III-7-6. A Semi-Phenomenological Approach to Multiple Meson Production

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A theoretical approach to the fire-ball model is made.

Taking account of the strong interaction among emitted pions in high energy jets and how the fire-ball disintegrates one may consider the fire ball as an unstable boson with spin 0 or 1. Two (or one) or more fire-balls would be produced in a peripheral nucleon (or pion)-nucleon collision since the momentum transfer between two colliding particles is very small.

Various quantities with respect to the production process of the fire-balls are calculated field-theoretically in some simple cases based on the above points of view. The numerical results are not inconsistent with experimental data.

1. Analysing the exprimental data of high energy jet showers in detail, Niu[1] and some authors[2] proposed the "fire-ball model." Theoretical foundations of this model have not obtained yet. If one brings some assumptions into the theory one might investigate the mechanism of the fire-ball model. On such a standpoint we study various features of this model by using the quantum field theory. The disintegration stage of the fire-ball seems to be independent of its production stage and do not probably characterize high energy phenomena. Then we treat the production process without going into the details of the disintegration process, which will be substituted by the information from experiments.

2. The fire-ball model is based on the fact that the angular distribution of secondaries in the apparent nucleon (or meson)-nucleon collisions appears to be separated into two or more particle groups. In many cases each particle group has the gradient two or more in the F-plot. The experimental data show that the secondaries have small momenta of order of $0.2\sim0.7\,\text{GeV}/c$ in the center of energy system of each particle group (the rest system of the fire-ball (RS))*. We could infer that an observed particle group is the decay product of a quasi-bound system since the interaction in the final states is strong among emitted pions. The features of the decay process may be similar to those of nucleon-antinucleon annihilations in Gev region. It may be admitted to regard this quasi-bound system as an unstable heavy boson with the appropriate spin and mass (M^*).

If the collision time, that is $\sim 1/(\mu\gamma_c)$, where μ is the pion mass, is shorter than the life time of the unstable boson, it would be reasonable to treat this boson as a free particle at the time of its production. This situation is justified if the following relation holds,

$$\gamma_c \gg M^*/(\mu\bar{\gamma})\,, \qquad (1)$$

where $\bar{\gamma}$ is the Lorentz factor of the fire-ball in CMS. As will be shown later, this condition is always satisfied in our results.

By taking into account the observed angular

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* If we assume the angular distribution of secondaries in RS as the form $\cos^m\theta^* d(\cos\theta^*)$ with $m=0$ and 2, the gradient of F-plot turns out to be larger than two when β_c/β_π^* (β_c and β_π^* are respectively the velocity of CMS and of the emitted pion in RS) is larger than unity. The angular distribution of new quanta proposed by Hasegawa[3], $\sin^2\theta^* d(\cos\theta^*)$, may be expalained by the above statement or the assumption that the new quantum is the vector boson introduced here.

distribution in RS for the time being, it is sufficient to assume the spin of the boson to be 0 or 1.

Osaka group (K.D., K. K., N.Y. and H.Y.) adopted the neutral scalar or pseudoscalar boson. On the other hand Tokyo group (T. K., K.M. and T.Y.) considered the vector boson with the isotopic spin one based upon the following idea: The vector boson with masses nearly equal to the nucleon mass or higher than the nucleon mass may be identified with ones which have been developed in discussions on the basic symmetries in the strong interaction of elementary particles.

The effective Hamiltonian densities corresponding to the above cases are given by

$$H_I=ig\bar{\psi}(x)\gamma_5\psi(x)\varphi(x)+G\bar{\psi}(x)\gamma_A\psi(x)B(x)+G_0\mathfrak{M}\varphi^2(x)B(x) \quad (2)$$

where

$$\gamma_A=\begin{cases}1\\ i\gamma_5\end{cases}, \quad G=\begin{cases}G_s\\ G_{ps}\end{cases} \text{ and}$$

$$G_0=\begin{cases}G_0 & \text{for } B(x)\text{: scalar} \quad (S)\\ 0 & \text{for } B(x)\text{: pseudoscalar (PS);}\end{cases}$$

and

$$H_I=ig\bar{\psi}(x)\gamma_5\tau_\alpha\psi(x)\varphi_\alpha(x)+iG\bar{\psi}(x)\frac{\tau_\alpha}{2}\gamma_\mu\psi(x)B_{\mu,\alpha}(x)+G_V\left(\varphi(x)\times\frac{\partial\varphi}{\partial x_\mu}\right)_\alpha B_{\mu,\alpha}(x) \quad (3)$$

Eq. (3) is the same as the Sakurai's[4].

3. We now study the production process of the fire balls using above mentioned Hamiltonians. Before going into the calculations it must be reminded that the momentum of interaction Δp for the symmetrical jets are smaller than several GeV/c according to the fire-ball model[1]. Especially small values of Δp, say 0.12~0.4 GeV/c, are also observed. These values give a clue to investigate the characteristics of jets from the view point of quantum field theory. That is to say the fire-ball production must be caused by a peripheral collision contrary to a central one such as in Fermi-Landau's theory. The smallness of Δp permits us to deal with the one-pion exchange process as the extreme case of the peripheral collisions.

4. The following three cases are investigated by the perturbation method.

(I) Diagrams represented by Fig. 1 (1) with the Hamiltonian given by the first and second term in Eq. (2).

(II) Diagrams represented by Fig. 1 (2) with the Hamiltonian given by the first and third term in Eq. (2) and

(III) Diagrams represented by Fig. 1 (1) and (2) with Eq. (3).

The interference term between the second and third term in Eq. (2) is neglected in order to obtain some informations about the difference between $\pi\pi B$ and NNB vertices in character. In case (III) the contribution corresponding to Fig. 1 (1) is not a main term since the second and the third term in Eq. (3) have a common coupling constant G_V.

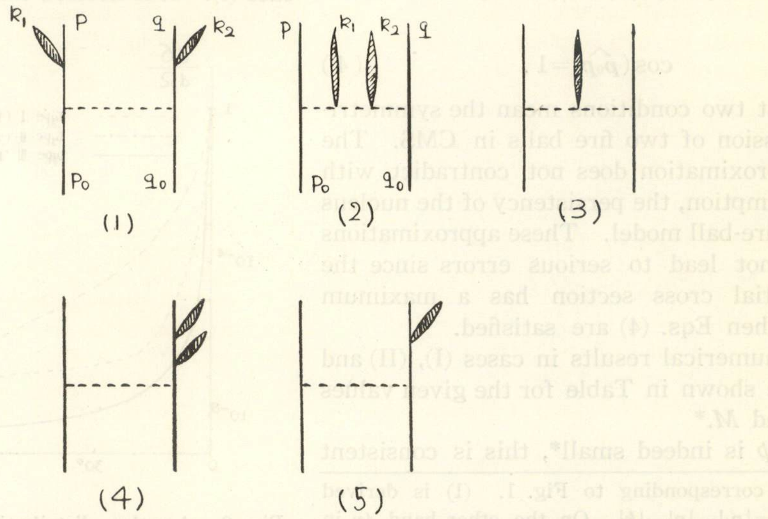

Fig. 1. We employ the diagram (1) and (2), and diagram (3), (4) and (5) are omitted.

Table I. Various quantities calculated.

E_0 (GeV)	M^* (GeV)	Type	α	K	$\bar{\gamma}$	Δp (GeV/c)	k_T (MeV/c)
50	2	I (S)	14	.91	23	.13	
		I (PS)	13	.71	18	.08	
	7.5	I (S)	7.1	.85	5.7	.72	0.1
		I (PS)	6.4	.74	4.7	.79	
300	2	I (S)	17	.98	150	.08	
		I (PS)	16	.40	60	.02	
	7.5	I (S)	15	.96	38	.13	
		I (PS)	15	.61	24	.16	
50	7.5	II	7.1	.26	1.8	.29	230
300	7.5	II	8.9	.25	10	.27	8
100	1	III	9	.5	50	.66	500

E_0: Initial nucleon energy in CMS.
M^*: The mass of a fire ball.
α: The sharpness of the angular distribution of fire ball defined by Eq. (5).
K: The mean value of inelasticity.
$\bar{\gamma}$: The mean value of Lorentz factor of fire ball in CMS.
Δp: The mean value of the transfer momentum between two nucleons in CMS.
k_T: The mean value of the transverse momentum of fire ball.

We omitted the diagrams shown in Fig. 1. (3) (4) (5) and of many fire-ball production. The results of our calculation give the rough information about a kind of apparent four center jets, among which two centers are emitted via excited final nucleons such as 3-3 resonance.

5. In order to obtain the numerical results we must integrate the phase volume of four particles in the final state. Since this is complicated we make the following approximations,

$$k_1+k_2=0\,,\quad M_1^*=M_2^*$$

and

$$\cos(\widehat{p_0 p})=1\,. \tag{4}$$

The first two conditions mean the symmetrical emission of two fire balls in CMS. The last approximation does not contradict with the assumption, the persistency of the nucleus in the fire-ball model. These approximations would not lead to serious errors since the differential cross section has a maximum value when Eqs. (4) are satisfied.

The numerical results in cases (I), (II) and (III) are shown in Table for the given values of E_0 and M^*.

(1) Δp is indeed small*, this is consistent with one of our assumptions.

(2) The angular distribution of fire balls has very sharp peaks in the forward and backward directions in CMS (see Fig. 2). In order to represent the sharpness of this distribution we define α as

$$10^\alpha=\frac{d\sigma/d\Omega(\theta_M{}^*=0°)}{d\sigma/d\Omega(\theta_M{}^*=90°)}\,. \tag{5}$$

And the α values are shown in Table.

(3) The transverse momenta of the fire balls (k_T) are actually small. k_T in cases (II) and (III), however, are larger than that in case (I). It is noticed that k_T values tabulated

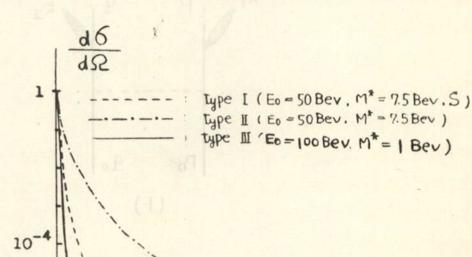

Fig. 2. Angular distribution of fire ball where the maximum values are normalized to unity.

* Δp corresponding to Fig. 1. (1) is derived from $\Delta p=|p_0|-|p|-|k|$. On the other hand Δp in Fig. 1. (2) is given by $\Delta p=\sqrt{(p_0-p)^2-(E_0-E_p)^2}$.

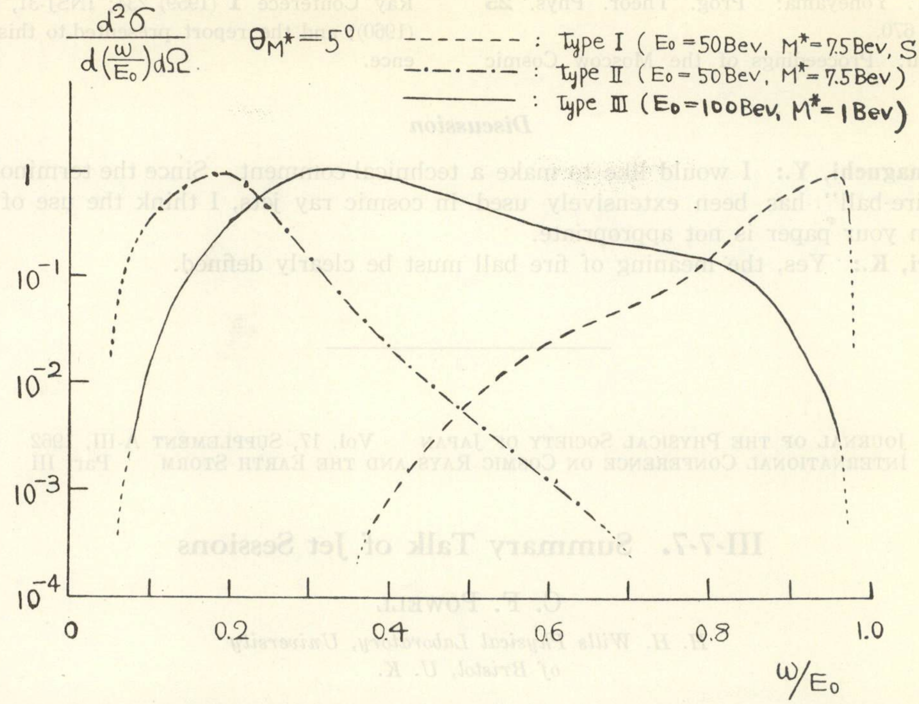

Fig. 3. Energy distribution of fire ball when the emitted angle θ_M^* is fixed. The maximum values are normalized to unity.

are underestimated because of the last assumption in Eq. (4).

(4) The Lorentz factors of the fire balls in CMS ($\bar{\gamma}$) and the inelasticity coefficients (K) are generally larger than the observed values. Especially in scalar boson cases of (I), K is nearly unity.

(5) The energy distributions of the fire balls in some cases are shown in Fig. 3.

(6) All cases calculated here satisfy the relation (1).

(7) In case (I) it is found that the multiplicity is nearly proportional to $(m/\gamma_c^{1.5})^{-0.5}$, where m means the parameter which characterizes the angular distribution of the secondary particles in CMS by $\cos^m \theta_s d(\cos \theta_s)$. This relation is not inconsistent with experimental data[5].

6. No serious discrepancy between our results and the experimental data is found except the $\bar{\gamma}$ values. If we introduce a phenomenological form factor to the boson vertex and cut off the high momentum of the boson, we could explain the experimental data along the idea developed in this report. Then our approach in which the strongly correlated particles are regrouped into a heavy boson seems to become a useful tool for the investigation on the high energy jets. Finally we have some speculation with respect to Δp. If Δp distribution has such broad maximum around 1 GeV/c as was shown by Niu[6], its maximum may be due to a vector (or pseudovector) boson having mass of the order of 1 GeV. The process corresponding to case (III) has not so small cross section even when one of internal lines is substituted by the above mentioned vector (or pseudovector) boson.

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Discussion

Yamaguchi, Y.: I would like to make a technical comment. Since the terminology of "fire-ball" has been extensively used in cosmic ray jets, I think the use of fire ball in your paper is not appropriate.

Mori, K.: Yes, the meaning of fire ball must be clearly defined.

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III-7-7. Summary Talk of Jet Sessions

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I want to attempt to describe very briefly some of the main features of high energy nuclear interactions, in so far as we have been able to elucidate them in the discussions on 'jets' during the past three days. If I make a mistake, some colleagues here will be kind enough to correct me.

I believe that one of the most important results of our discussions has been that we begin to see substantial progress in the very difficult field of high energy nuclear interactions. For a long time we have been very unsure of the energy of the primary particles which produce the interactions we observe in our expansion chambers or emulsions. We have been forced to use estimates that we knew to be rather unreliable. In particular, we have commonly assumed that in nucleon-nucleon collisions there is a forward-backward symmetry in the C-system of the collision, so that as many particles are emitted forward as backward. Under this assumption, we estimated the velocity of the C-system, and thence the primary energy. We knew this procedure was unreliable for several reasons; the number of secondary particles is small and we observe only the charged and not the neutral particles; and we are often dealing with collisions which are not between two nucleons but which involve a proton and a heavier nucleus. We also knew that, apart from statistical fluctuations, if there is any structure in a nucleon, the assumption of fore and aft symmetry, may break down in individual collisions; and that only for a statistically significant sample can we firmly rely upon a true forward and backward symmetry. So, we have been on very uncertain ground.

We are now beginning to get out of this difficult situation through the introduction of more powerful methods. First there are the pioneer experiments made in Moscow with what is called the ionization calorimeter. This apparatus allows the observation of the effects of collisions of the primary protons with light nuclei, lithium and protons, and the measurement of the momentum of the charged secondary particles thus produced in an expansion chamber. Secondly, the energy of the primary particle may also be estimated from the total release of ionization in a great assembly of lead and counters, the calorimeter. This has proved to be a very important instrument. As we have heard, the results obtained with it already demonstrate that, in proton-proton collisions, the secondary particles are not always distributed with fore and aft symmetry in the C-system. In about half of the collisions there is such a