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[9]Note that $A$ is proportional to the strong-interaction coupling constant and depends on the vector electromagnetic form factors of the neutron and proton as well as on $G_A(q^2)/G_A(0)$. We used $G_{Mp}/\mu_p=\sqrt{f(q)}/(1+q^2/10.71)^2$, where $f(q)$, given in Ref. 5, takes account of the known deviations from the simple dipole expression. We also used $G_{Mn}/\mu_n=G_{Mp}/\mu_p$, $G_{Ep}=(1-0.06q^2)G_{Mp}/\mu_p$, and $G_{En}=-\mu_n G_{Ep}\tau/(1+5.6\tau)$ with $\tau=q^2/4M_n^{\,2}$. For a discussion of the form factors, see R. Wilson, in *Proceedings of the Fifth International Symposium on Electron and Photon Interactions at High Energies, Ithaca, New York, 1971*, edited by N. B. Mistry (Cornell Univ. Press, Ithaca, N.Y., 1972).
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# Hadron Production by Electron-Positron Annihilation at 4-GeV Center-of-Mass Energy*

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We have measured the total cross section for electron-positron annihilation into three or more hadrons, with at least two charged particles in the final state. The measurement was made at a center-of-mass energy of 4 GeV with a $2\pi$-sr nonmagnetic detector. With 88 events detected, we obtain a model-independent lower limit on the hadron production cross section of $9.6\pm1.4$ nb; a calculation of detection efficiency based on invariant phase-space production of pions leads to a total cross section of $26\pm6$ nb. This cross section is $4.7\pm1.1$ times the theoretical total cross section for $e^+e^-\to\mu^+\mu^-$. The average charged multiplicity is $\bar{n}=4.2\pm0.6$.

We report a measurement of the total cross section for electron-positron annihilation into three or more hadrons, with at least two charged particles in the final state. The experiment was performed at the Cambridge Electron Accelerator bypass,[1] at a center-of-mass energy of 4 GeV. We used the $2\pi$-sr bypass on-line detector (BOLD)[2] which simultaneously measured $e^+e^-$ elastic scattering[3] and $e^+e^-$ annihilation into photon pairs.[4]

The apparatus was triggered by charged particles or electromagnetic showers in at least two of the four quadrants. Charged $\pi$ mesons with a kinetic energy greater than 95 MeV or showers with an energy greater than 800 MeV could trigger the apparatus. A trigger was considered to be caused by a multibody event if it satisfied the following criteria:

(1) BOLD detected two or more prongs. These had to come from a volume centered around the interaction region and penetrate material with a perpendicular thickness equivalent to 10.7 g/cm$^2$ of iron.

(2) If an event had only two prongs, they had to be noncollinear with an angle in space $\Delta\alpha$ between them given by $\Delta\alpha<160°$, and have a difference in azimuthal angle $\Delta\varphi$ given by $|\Delta\varphi|<160°$. $\Delta\varphi$ is defined in the range $-180°\leq\Delta\varphi\leq180°$.

(3) The vertex point of all the prongs had to lie in a volume $\Delta x\times\Delta y\times\Delta z=4\times3\times9$ cm$^3$ about the interaction point as determined by $e^+e^-$ elastic scattering events[2] ($z$ is the coordinate along the beam direction).

In the first scan of the $1.3\times10^6$ triggers we found 91 events which satisfied these criteria. In a rescan of 28% of the data, 1 additional event was found. This gives a total of 92 multibody events and an overall scanning efficiency of (97 ± 3)%.

Backgrounds not associated with $e^+e^-$ collisions which might imitate a multibody event could originate in cosmic-ray showers or beam-gas scattering. Events due to cosmic rays are expected to show a uniform spatial distribution of vertex points. No additional events were found by increasing the acceptable interaction region volume by a factor of 3.

Events due to beam-gas scattering should produce a distribution of vertex points continuous along the beam direction. However, increasing the acceptable $\Delta z$ by a factor of 2 did not lead to any additional events. Also, a single-beam run with the time integral of the gas pressure in the interaction region times the beam current equivalent to 50% of that accumulated during data taking showed no events. This result agrees with calculation. Therefore, we estimate the background from these sources to be negligible.

Contamination of our event sample from other processes besides $e^+e^-$ annihilation into hadrons has been considered for the following reactions:

(1) $e^+e^- \to e^+e^-\gamma$ and $e^+e^- \to \mu^+\mu^-\gamma$ can produce non-back-to-back two-prong events. We calculate in the peaking approximation that 14 $e^+e^-\gamma$ and 1.2 $\mu^+\mu^-\gamma$ final states would be detected with $\Delta\alpha < 160°$ and $|\Delta\varphi| \cong 180°$. The condition $|\Delta\varphi| < 160°$ reduces contamination from $\mu^+\mu^-\gamma$ to a negligible level. To the extent that the peaking approximation breaks down we expect a few $e^+e^-\gamma$ final states satisfying the selection criteria. Four events were identified as $e^+e^- \to e^+e^-\gamma$ by their visually observed showers and large shower counter pulse heights and were therefore subtracted from the sample.

(2) $e^+e^- \to e^+e^-e^+e^-$, $e^+e^-\mu^+\mu^-$, and $e^+e^-\pi^+\pi^-$. The trigger condition was inefficient for these two-photon processes.[5] We observed 2 $e^+e^- \to e^+e^-e^+e^-$ events and 3 $e^+e^- \to e^+e^-\mu^+\mu^-$ (or $e^+e^-\pi^+\pi^-$) events, with $|\Delta\varphi| \cong 180°$. We expect less than 0.7 such events in our sample with $\Delta\alpha$, $|\Delta\varphi| < 160°$, and none were identified. The calculated total number of events for processes (1) and (2) agrees with the data.

(3) $e^+e^- \to e^+e^-M^0$, where $M^0 = \eta$, $\eta'$ (957 MeV), or a multihadron state. The $M^0$ system center-of-mass motion reduces the detection efficiency for low-mass states. Assuming appropriate production mechanisms[5] for the neutral state we estimate less than 2 events from this source.

Accordingly, we made no corrections for the processes listed under (2) and (3).

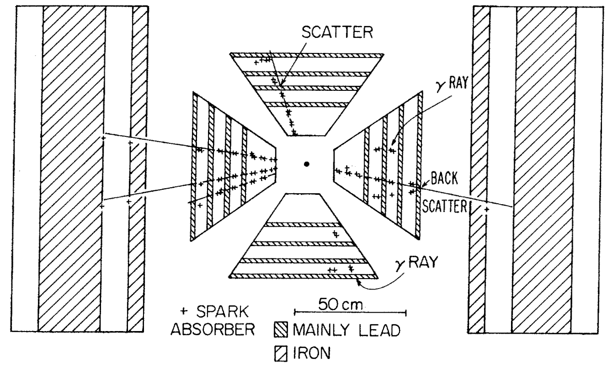


FIG. 1. A view along the beam line of a five-prong event in BOLD. Clearly seen are a backward scatter, a large-angle scatter, a $\gamma$ conversion, and particles stopping in the iron absorber.

After elimination of the 4 events identified as $e^+e^-\gamma$ final states we are left with 31 two-prong, 29 three-prong, 20 four-prong events. A five-prong event, which illustrates the hadronic nature of the prongs, appears in Fig. 1. Over all, 18% of the 269 prongs in our event sample scattered through angles greater than 8° in the BOLD radiators, 5 particles scattered through angles greater than 90°, and 3 ended in nuclear stars. We assume therefore that these events are due to electron-positron annihilation into hardons.

Based on the final count of 88 events, the scanning efficiency, and a time integrated luminosity of $(9.45 \pm 0.86) \times 10^{33}$ cm$^{-2}$ (measured with the monitoring reaction $e^+e^- \to e^+e^-\gamma\gamma^3$), we calculate a model-independent lower limit on the $e^+e^- \to$ multibody hadron production cross section of $9.6 \pm 1.4$ nb.

The total cross section is this number divided by the event detection efficiency $\epsilon_T$. The calculation of $\epsilon_T$ is of course model dependent. We have assumed that all particles are pions produced according to an invariant phase-space distribution.[6] This latter assumption is in agreement with the angular distribution of the prongs as well as the distribution of the angle in space between pairs of prongs evaluated from the data. In order to evaluate $\epsilon_T$, a Monte Carlo program based on NVERTEX was used to compute the efficiencies $\epsilon(p, q)$ for detecting $p$ prongs in BOLD from the reaction $e^+e^- \to q\pi^\pm + n\pi^0$, with $q = 2$, 4, 6, or 8, $n \leq 2$, and $q + n \leq 8$. These assumed final states are listed, together with the corresponding efficiencies, in Table I. (The efficiencies depend weakly on the value of $n$; an average over $n$ was

TABLE I. Average detection efficiency.

| | | Assumed final states | | | |
|---|---|---|---|---|---|
| Number of prongs $p$ | Number of observed events $N_p$ | $\pi^+\pi^-\pi^0$ $\pi^+\pi^-2\pi^0$ $q=2$ | $2\pi^+2\pi^-$ $2\pi^+2\pi^-\pi^0$ $2\pi^+2\pi^-2\pi^0$ $q=4$ | $3\pi^+3\pi^-$ $3\pi^+3\pi^-\pi^0$ $3\pi^+3\pi^-2\pi^0$ $q=6$ | $4\pi^+4\pi^-$ $q=8$ |
| 2 | 31[a] | 0.116 | 0.193 | 0.146 | 0.094 |
| 3 | 29 | 0 | 0.178 | 0.253 | 0.217 |
| 4 | 20 | 0 | 0.049 | 0.163 | 0.244 |
| 5 | 8 | 0 | 0 | 0.049 | 0.141 |
| 6 | 0 | 0 | 0 | 0.007 | 0.056 |

[a] $|\Delta\varphi|, \Delta\alpha < 160°$.

used.) The program took account of the structure of BOLD and the event selection criteria. Nuclear absorption,[7-9] the production of secondaries, and ionization losses were also included.

The observed number of events with prong count $p$, $N_p$, gives rise to four linear equations in the four unknown partial cross sections $\sigma(e^+e^- \to q\pi^\pm + \text{neutrals}) \equiv \sigma_q$:

$$N_p = L \sum_{q=2,4,6,8} \epsilon(p,q)\sigma_q, \quad p = 2, 3, 4, 5,$$

where $L$ is the time-integrated luminosity. These equations have been solved, with the restriction that $\sigma_q \geq 0$, using the method of least squares. The partial cross sections were not well determined, but $\epsilon_T = (38 \pm 8)\%$, $L\sigma_{\text{tot}} = 234 \pm 52$ (where $\sigma_{\text{tot}} = \sigma_2 + \sigma_4 + \sigma_6 + \sigma_8$), and the average charged

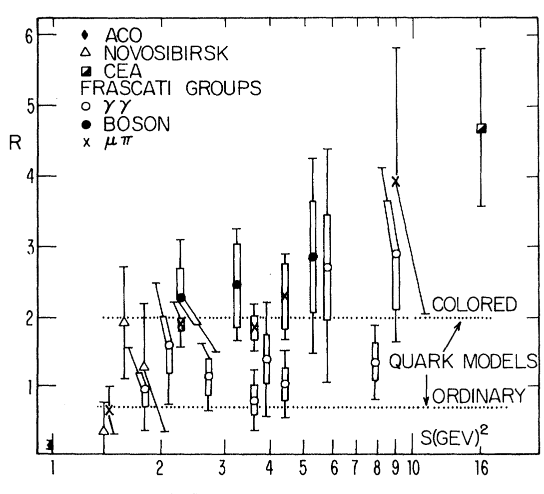


FIG. 2. $R = \sigma(e^+e^- \to \text{multibody hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$ versus the square of the center-of-mass energy $s$ in GeV$^2$. The dotted lines give the asymptotic predictions of parton models assuming ordinary and colored quarks.

multiplicity $\bar{n}$ is $\bar{n} = 4.2 \pm 0.6$. The quoted errors were calculated on the basis of statistical (Poisson) fluctuations in the $N_p$.

11 two-prong events with $|\Delta\varphi| > 160°$ were identified as multibody hadron events by the presence of extra $\gamma$ rays, scatterings, or by additional short-range tracks. If we include these 11 events in the sample, and redo the efficiency calculation, we find $L\sigma_{\text{tot}} = 218 \pm 38$ which is consistent with the above.

The measured cross section includes processes where the initial electron or positron has radiated. This leads to a contribution to the multibody cross section from $e^+e^-$ annihilation at a lower effective center-of-mass energy. A calculation[10] based on smoothed interpolation of measured cross sections[11-13] and an estimate of detection efficiency shows that less than 5% of the events include a photon of energy more than 1 GeV radiated from the initial state. No correction was applied for this effect.

From the values of $L$, $L\sigma_{\text{tot}}$, and the scanning efficiency, we calculate the production cross section for electron-positron annihilation into three or more hadrons to be $26 \pm 6$ nb. The ratio $R$ of this cross section to the theoretical total cross section for $e^+e^- \to \mu^+\mu^-$ at 4 GeV center-of-mass energy is $4.7 \pm 1.1$. This is compared with recent data[11-13] in Fig. 2. Parton models suggest that, in the asymptotic region, this value should be $\sum_i (\frac{1}{4} + \frac{3}{2}s_i)q_i^2$, where $q_i$ are the charges of the basic constituents of the hadrons with spin $s_i = 0$ or $s_i = \frac{1}{2}$. The elementary quark model gives $R = \frac{2}{3}$. Quarks with "color" give $R = 2$.

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## ERRATUM

REACTION $p+p\to\gamma+$ANYTHING AT 205 GeV AND ITS IMPLICATIONS FOR $\pi^0$ PRODUCTION. G. Charlton, Y. Cho, M. Derrick, R. Engelmann, T. Fields, L. Hyman, K. Jaeger, U. Mehtani, B. Musgrave, Y. Oren, D. Rhines, P. Schreiner, H. Yuta, L. Voyvodic, R. Walker, J. Whitmore, H. B. Crawley, Z. Ming Ma, and R. G. Glasser [Phys. Rev. Lett. 29, 1759 (1972)].

In Fig. 1(a), the ordinate label $d\sigma/dx$ (b) should be replaced by $2d\sigma/dx$ (b). In Fig. 1(b) $d\sigma/dP_\perp^2$ (b/GeV$^2$) should read $\frac{1}{2}d\sigma/dP_\perp^2$ (b/GeV$^2$), and in Fig. 1(c), $2P_\perp F_2(P_\perp^2)$ should read $P_\perp F_2(P_\perp^2)$ (mb/GeV).