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Transverse momenta of secondaries from 200 GeV/c proton-nucleus interactions

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Abstract. A study of 100 interactions, produced by secondary particles from 200 GeV/c proton interactions in nuclear emulsions, has been made to estimate the transverse momenta of the secondary particles. The data have been analysed by different methods of energy estimation and the weighted average values of p_t have been compared as estimated from various methods. An average value of p_t equal to $0{\cdot}38 \pm 0{\cdot}03$ GeV/c, in proton-nucleus interactions at 200 GeV/c, has been obtained from the production mechanism method.

Keywords. Proton-nucleus interactions; transverse momenta; production mechanisms.

1. Introduction

The measurement of transverse momenta of secondary particles produced in p-nucleus interaction have been mainly made from cosmic ray events (Hansen and Fretter 1960; Debenedetti *et al* 1956; Glasser *et al* 1959; Edwards *et al* 1958). Cosmic rays have a wide spectrum of composition and energy which makes such estimates less reliable. We have measured the transverse momenta of secondaries, produced by 200 GeV/c protons (from FNAL) in nuclear emulsions, from the angular measurements of the resulting secondary interactions. The energies of the interacting secondaries are estimated from various methods discussed in the next section. Multiple scattering measurements have also been made on 14 suitable tracks which give the secondary interactions analysed in the present work.

2. Theory

The methods of energy estimation include the Duller-Walker (1954) plot method, Yajima-Hasegawa (1965) method applying asymmetry corrections and the methods based on production mechanisms.

2.1. *Duller-Walker plot*

The value of γ_c is given by (Duller *et al* 1954)

$$\gamma_c \tan \theta = \sin \theta^* \, / \, [\cos \theta^* + (\beta c/\beta^*)]$$

where θ^* and β^* refer to angle and velocity of shower track respectively in units of c in the centre of mass (cm) system.

$F(\theta)$ is a function proportional to the number of particles emitted with angles less than θ and is normalised to $F(\pi)=1$. Taking the isotropic distribution of the particles in the cm system, we derive the equation

$$\log \frac{F(\theta)}{[1-F(\theta)]} = 2 \log \tan \theta + 2 \log \gamma_c$$

where θ is the angle of the shower track in the lab. frame. Thus a straight line plot of $\log [F(\theta)/\{1-F(\theta)\}]$ versus $\log (\tan \theta)$ should give a slope of 2. It has been found that the assumption of isotropy affects the energy estimation in low multiplicity events (Sardar Singh 1971).

2.2. *Yajima-Hasegawa method*

As the assumption of symmetry of emission of particles is not always true, the correction for asymmetry has been taken into account in the formula given by Yajima and Hasegawa (1965)

$$\gamma_c = \frac{1}{[(1+\mu^2)/p_t^2]^{1/2}} \left(\frac{1-z}{1+z}\right)^{1/2} \left(\frac{\Sigma \cot \theta_i}{\Sigma \tan \theta_i}\right)^{1/2},$$

where p_t, the transverse momentum, is assumed to be constant and μ is the mass of the emitted particle. Z is the asymmetry factor defined by

$$Z = (\alpha - \beta)/[2-(\alpha+\beta)],$$

where $$\alpha = \frac{\Sigma_f \operatorname{cosec} \theta_f}{\Sigma_i \operatorname{cosec} \theta_i} \text{ and } \beta = \frac{\Sigma_b \tan \theta_b}{\Sigma_i \tan \theta_i}.$$

The summations over f, b and i refer to the summation over forward and backward emitted particles in the c.m. system and over all the secondaries respectively. The forward and backward emitted particles can be defined, by the median angle of the set of particles, to a first approximation.

2.3. *Production mechanism method*

Analyses of interactions of protons with complex nuclei are made using two mechanisms (i) cascade mechanism resulting from consecutive single nucleon collisions and (ii) coherent production due to simultaneous interaction of the particle with a number of nucleons in the target (Bhowmik *et al* 1972). The mechanism of interaction is indicated by applying certain criteria using measured parameters of the interactions as discussed in the following sections.

2.3.1. *Cascade mechanism*: The formula yielding the energy E_0 is given by

$$E_0 = N \langle E \rangle / (1-\bar{\eta}),$$

where $$\langle E \rangle = \langle (m^2 + p_t^2 \operatorname{cosec}^2 \theta)^{1/2} \rangle,$$

N is the total number of particles emitted (corrected for loss of particles during interaction and enhancement due to subsequent production and also excluding the persisting particle) and

$$\bar{\eta} = \sum_{i=1}^{\nu} (1/\nu)^{1/(i-1)}/\nu.$$

ν being the total number of collisions in the nucleus, m, p_t and θ are the rest mass, transverse momenta and angle of emission of the emitted particle with respect to the primary direction respectively.

2.3.2. *Coherent production*: Here the energy is computed using the formula

$$E_0 = (m_0^2 + N'^2 \langle p_t \cot \theta \rangle'^2)^{1/2}$$

where N' is the number of particles emitted including the persisting primary and m_0 is the rest mass of the incident particle. The average $\langle p_t \cot \theta \rangle'$ is taken over all the secondaries.

2.3.3. *Criterion for production mechanisms*

(a) If $[\langle (1+p_t^2 \operatorname{cosec}^2 \theta/m_\pi^2)^{1/2} \rangle - \langle p_t \cot \theta/m_\pi \rangle]$,

exceeds unity, the interaction is through cascade mechanism; otherwise it takes place through coherent production

(b) Also if $\sum_i \sin \theta_i > A^{-1/3}$

the interaction is through cascade mechanism; otherwise it takes place through coherent production.

Here A is the mass number of the target nucleus. The average value of A is taken to be 12 and 108 for light and heavy groups of emulsion nuclei respectively. We have used both the criteria for our analyses.

2.3.4. *Determination of E, ν, N and N'*: Assuming a transverse momentum distribution of the form (Morrison 1963)

$$f(p_t)\, dp_t = p_t \exp(-p_t/p_0)\, dp_t; \quad (p_0 = 0{\cdot}17 \text{ GeV/c}),$$

the value of $\langle E \rangle$ is calculated as

$$\langle E \rangle = \langle (m^2 + p_t^2 \operatorname{cosec}^2 \theta)^{1/2} \rangle$$

$$= \frac{1}{N_s} \sum_{i=1}^{N_s} \left[\int_0^R (m_i^2 + p_t^2 \operatorname{cosec}^2 \theta_i)^{1/2} f(p_t)\, dp_t \Big/ \int_0^R f(p_t)\, dp_t \right],$$

where N_s is the number of charged shower particles in an event and $R = 1$ GeV/c is taken to be the maximum value of p_t.

The number of collisions ν is calculated from the expression given by Babecki and Nowak (1977).

$$\nu = a + bNg + cNg^2$$

where $a = 1{\cdot}45 \pm 0{\cdot}05$, $b = 0{\cdot}058 \pm 0{\cdot}04$, $c = -0{\cdot}15 \pm 0{\cdot}004$ and Ng is the number of grey prongs in the event.

$$N = 1{\cdot}5\ [(N_s - 1) - 0{\cdot}1\ N_h\ (0{\cdot}95\ (\langle E\rangle - m_\pi)^{0{\cdot}49})] + 0{\cdot}23\ N_h,$$

and $N' = N + 1{\cdot}5$. Values of N and N' are corrected for the loss of particles and for those created during the interaction.

3. Experimental details and discussion

The data have been collected from three pellicles of an emulsion stack which had been exposed to 200 GeV/c protons at FNAL. Details of the exposure, etc. are given elsewhere (Gurtu *et al* 1974). Primary interactions were located within the volume of the emulsion leaving 25 μm near air and glass surfaces. The shower tracks situated in the forward cone of 10° of the interaction were systematically followed till they leave the emulsion or interact.

A total of 100 interactions have been recorded out of which 7 are events with multiplicity equal to one. The N_s distribution of the secondary interactions are shown in figure 1. The average multiplicity of 93 events is 4·6 for the secondary interactions. In deciding as to whether the interacting shower is a proton or a pion, the shower emitted at the minimum angle in the primary interaction is accepted as

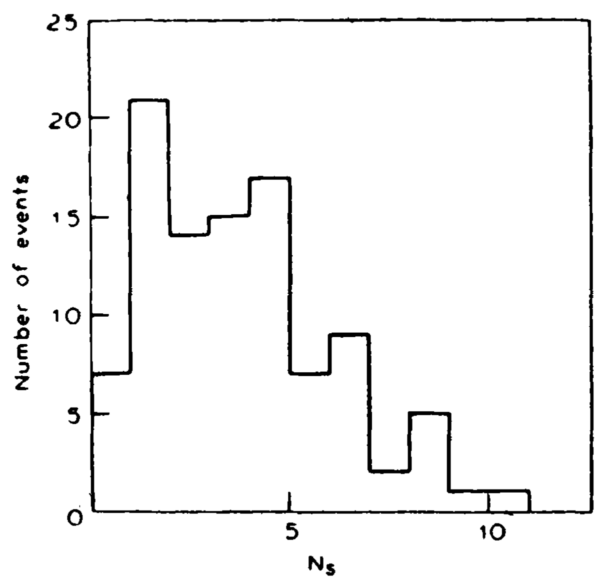

Figure 1. Distribution of N_s for all secondary interactions

a persisting proton. About 20% of the interactions are found to be due to persisting protons. Angular measurements in the secondary interactions were accurately made using a Cooke's microscope under a magnification of 1000×.

As the average multiplicity is 4·6, Duller-Walker (1954) plots cannot be drawn for individual events. We have, therefore, grouped such secondaries emitted within range of angles 0°–1°, 1°–2°, 2°–3°, etc. and the average energies of the secondaries have been calculated from the Duller-Walker plots. The class of stars grouped together in such an angular range include both π-nucleon and π-nucleus types of interactions. The energies have been calculated by the method mentioned above and the results of $\langle p_t \rangle$ are shown in table 1. Since we have analysed secondary interactions in the forward cone of the primary, the p_t refers to forward cone secondaries only.

The value given by Yajima-Hasegawa (1965) method, being based on the method of energy estimation for nucleon-nucleon collisions, is less reliable and has been included for comparison. An estimation of the asymmetry factor reveals that the shower particle emission is symmetric in the forward direction for about 25% of the secondary interactions. The methods based on production mechanism have been shown to be relatively more accurate for energy estimation in the case of proton-nucleus interactions of known energy (Bhowmik *et al* 1972) (i.e. 23 GeV/c and 50 GeV/c). The transverse momenta estimated from the production mechanism method, therefore, appear to be more reliable.

Out of the 100 tracks producing these secondary interactions, we have selected several tracks suitable for multiple scattering measurements. Only those tracks with suitable energy (less than 10 GeV/c) and sufficient length were chosen so as to get sufficient number of large cell lengths required for making scattering measurements at these energies. Only 14 tracks were found suitable out of the 100 interacting secondaries. The scattering measurements were performed using a Koristka microscope. Cell lengths of values varying from 1000 to 2500 μms were used. The observed signal has been corrected for both cell-dependent (stage, grain, reading and temperature) and cell-independent (spurious scattering, etc.) noises. Cell-independent noises have been eliminated using the method of Biswas *et al* (1957). For cell-dependent noises, the relative scattering measurements have been made on primary

Table 1. Average transverse moments for p-nucleus interactions at 200 GeV/c as estimated by various methods of energy estimation

Method of energy estimation	No. of events	Average transverse momenta (GeV/c)	
Duller-Walker Plot			
0°-1°	41	0·326	0·364 ± 0·016
1°-2°	26	0·388	
2°-3°	13	0·378	
Yajima-Hasegawa method	52	0·431 ± 0·032	
Production Mechanism			
(i) Cascade	68	0·376 ± 0·026	
(ii) Coherent	58	0·380 ± 0·026	
Multiple scattering	14	0·320 ± 0·064	

beam tracks (200 GeV/c proton) adjacent to these tracks, using overlapping cells. The signal obtained from the primary track is used to apply suitable corrections for spurious scattering and other distortions to the track under study.

In order to show the internal consistency of the methods of energy and hence p_t estimation, the values of p_t for 8 events obtained from different methods have been shown in table 2. The individual values agree reasonably well with each other. The average values of p_t, however, would be more accurate. The distributions of p_t by the different methods of p_t estimation are given in figure 2.

Table 2. Individual values of p_t for 8 events as measured by various methods
Transverse momentum (in GeV/c) estimated from

Event No.	Yajima-Hasegawa method	Cascade mechanism	Coherent mechanism	Multiple scattering
11	—	0·145	0·206	0·278
19	0·144	0·099	—	0·189
44	0·309	0·325	0·248	—
47	0·478	0·474	0·392	—
56	—	0·089	0·080	0·078
59	—	0·136	0·176	0·159
100	0·464	0.479	0·418	—

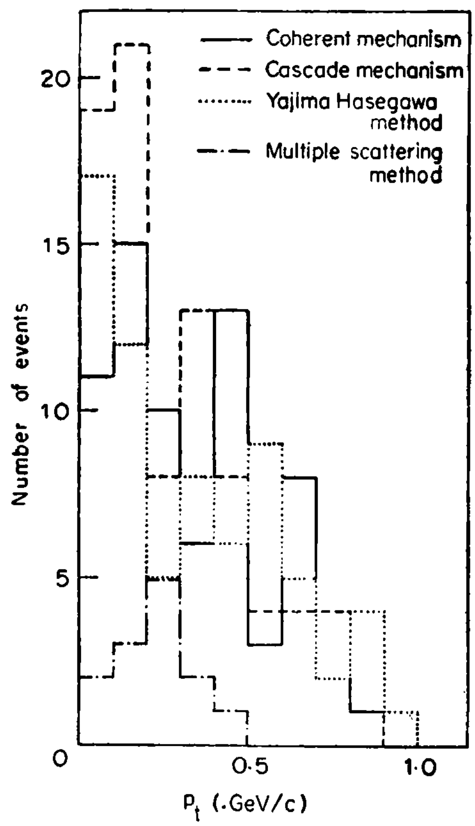

Figure 2. Distribution of p_t as measured from different methods

Though none of these methods of energy estimation is above criticism, yet the weighted average value of p_t have been found, within errors, to be comparable; the average value of $p_t = 0{\cdot}38 \pm 0{\cdot}03$ GeV/c being more reliable as estimated from production mechanism method.

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