Four-momentum transfer between fireballs in proton-nucleus interactions at 400 GeV

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In 400-GeV proton-nucleus interactions, the fireball candidates are defined by employing three methods (Duller-Walker plot, target plot, and Berger's criterion) simultaneously on each individual event. The lower limit of four-momentum transfer (q_l) between the fireballs is studied. The value of q_l is found to increase with secondary particle multiplicity. The q_l distribution favors the exchange of heavy mesons such as the f meson between the fireballs.

I. INTRODUCTION

It was observed in the early stages of the development of high-energy physics that some characteristics of high-energy interactions, such as multiplicity, angular distribution, and inelasticity, varied from event to event even though the primary energy and the target were kept the same. This situation seemed to suggest that, apart from the incident energy, there must be at least one more parameter which determined the outcome of an interaction and also that the above characteristics might be a more complicated function of at least two independent variables including incident energy. Although the immediate choice was the impact parameter, it was difficult to estimate its magnitude from the experimentally observable parameters. This prompted Niu[1] to propose a new parameter, momentum of interaction, which he defined for the restricted case of forward and backward symmetry in center-of-mass system. A more general version of this parameter, which includes the asymmetrical case also, is the four-momentum transfer. This represents the magnitude of the effect of the collision and strongly reflects the dynamics of high-energy interaction process. The fact that this parameter is a Lorentz-invariant quantity and that it can be easily obtained from experiment further enhances its importance as a tool for probing the mechanism of multiparticle production.

Niu[1] observed a value ~ 1 GeV/c, for the average longitudinal component of the four-momentum transfer, $\langle q_l \rangle$, between two fireballs. Kobayakawa and Nishikawa[2] obtained $\langle q_l \rangle = 1.27\pm0.1$ GeV/c with a distribution suggesting a heavier boson and nucleon-antinucleon pair instead of pion as the particle exchanged between the fireballs. Shivpuri and Jain[3] on the other hand have reported the q_l distribution favoring a Pomeranchuk pole exchange. The above investigations were done on cosmic-ray interactions and suffered from the usual limitations such as low statistics and uncertainty in the primary energy of cosmic rays. More recently, Daftari *et al.*[4] have investigated the four-momentum transfer between two groups of secondary particles in proton-emulsion nucleus interactions at 200 GeV and obtained a distribution supporting the Pomeranchuk-pole-exchange model with $\langle q_l \rangle = 1.89\pm0.15$ GeV/c.

The present work is undertaken to study the four-momentum transfer between two fireballs in proton–emulsion-nucleus interactions at 400 GeV, with special emphasis on determining the nature of the particle exchanged between the fireballs and also to investigate the correlation between q_l and the shower particle multiplicity. Most of the earlier works[3,4] depended only on the Duller-Walker (DW) plot[5] for determining the number of fireballs and for estimating the number of particles into which a fireball decays. There are several competing mechanisms[6] for particle production such as the isobar formation and the directly produced particles. Following the DW plot only to isolate the particles belonging to a fireball, introduces an uncertainty which is nontrivial. There is nothing to preclude the particles produced through other mechanisms from lying on the same line in the DW plot. They will be wrongly assumed to belong to the same fireball and their contributions cannot be eliminated. This will give rise to incorrect values of fireball parameters. In order to avoid this uncertainty, in this paper we have employed the DW plot, the target plot,[7] and Berger's criterion[8] simultaneously for an interaction to identify the particles resulting from the decay of a fireball. It is well known that particles belonging to a fireball lie approximately on a straight line in the DW plot[5,9,10] and form a cluster of points in the target plot. Although there is a finite probability for the particles produced by other processes and thus unrelated to the fireball to lie on the straight line or within the cluster of points, the chances of such particles lying on a straight line also falling within the cluster in the target plot (and vice versa) and also satisfying the Berger's criterion are very low. Hence, we can assume that the particles related to the fireballs can be identified with very low uncertainty employing the above methods. The isotropic emission of particles in the fireball system stipulates a slope of 2 for the straight line in the DW plot. Fluctuations in the value of the slope can occur due to the following reasons.

(1) The low multiplicity of the fireball-decay particles is likely to impair the isotropy.

(2) The data for this paper are from p-nucleus interactions in composite emulsion with the light (H, C, N, O) as well as the heavy (Ag, Br) target nuclei. Since the fireballs are supposed[1,11] to be slower bodies (compared

to the persisting nucleons) which decay in flight instantaneously, there is a high probability of the decay taking place inside the nucleus at least in the case of heavier target nuclei such as Ag and Br. In such cases it is reasonable to expect nuclear space-time effects on the decay products. This effect may result in disturbing the configuration of the particles while retaining the observed features of strong correlations between them.

In view of the above factors, a slope of 2 is not insisted upon. Besides fluctuations in the values of slope there might be distortion of linearity in the DW plot on account of the same factors. In fact, when fitted to straight line the values of the slope are found to vary between 1 and 4 in this work. The deviations from the value of 2 for slope have also been reported by Hasegawa.[9] Cocconi[10] is also of the view that a slope of 2 cannot be insisted when the multiplicity of the fireball-decay particles is low. The criteria followed in this paper for identifying the particles resulting from fireball decay are given below.

(1) The points corresponding to the particles have to lie on an approximately linear segment with a slope of 2^{+2}_{-1} in the DW plot. The particles resulting from a fireball or cluster are closely spaced in pseudorapidity $(-\ln \tan\theta/2)$ due to strong correlations between them. Hence they tend to aggregate along approximately a linear branch in the DW plot.

(2) The particles have to form a bunch of points closely spaced in the target plot for the following reasons: First, the existence of strong correlations between the particles constrains them to be closely spaced and second, the tendency of the particles to follow the direction of the fireball due to its large longitudinal momentum. The effect of both these factors is to restrict the particles to form a cluster in the azimuthal plane.

(3) The particles have to satisfy Berger's[8] criterion for the formation of a cluster.

Only those particles which satisfy all the above criteria simultaneously are grouped (target plot) as belonging to a fireball. No quantitative definition of a bunch is attempted in this paper.

Out of the 186 interactions examined, 104 turned out to be two fireball candidates. Taking $\langle p_t \rangle$ to be $=0.3$ GeV/c, the value of $\langle q_l \rangle = 1.5 \pm 0.15$ GeV/c is obtained with a distribution that favors the Dremin and Chernavsky[12] (DC) model with a heavy meson such as the f meson as the exchanged particle instead of a pion. The longitudinal component of the four-momentum transfer q_l has been found to show an increasing tendency with the shower-particle multiplicity N_s.

II. EXPERIMENTAL DETAILS

A stack of G5 nuclear-emulsion pellicles each of size $15 \times 10 \times 0.06$ cm^3 and exposed to 400-GeV protons at Fermilab was area scanned for primary interactions. Care was taken to exclude interactions lying within the top or bottom 20 μm thickness of the emulsion and also those with the beam tracks making angles $> 3°$ with the mean beam direction. The interactions resulting from the secondaries of other interactions were avoided by following the beam track up to the leading edge of the pellicle. While area scanning of the events only those interactions lying beyond 1 cm from the edge of the pellicle were picked up. A total of 2031 events were obtained by area scanning and the angle measurements were done on all these interactions. Following the usual nomenclature[13] for classifying the secondary particles, tracks having ionization $< 1.4 I_{\min}$ were called shower tracks (N_s), tracks having ionization $> 1.4 I_{\min}$ but less than $10 I_{\min}$ were termed grey tracks (N_g) while those with ionization $> 10 I_{\min}$ were called black tracks (N_b), where $I_{\min}$ is the ionization of the primary. The total number of black and grey tracks is equal to the number of heavily ionizing tracks (N_h). The space and azimuthal angles of the shower particles were measured by the coordinate method. For this the coordinates at the vertex of the interaction and of two points on each shower track including the beam have been measured. The number of events randomly selected for analysis in this paper is 186, whose values of $N_s = 13-28$. The contributions of shower tracks with the smallest and the largest emission angles were excluded in the distributions, as these are assumed to be because of the persisting nucleons.

III. METHODS USED FOR IDENTIFICATION OF FIREBALLS

(a) The Duller-Walker plot (DW plot). Figure 1 shows the DW plot ($\log_{10}[F/(1-F)]$ vs $\log_{10}\tan\theta$) for some of the typical interactions, where F denotes the fraction of the number of particles lying within the laboratory angle θ. Some of the points lying outside the figure have not been shown. The secondary particles produced via fire-

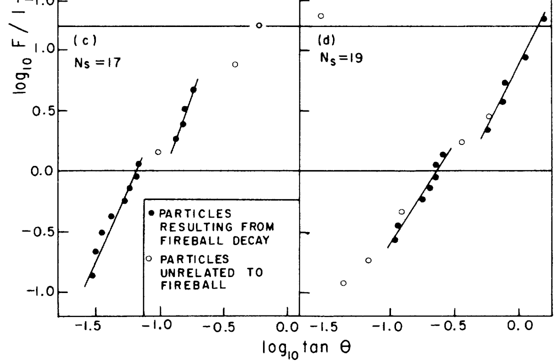

FIG. 1. Duller-Walker plots for some of the typical interactions.

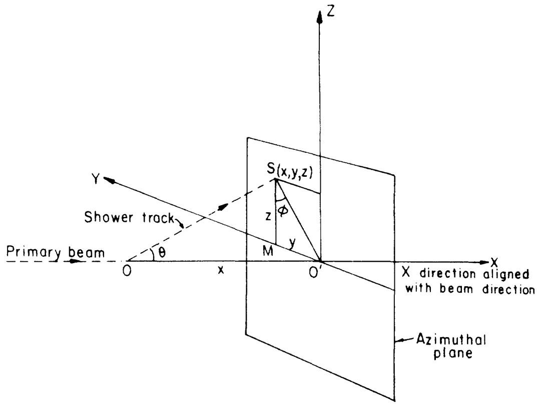

FIG. 2. The schematics of a primary particle interacting with a nucleus and producing a shower track. O is the vertex of the interaction taken as the origin.

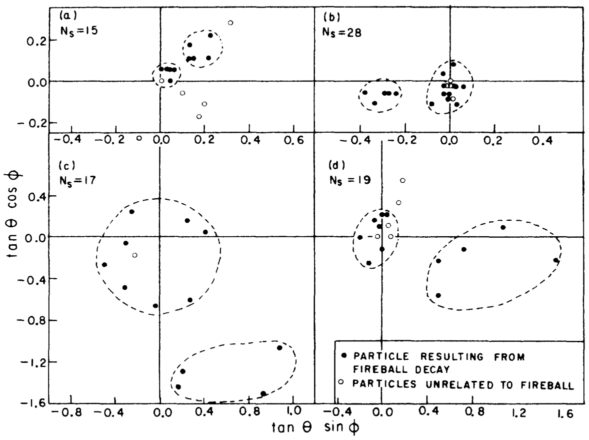

FIG. 3. The target plots for the same interactions as those of Fig. 1.

ball decay will have their emission angles close to each other. Hence the corresponding points in the DW plot will aggregate nearly along a straight line. If the fireball decays isotropically[5] then the straight line will have a slope 2. Heisenberg,[14] Fermi,[15] and Landau[16] predicted lower values for the slope. While the distribution of particles predicted by Heisenberg[14] gives a straight line, those predicted by Fermi[15] and Landau[16] lead to plots that are approximately linear. Particle production via the disintegration of two fireballs (or clusters) is distinguished[10] by the presence of two branches in the DW plot, each approximately a straight line and separated in $\log_{10}\tan\theta$ space. Particles resulting from processes other than fireball decay, generally lie scattered away from the straight lines in the plot.

(b) The target plot. Figure 2 shows the schematics of a primary particle interacting at 0, producing a shower track which hits at S on the azimuthal plane. The coordinates of S are x, $y=x\tan\theta\sin\phi$, and $z=x\tan\theta\cos\phi$, if we take the vertex of the interaction as the origin. The decay products of a fireball are known[7] to form a cluster of such points in the azimuthal plane since they are centered around the direction of flight of the fireball and have strong correlations between them. A plot in the azimuthal plane of such points for all the particles of an interaction can be done by taking the y and z coordinates, respectively, proportional to $\tan\theta\sin\phi$ and $\tan\theta\cos\phi$. Such a plot is known as the target plot which is shown for some interactions in Fig. 3. The interactions chosen here are the same as those in Fig. 1, in order to investigate the correspondence between DW and target plot. In the target plot there would be as many bunches of points as the number of fireballs in the interaction; the points corresponding to particles unrelated to the fireballs being scattered outside the bunches in most cases. In a bunch, although there might be some particles unrelated to the fireball, it is quite unlikely that such particles will lie on the same branch in the DW plot also, since such unrelated particles having both θ and ϕ matching with those of the decay products of a fireball can be assumed improbable for simplicity.

(c) Berger's criterion. The clustering of particles in rapidity space is characteristic of the decay products of a fireball because of strong correlations among the particles. As a quantitative measure of this, Berger, Fox, and Krzywicki[8] have defined a dispersion parameter δ, given by

$$\delta=\left[\frac{1}{N-1}\sum_{i=1}^{N}(\bar{Y}-Y_i)^2\right]^{1/2},$$

where N is the number of charged particles into which a fireball (or a cluster) disintegrates, $\bar{Y}$ is the mean rapidity of N particles, and Y_i the rapidity of the ith particle. They suggested, that a value of $\delta\leq 0.9$, corresponds to an isotropically decaying cluster or fireball.

After plotting both the DW plot and the target plot (Figs. 1 and 3) for individual interactions, each fireball

TABLE I. Number of interactions containing two, one, and zero fireball (FB) candidates and percentage of two fireball candidates for different N_h regions.

N_h	Number of interactions examined	Two FB candidates	One FB candidates	Zero FB candidates	Percentage two FB candidates
$N_h\leq 1$	26	13	2	11	50 ±14
$2\leq N_h\leq 5$	46	26	8	12	56.5±11
$N_h\geq 9$	88	50	11	27	56.8±8
All N_h	186	104	22	60	55.9±5.5

candidate was then subjected to Berger's criterion test. The number of particles associated with a fireball was decided only after all the above three criteria were satisfied. For instance, the grouping of particles (solid circles) in the target plot as belonging to a fireball, is based on the assumption that they (1) form a bunch, (2) lie on a linear segment in the DW plot, and (3) satisfy Berger's criterion. The results are given in Table I.

IV. THE ESTIMATION OF THE FOUR-MOMENTUM TRANSFER

The four-momentum transfer between two interacting objects can be best understood if we divide the collision into two parts—one on the side of the incident particle and the other on the target side. If $(\mathbf{P}_{10},E_{10})$ and $(\mathbf{P}_{20},E_{20})$ are the four-momenta of the initial interacting particles, and $(\mathbf{P}_1,E_1)$ and $(\mathbf{P}_2,E_2)$ their four-momenta after collision, respectively, the following relations relating the four-momentum transfer $(\Delta\mathbf{P},\Delta E)$ between the two parts are necessitated by the overall energy-momentum conservation:[17]

$$\Delta\mathbf{P}=\mathbf{P}_{10}-\mathbf{P}_1-\sum_1 \mathbf{P}_i , \quad -\Delta\mathbf{P}=\mathbf{P}_{20}-\mathbf{P}_2-\sum_2 \mathbf{P}_j ,$$

$$\Delta E=E_{10}-E_1-\sum_1 \epsilon_i , \quad \Delta E=E_{20}-E_2-\sum_2 \epsilon_j ,$$

where $(\mathbf{p}_i,\epsilon_i)$ and $(\mathbf{p}_j,\epsilon_j)$ are the four-momenta of the produced pions in the two parts. If $\Delta\mathbf{P}_t$ and $\Delta\mathbf{P}_1$ are the transverse and longitudinal components of $\Delta\mathbf{P}$, then the squared four-momentum transfer (q^2) between the two parts will be given by

$$q^2=(\Delta P_t)^2+(\Delta P_1)^2-(\Delta E)^2 . \tag{1}$$

The longitudinal components of the four-momentum transfer (q_l) is defined as

$$q_l^2=(\Delta P_1)^2-(\Delta E)^2 . \tag{2}$$

It has been shown[16,9] that if one assumes that the transverse momenta (p_t) of the produced pions are small and nearly constant, Eq. (2) can be reduced to the following form:

$$q_l^2=\langle p_t\rangle^2 \left[\sum_1 \tan\theta_i\right]\left[\sum_2 \cot\theta_j\right] , \tag{3}$$

where θ_i and θ_j are the emission angles in the laboratory system of the pions in the two parts. In arriving at Eq. (3), terms of higher order in transverse momenta and masses of pions have been neglected and since q_l^2 is always $\leq q^2$, this equation gives only a lower value of the squared four-momentum transfer.

The squared four-momentum transfer between two fireballs can be directly written from Eq. (1) as

$$q^2=(P_f-P_b)^2-(E_f-E_b)^2 , \tag{4}$$

where P_f,E_f and P_b,E_b are the momenta and energy of the forward and backward fireballs, respectively. With θ_i and θ_j representing, respectively, the emission angles of the decay products of the two fireballs, Eq. (3) gives the longitudinal component of the four-momentum transfer between them. It is to be noted that in the formulation of Eq. (3) only the charged pions were considered. Due allowance to the presence of neutral pions is made by multiplying the right-hand side of Eq. (3) by $(1.5)^2$. Thus

$$q_l^2=(1.5)^2\langle p_t\rangle^2 \left[\sum_1 \tan\theta_i\right]\left[\sum_2 \cot\theta_j\right] . \tag{5}$$

This affords us an easy means of calculating q_l as it involves only the emission angles of the pions in the laboratory system which can be easily measured for individual pions.

V. RESULTS AND DISCUSSION

Table I shows the analysis of 186 interactions for fireball candidates for different N_h categories. As is usual in emulsion experiments[11] the three N_h categories of interactions, viz., $N_h \leq 1$, $2 \leq N_h \leq 5$, and $N_h \geq 9$ can be regarded as belonging to nucleon, CNO, and AgBr targets, respectively. In order to ensure a higher percentage of light-nucleus interactions in the sample, events with $N_h=6$, 7, and 8 have not been taken into account since such events could also come from collisions with heavy nuclei. It is clear from Table I that the percentage of two fireball candidates does not vary with the target mass. This supports an idea that the fireballs are produced in elementary hadron-hadron collisions and the rest of the nucleons in the target nucleus remain spectators during the collision.

In Table II there are given values of average q_l corresponding to the different shower particle multiplicities along with the average number of particles associated with the forward and backward fireballs. The shower multiplicity corresponding to forward and backward fireballs is denoted by $N_s f$ and $N_s b$, respectively. The average number of particles into which a fireball decays is obtained as 5.8 ± 0.4. Taking the value of $\langle p_t\rangle=0.3$

TABLE II. Values of multiplicity, shower multiplicity corresponding to forward and backward fireballs, and the corresponding mean value of q_l.

N_s	$N_s f$	$N_s b$	$\langle q_l\rangle$
13	4.2	3.9	0.981
14	4.0	4.8	1.053
15	4.8	4.0	1.116
16	5.1	4.7	1.286
17	6.4	5.0	1.589
18	6.3	4.4	1.384
19	6.9	5.5	1.540
20	7.6	5.1	1.651
21	5.8	6.8	1.484
22	6.9	4.9	1.498
23	6.0	5.5	1.615
24	6.7	6.0	1.645
25	7.3	6.9	1.756
26	6.6	6.2	1.998
27	7	8.3	1.770
28	7.2	6.8	1.68

GeV/c, the average value of the lower limit of the four-momentum transfer, $\langle q_l \rangle$, for all the two fireball candidates is found to be 1.50 ± 0.15 GeV/c.

Our value of the average number of particles into which a fireball decays agrees with Frautschi's[11] prediction that a fireball decays into about six pions on an average. Figure 4 clearly suggests a correlation between q_l and N_s; the former showing an increasing tendency with the latter. This is also seen from Table II. This behavior of q_l can be well explained by regarding the reciprocal of the four-momentum transfer as a measure of the impact parameter in the collision. Since, for a given primary energy, a central collision produces more particles than a peripheral one and the smaller the impact parameter the greater the centrality of collision, the increase of N_s with q_l then follows as a logical consequence.

The distribution of q_l (Fig. 5) is observed to be moderately wide with a peak at $q_l = 1.4$ GeV/c. To find the particle exchanged between the two fireballs, a fit of our distribution with models such as the Pomeranchuk-pole-exchange model, multiperipheral model, and Dremin and Chernavsky (DC) model was tried. It was observed that neither the multiperipheral model where a pion is exchanged between the interacting partners nor the Pomeranchuk-pole-exchange model agrees with our distribution. On the other hand, a reasonably good fit is observed with the DC model[12,2] in which the exchanged pion is replaced by an f meson of mass 1.264 GeV. The distribution predicted by this model is

$$f(q_l)dq_l \propto q_l^5 (q_l^2 + m_B^2)^{-2} \exp(-a' q_l^2) dq_l \ ,$$

where m_B is the rest mass of the exchanged particle and a' is given by

$$a' = \frac{1}{2} \frac{\tilde{q}_l^2 + 5 m_B^2}{\tilde{q}_l^4 + m_B^2 \tilde{q}_l^2} \ ,$$

where $\tilde{q}_l$ is the most probable value of q_l which is easily obtained from the experimental distribution. The above distribution uses the approximation $q^2 \sim q_l^2$. In Fig. 5

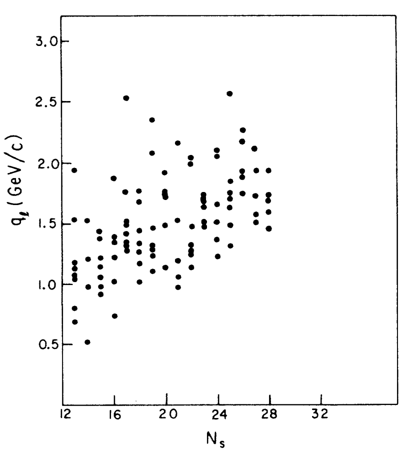

FIG. 4. The correlation of q_l with shower-particle multiplicity.

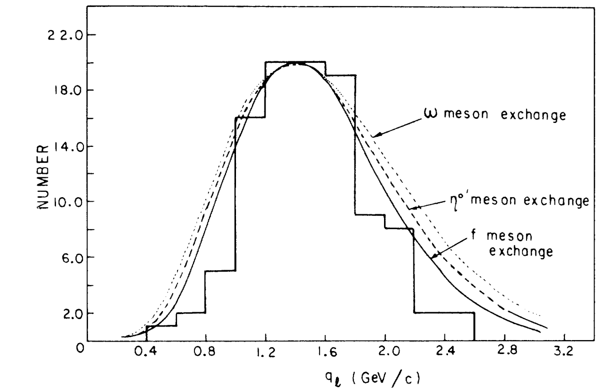

FIG. 5. The experimental q_l distribution. The curves represent the predictions of the Dremin and Chernavsky model assuming the exchange of f meson, ω meson, and $\eta^{0'}$ meson between the two fireball vertices.

our experimental q_l distribution is shown along with those predicted by the DC model. While the solid curve is for the f meson as the exchange particle, the broken and the dotted curves are for $\eta^{0'}$-meson and ω-meson exchange, respectively. The value of χ^2/DF is $=0.93$, 1.40, and 1.68 for the solid, broken, and dotted curves, respectively. It is obvious that the experimental q_l distribution is consistent with the DC model which exchanges heavy mesons such as the f meson.

The multiperipheral model[18] predicts for $\langle q_l \rangle$ a much lower value which is of the order of magnitude of pion mass. This follows from the notion that it is the excitation of the outer pion cloud of the colliding nucleons that is responsible for the multiparticle production. The studies of four-momentum transfer between fireballs by earlier workers[2,3] have favored the exchange of particles much heavier than pions. As already pointed out, our study favors the DC model with the f-meson exchange. To explain this exchange of heavier boson between fireballs, we use the linked-heavy-particle model.[19,20] According to this model the nucleon is composed of a central core of a nucleon-antinucleon pair which is covered with heavy meson layers and the outer pion clouds. In any high-energy collision between nucleons, the pion cloud plays only a secondary role of transmitting the impact of the collision into the inner heavy-meson clouds. It is the excitation of this inner cloud which dominates the multiparticle production process. The production of a number of fireballs through heavy-particle links is an extension of this idea. We feel that incorporating this idea and, hence, replacing the pion in Dremin and Chernavsky model by heavy particles such as the f meson as the exchanged particle, explains our experimental four-momentum-transfer distribution as well as the high value of $\langle q_l \rangle$.

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[1]K. Niu, Nuovo Cimento **10**, 994 (1958).

[2]Keizo Kobayakawa and Kiyoshi Nishikawa, Suppl. Prog. Theor. Phys. **33**, 55 (1965).

[3]R. K. Shivpuri and P. L. Jain, Lett. Nuovo Cimento **3**, 535 (1970); Nuovo Cimento **70A**, 632 (1970).

[4]I. K. Daftari *et al.*, Phys. Rev. D **23**, 14 (1981).

[5]N. M. Duller and W. D. Walker, Phys. Rev. **93**, 215 (1954).

[6]K. Imaeda *et al.*, Suppl. Nuovo Cimento **1**, 1197 (1962).

[7]A. G. Agnese and A. Wataghin, Nuovo Cimento **5A**, 1 (1971); **13A**, 144 (1973). S. K. Kaul and S. Singh, Ind. J. Pure Appl. Phys. **13**, 520 (1975).

[8]E. L. Berger, G. C. Fox, and A. Krzywicki, Phys. Lett. **43B**, 132 (1973).

[9]S. Hasegawa, Prog. Theor. Phys. **29**, 128 (1963).

[10]G. Cocconi, Phys. Rev. **3**, 1699 (1958).

[11]S. C. Frautschi, Nuovo Cimento **28**, 409 (1958).

[12]I. M. Dremin and D. S. Chernavsky, Yad. Fiz. **16**, 394 (1963) [Sov. Phys. JETP **16**, 394 (1963)].

[13]Chandra Gupt, R. K. Shivpuri, N. S. Verma, and A. P. Sharma, Phys. Rev. D **26**, 2202 (1982).

[14]L. Von Lindern, Nuovo Cimento **5**, 491 (1957).

[15]E. Fermi, Phys. Rev. **81**, 683 (1951).

[16]S. Z. Belenki and L. D. Landau, Suppl. Nuovo Cimento **3**, 15 (1956).

[17]G. Fujioka *et al.*, Suppl. Nuovo Cimento **1**, 1143 (1963).

[18]D. Amati *et al.*, Nuovo Cimento **26**, 896 (1962).

[19]T. Kobayashi, M. Namiki, and T. Ohba, Prog. Theor. Phys. **31**, 840 (1964).

[20]T. Kobayashi and M. Namiki, Suppl. Prog. Theor. Phys. **33**, 1 (1965).