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Charge multiplicity in e^+e^- annihilation and the multiple production of charmonium states

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Multiple production of charmonium states will increase the average charge multiplicity in e^+e^- annihilation considerably, and may simulate multijet events. The process is analyzed by using the multiperipheral production mechanism. The measurement of inclusively produced charmonium states is urged in order to justify the discovery of gluons in e^+e^- annihilation.

The average charge multiplicity of the process of e^+e^- annihilation into hadrons has been measured over a wide range of center-of-mass energies.[1] The average charge multiplicity in e^+e^- annihilation is larger than in pp collisions; the difference seems to increase when the center-of-mass energy increases above 10 GeV. In this paper it is pointed out that the multiple production of charmonium states is not suppressed in e^+e^- annihilation and will contribute to the rapid increase of the average charge multiplicity at high energies. The possibility that multijet events will be simulated by the multiple production of charmonium states and their successive decays is discussed at the end of this paper.

Various features of the hadron-production process in e^+e^- annihilation resemble those in pp collisions. For example, the average charge multiplicity and the average transverse momentum of hadrons increase with energy in both reactions; the invariant inclusive spectrum of charged hadrons, when normalized by the total cross section, expands in rapidity space, and its central plateau rises as the center-of-mass energy increases in both reactions. Therefore the multiperipheral production mechanism,[2] which is widely used in analyzing the multiple-hadron-production phenomena of high-energy hadron-hadron collicions, will be used in this paper for the description of multiple-hadron production in e^+e^- annihilation. One of the properties of the multiperipheral production mechanism that is very relevant to the discussion here is that the average charge multiplicity grows like

$$\langle n_{\mathrm{ch}}\rangle = a + b\ln s\,, \tag{1}$$

where $s \equiv E_{\mathrm{c.m.}}{}^2$. The above formula is derived from the property of the multiperipheral production mechanism that the final-state hadrons are emitted one by one in rapidity space with approximately constant rapidity gap, and from the fact that the available rapidity phase space is expanding in proportion to $\ln s$. However, when particles are emitted as a cluster from the multiperipheral chain instead of as individual particles, additional terms need to be added to the right-hand side of Eq. (1). The phenomena of clustering is observed in high-energy hadron-hadron collisions; the average charge multiplicity in pp collisions can be parametrized as[3]

$$f_{pp}(s) \equiv \langle n_{\mathrm{ch}}\rangle_{pp} = 0.88 + 0.44\,(\ln s) + 0.118\,(\ln s)^2\,. \tag{2}$$

The multihadron-production process in e^+e^- annihilation can be classified into two categories, the standard production process and the multiple production of $c\bar{c}$ (or $b\bar{b}$) states. The standard production process in e^+e^- annihilation is represented schematically in Fig.1, where dotted lines represent ordinary quarks (u, d, or s) and solid lines represent heavy quarks (c or b). The objects labeled $1, 2, \ldots, n$ in Fig. 1 represent ordinary hadrons or clusters of ordinary hadrons, and the object denoted as A_ξ ($\bar{A}_\xi$) represents a hadron or a cluster of hadrons with nonzero c ($\bar{c}$) or b ($\bar{b}$) quantum number. The diagrams of Fig. 1 can be interpreted either as dual unitarity diagrams,[4] or as diagrams in which the timelike photon γ^* creates the $q\bar{q}$ quark pair and then the multiperipheral-type hadronization process follows. The question of whether they are dual diagrams or naive-parton-model diagrams is irrelevant to the discussion in this paper. The cross

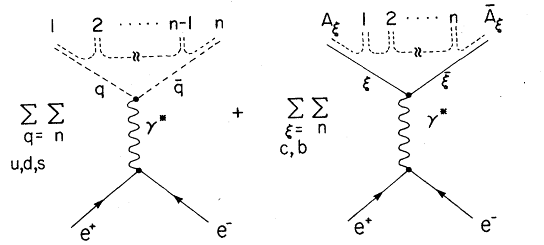

FIG. 1. The standard multiperipheral process for producing hadrons in e^+e^- annihilation. Dotted lines represent u, d, or s quarks and the solid lines denoted as ξ or $\bar{\xi}$ represent heavy c, b quarks or antiquarks. The objects labeled as $1,2,\ldots,n$ are ordinary hadrons or clusters of ordinary hadrons. The object denoted as A_ξ is a ξ-flavored hadron or hadron cluster.

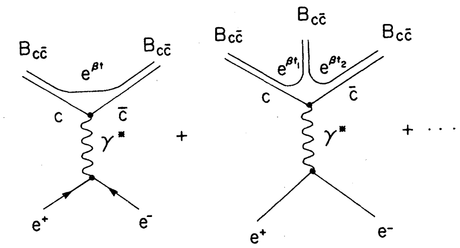

FIG. 2. The multiperipheral process for producing many charmonium states. $B_{c\bar{c}}$ represents a charmonium state. The factors $\exp(\beta t_i)$ represent four-momentum-transfer damping of the multiperipheral propagators.

section for producing m charged hadrons in the standard production process is denoted by $\sigma_0^m(s)$, and the average charge multiplicity of the standard production process is defined as

$$f_0(s) \equiv \sum_m m\sigma_0^m(s) \Big/ \sum_m \sigma_0^m(s)\,. \tag{3}$$

The multiperipheral mechanism for producing ordinary hadrons in the standard production process of e^+e^- annihilation is assumed to be very similar to the multiperipheral mechanism for producing hadrons in pp collisions. Of course, the features in the fragmentation regions of e^+e^- annihilation should be different from those of pp collisions; the difference in the fragmentation regions effects only the values of the constant a in Eq. (1). Therefore, $f_0(s)$ of Eq. (3) can be written as

$$f_0(s) = f_{pp}(s) + d\,, \quad d \approx 1.0 \tag{4}$$

where the value of d is determined by comparing $f_{pp}(s)$ of Eq. (2) with the data[1] of the average charge multiplicity in e^+e^- annihilation below the production threshold of two charmonium states.

The multiple production of charmonium states according to the multiperipheral mechanism is represented schematically in Fig. 2, where solid lines represent charmed quarks and $B_{c\bar{c}}$ represents a charmonium state. The emission of ordinary hadrons from the multiperipheral chains in Fig. 2 is suppressed by the Okubo-Zweig-Iizuka (OZI) selection rule.[5] It is worthwhile to note that the couplings of $c\bar{c}$ quark pairs to charmonium states are typical strong-interaction couplings with the same order of magnitude as the couplings of $q\bar{q}$ ($q = u, d$) quark pairs to ordinary vector mesons. Therefore, the multiple production of charmonium states is not suppressed in e^+e^- annihilation, though it is suppressed in pp collisions due to the OZI selection rule. It should also be noted that the cross section for producing multiple charmonium states still may be suppressed due to the heavy masses of the charmonium states if the available energy is not very large. The suppression of the production of heavy objects at not very large energies is a natural result of the multiperipheral mechanism,[6] because of the fast damping of the multiperipheral propagators as the corresponding four-momentum transfer increases. However, the suppression of the production of heavy-mass objects is only temporary in the multiperipheral model; the production cross sections will reach their full strength when the energy becomes sufficiently large. For example, at the energies not very far from the threshold the first diagram of Fig. 2 is suppressed because of the peripheral nature of the diagram, but the suppression disappears as the center-of-mass energy increases far above the threshold energy for producing two charmonium states.

The cross section for producing m charmonium states is denoted by $\sigma_1^m(s)$; the average multiplicity of charmonium states is defined as

$$f_c(s) \equiv \sum_m m\sigma_1^m(s) \Big/ \sum_m \sigma_1^m(s)\,. \tag{5}$$

According to the multiperipheral model, $f_c(s)$ can be expressed as

$$f_c(s) \approx \Delta_c^{-1}[2\ln(s/\langle m_{c\bar{c}}\rangle^2)]\,, \tag{6}$$

where Δ_c is the average rapidity gap of the multiperipheral production of charmonium states, and $\langle m_{c\bar{c}}\rangle$ is the average mass of the emitted charmonium states. The factor $2\ln(s/\langle m_{c\bar{c}}\rangle^2)$ in Eq. (6) is the available length of rapidity space. The clustering effect in the production of charmonium states is ignored in Eq. (6), though this clustering effect will be important at very high energies beyond the presently reachable energy. For such energies, more terms need to be added in the right-hand side of Eq. (6). The threshold factor $\alpha_c(s)$ for the production of heavy-mass charmonium states is defined as

$$\alpha_c(s) \equiv \sum_m \sigma_1^m(s)/\sigma_{c\bar{c}}(s), \tag{7}$$

where $\sigma_{c\bar{c}}$ is the cross section for producing a $c\bar{c}$ quark pair.

The ratio of the cross section for producing a $q\bar{q}$ quark pair to the total cross section of e^+e^- annihilation into hadrons is denoted by $\delta_q(s)$ ($q = u, d, s, c, b$). The average charge multiplicity of e^+e^- annihilation can be written as

$$\begin{aligned} F(s) \equiv \langle n_{\text{ch}} \rangle = \{&\delta_u(s) + \delta_d(s) + \delta_s(s) + \delta_b(s) \\ &+ \delta_c(s)[1 - \alpha_c(s)]\} f_0(s) \\ &+ \delta_c(s)\, \alpha_c(s) f_c(s) \langle n_{\text{ch}} \rangle_{c\bar{c}}, \end{aligned} \tag{8}$$

where $\langle n_{\text{ch}} \rangle_{c\bar{c}}$ is the average charge multiplicity from the decay of charmonium states. The multiple production of $b\bar{b}$ states and of $s\bar{s}$ states are ignored in Eq. (8), though the mechanism of these production processes is very similar to that of the multiple production of $c\bar{c}$ states. The multiple production of $b\bar{b}$ states is ignored because δ_b is small and because it should not be important in the currently accessible energy region, $E_{\text{c.m.}} \leq 40$ GeV. The multiple production of $s\bar{s}$ states is ignored due to the smallness of both δ_s and $\langle n_{\text{ch}} \rangle_{s\bar{s}}$ compared to δ_c and $\langle n_{\text{ch}} \rangle_{c\bar{c}}$.

The values of $F(s)$ in Eq. (8) are estimated as follows. The values of $\delta_q(s)$'s ($q = u, d, s, c, b$) are estimated from the naive parton model; they are $\delta_u + \delta_d + \delta_s = 0.6$, $\delta_b = 0$, and $\delta_c = 0.4$ for $E_{\text{c.m.}}$ below the $b\bar{b}$ threshold, and $\delta_u + \delta_d + \delta_s + \delta_b = \frac{7}{11}$ and $\delta_c = \frac{4}{11}$ for $E_{\text{c.m.}}$ above the $b\bar{b}$ threshold. The values $\langle m_{c\bar{c}} \rangle \approx 3.4$ GeV and $\Delta_c \approx 1$ are used in the estimate; $\langle n_{\text{ch}} \rangle_{c\bar{c}}$ is about 3.8.[7] The threshold factor $\alpha_c(s)$ of Eq. (7) is estimated by comparing with the computed increase of the cross section of the first diagram of Fig. 2, where an exponential damping function of four-momentum transfer, $\exp(\beta t)$, is used for computation. The result suggests that $\alpha_c(s)$ may be parametrized as

$$\alpha_c(s) = \alpha_0(e^{2\beta t_0} - e^{2\beta t_1}) \tag{9}$$

where

$$t_{0,1} = \langle m_{c\bar{c}} \rangle^2 + m_c^2 - \tfrac{1}{2}s \pm \tfrac{1}{2}[(s - 4\langle m_{c\bar{c}} \rangle^2)(s - 4m_c^2)]^{1/2}$$

with + and − signs for t_0 and t_1, respectively, and m_c is the mass of charmed quarks that is taken to be about 1.6 GeV. The factor α_0 determines the fraction of $\sigma_{c\bar{c}}$ that is due to the multiple production of charmonium states when $s \to \infty$; the value of β controls the speed of increase of $\alpha_c(s)$. The values of $F(s)$ for $\alpha_0 = 0.5$ and $2\beta = 5.0$ are plotted as the solid line in Fig. 3 along with various data,[1] and the result for $\alpha_0 = 0$ is plotted as the broken line in Fig. 3. The variation due to the value of 2β is not very large; for the case $\alpha_0 = 0.5$, if 2β is varied from 1 to 10, $F(s)$ changes ± 1.0 from the solid curve of Fig. 3 at $E_{\text{c.m.}} = 30$ GeV, and changes (+1.0, −0.2) at $E_{\text{c.m.}} = 13$ GeV. The uncertainties due to the variation of $\langle m_{c\bar{c}} \rangle$, m_c, and Δ_c in the reasonable ranges are small.

It should be obvious from the above discussion and the estimate presented in Fig. 3 that the multiple production of charmonium states can contribute significantly to the average charge multiplicity of e^+e^- annihilation at high energies. The second diagram of Fig. 2 will simulate three-jet events when the three produced charmonium states decay into many hadrons. The abundance of this kind of simulated three-jet or multijet events depends on the size of the inclusive production cross section of charmonium states. Its abundance depends also on the probability of emitting charmonium states at large angles measured with respect to the direction of the $c\bar{c}$ quark pair; in other words the abundance of simulated multijet events depends also on the average transverse momentum of the emitted charmonium states. From the production of J/ψ particles in high-energy pN collisions, the average transverse momentum of produced J/ψ particles is known to be about 1 GeV/c,[8] which is considerably larger than the average transverse momentum of inclusively produced pions. Therefore, it is im-

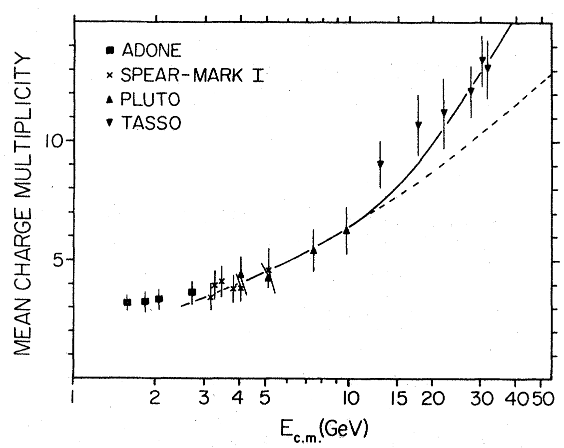

FIG. 3. The average charge multiplicity computed from Eq. (8) is represented as the solid curve ($\alpha_0 = 0.5$, $2\beta = 5.0$) and the broken curve ($\alpha_0 = 0$). The data are from Refs. 1. The error bars include both the statistical and the systematic errors; if the systematic errors are not given in the references, 10% systematic errors are assigned for each data point.

portant to measure the inclusive spectra of multiply produced charmonium states in e^+e^- annihilation in order to verify the claim[9] that the observation of multijet events implies the emission of hard gluons. The combination of multijet events simulated from the decays of the multiply produced charmonium states (as discussed in this paper) and from the decay of a heavy c-flavored and b-flavored particle emitted in the fragmentation region[10] may account for the majority of the observed multijet events in e^+e^- annihilation. If so, the explanation from the hard-gluon radiation becomes unnecessary.

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[1] C. Bacci *et al.*, Phys. Lett. 86B, 234 (1979); G. G. Hanson, in *Gauge Theories and Leptons*, proceedings of the XIII Recontre de Moriond, Les Arcs, France, 1978, edited by J. Trân Thanh Vân (Edition Frontieres, Gif-sur-Yvette, 1979); Ch. Berger *et al.*, Phys. Lett. 81B, 410 (1979); R. Brandelik *et al.*, *ibid.* 89B, 418 (1980).

[2] D. Amati, S. Fubini, and A. Stanghellini, Nuovo Cimento 26, 896 (1962); G. F. Chew and A. Pignotti, Phys. Rev. 176, 2112 (1968); G. F. Chew, T. W. Rogers, and D. R. Sneider, Phys. Rev. D 2, 765 (1970); for a review of this subject see, for example, W. Frazer *et al.*, Rev. Mod. Phys. 44, 284 (1972).

[3] W. Thomé *et al.*, Nucl. Phys. B129, 365 (1977).

[4] For a review of this topic, see G. F. Chew and C. Rosenzweig, Phys. Rep. 41C, 263 (1978); G. Cohen-Tannoudji, F. Hayot, and R. Peschanski, Phys. Rev. D 17, 2930 (1978).

[5] S. Okubo, Phys. Lett. 5, 165 (1963); G. Zweig (unpublished); J. Iizuka, Prog. Theor. Phys. Suppl. 37-38, 21 (1966).

[6] G. F. Chew and J. Koplik, Nucl. Phys. B79, 365 (1974).

[7] R. Baldini-Celio *et al.*, Phys. Lett. 58B, 471 (1975).

[8] D. M. Kaplon *et al.*, Phys. Rev. Lett. 40, 435 (1978).

[9] D. P. Barber *et al.*, Phys. Rev. Lett. 43, 830 (1979); R. Brandelik *et al.*, Phys. Lett. 86B, 243 (1979); Ch. Berger *et al.*, *ibid.* 86B, 418 (1979); W. Bartel *et al.*, *ibid.* 91B, 142 (1980).

[10] C. K. Chen, Phys. Rev. D 23, 712 (1981).