similar result has been observed by Sato and Sugimoto (1977), Halzen and Gaisser (1975), Filho *et al* (1979) and Lattes *et al* (1975). In table 5 we present $\langle p_t \rangle$ for small and large p_t events as observed by different authors. From the table we observe that different authors have obtained similar values of $\langle p_t \rangle$ for the two types of events. The small differences may be attributed to the difference in selection biases and the observed ranges of p_t and θ_γ. In table 4, we present the number of small and large p_t events in different ranges of ΣE_γ. From the table it is clear that the number of large p_t events increases with energy. Sato and Sugimoto (1977) have also shown that the production cross-section of large p_t events increases with primary energy. As $\langle p_t \rangle$ is larger for large p_t events, the $\langle p_t \rangle$ for all events (low as well as large p_t events) must increase with primary energy as observed by several authors (Agrawal *et al* 1979; Sato *et al* 1976).

The estimated values of M_γ for the two types of events are given in tables 1 and 2. The average values of M_γ for small and large p_t events are (2·41 ± 0·48) GeV and (7·93 ± 1·58) GeV respectively. In tables 1 and 2, the average value of γ-ray energy

Table 3. Percentage of γ-rays in different ranges of normalised angle of emission ($\theta_\gamma \, \Sigma E_\gamma$).

	$\langle \Sigma E \rangle_\gamma$ (GeV)	Range of $\theta_\gamma \, \Sigma E_\gamma$ (rad. GeV)		
		0.1 – 1·0	1.0 – 10.0	10 – 100
Small p_t events	1400	35%	60%	5%
Large p_t events	4500	7%	63%	30%

Table 4. Number of small and large p_t events in different ΣE_γ ranges.

Range of ΣE_γ / No. of events	1000-2000 (GeV)	2000-5000 (GeV)	5000 >(GeV)
Small p_t	17	9	3
Large p_t	10	6	7

Table 5. Average values of transverse momentum $\langle p_t \rangle$ of γ-rays for small and large p_t events as observed by different workers.

Reference	No. of events analysed	Range of ΣE_γ (TeV)	Minimum energy E_γ (GeV)	Range of θ_γ (rad.)	Range of p_t (GeV/c)	$\langle p_t \rangle$ (GeV/c)	
						Small p_t events	Large p_t events
Sato and Sugimoto (1977)	15	0·6-5	30	10^{-4}-10^{-2}	0·3-1·2	0·166	0·30
Lattes *et al* (1971)	84	10-30	150	10^{-5}-10^{-3}	0·1-1·8	0·12 ± 0·07	0·28 + 0·018
Chinellato *al* (1977)	—	9-42	100	10^{-5}- $2{\cdot}9 \times 10^{-3}$	0·1-1·8	0·125	0·250
Present analysis	52	1-15	50	10^{-5}-10^{-2}	0·2-1·8	0·166 ± 0·016	0.375 ± 0·027

in the emission system, $\langle E_{\gamma e}\rangle$ for each event is also given. The average values of $E_{\gamma e}$ for small and large p_t events are (0·344 ± 0·038) GeV and (0·599 ± 0·069) GeV respectively. The large values of $\langle E_{\gamma e}\rangle$ for large p_t events coupled with the fact that the average γ-ray multiplicity for these events is large, suggest that these events could be interpreted in terms of the production and decay of fireballs with larger masses M_γ, while small p_t events could be due to the production of fireballs with smaller masses. Chinellato *et al* (1977) have explained their data in terms of the production of three types of fireballs with $M_\gamma \simeq (1{\cdot}3 \pm 0{\cdot}2)$ GeV, (8 ± 1) GeV and (60—80) GeV. The average transverse momentum for the three types of interactions are 0·125 GeV/c, 0·250 GeV/c and 0·500 GeV/c. We have not been able to observe the third type of interaction characterized by very high value of $\langle p_t\rangle$ (~0·5 GeV/c) as the energy in our case is not sufficient for this type of interaction to take place.

4. Conclusions

From the analysis of 52 high energy interactions we conclude:

(i) High energy interactions exhibit a two-component structure. One component is characterized by small and the other by large Σp_t value. The average transverse momentum of γ-rays in small p_t events is (0·166 ± 0·016) GeV/c and it is (0·375 + 0·027) GeV/c in large p_t events.

(ii) The f-distribution of π°-mesons is steeper for large p_t events.

(iii) The two types of events could be interpreted in terms of the production of small and large mass fireballs.

(iv) The average values of the invariant mass of fireballs for small and large p_t events are (2·41 ± 0·48) GeV and (7·93 ± 1·58) GeV respectively.

References

Agarwal A K, Hasan R and Swami M S 1979 *Pramana* **12** 45

Alper B *et al* 1975 *Nucl. Phys.* **B87** 19

Banner M *et al* 1973 *Phys. Lett.* **B44** 537

Busser F W *et al* 1973 *Phys. Lett.* **B46** 471

Carey D C *et al* 1974 *Phys. Rev. Lett.* **33** 330

Chinellato J A *et al* 1977 *Proc. 15th Int. Cosmic Ray Conf.* Plovdiv Vol. **7** 195

Cronin J W, Frisch H J, Shochet M J, Boymond J P, Piroue P A and Summer K L 1973 *Phys. Rev. Lett.* **31** 1426

Feinberg E L 1972 *Phys. Rep.* **C5** 237

Filho J B *et al* 1979 *Proc. 16th Int. Cosmic. Ray. Conf. Kyoto* Vol. **6** 362

Hasan R, Agarwal A K and Swami M S 1979 *Pramana* **12** 33

Halzen F and Gaisser T K 1975 *Proc. 14th Int. Cosmic Ray Conf. Munich* Vol. **7** 2216

Kopylov G J 1973 *Nucl. Phys.* **B52** 126

Lattes C M G *et al* 1971 *Prog. Theor. Phys. Suppl.* **47** 1

Lattes C M G *et al* 1975 *Proc. 14th Inst. Cosmic Ray Conf. Munich* Vol. **7** 2426

Malhotra P K *et al* 1965 *Nuovo Cimento* **40** 404

Sato Y and Sugimoto H 1977 *Proc. 15th Int. Cosmic Ray Conf.* Plovdiv Vol. **7** 139

Sato Y, Sugimoto H and Saito T 1976 *J. Phys. Soc. Jpn.* **41** 1821