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[6]A new result has been reported by the single-arm spectrometer group [NAL Report No. NAL-73/83-EXP (unpublished)] which is $\bar{d}/\pi^- = 2.4\times10^{-6}$ at 80 GeV/c and 3 mr. It also "scales," giving 6×10^{-3} for the quantity listed here.
[7]A similar search has recently been reported by L. B. Leipuner *et al.*, Phys. Rev. Lett. 31, 1266 (1973).

Hadron Production by Electron-Positron Annihilation at 5 GeV Center-of-Mass Energy*

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We have measured the cross section σ for electron-positron annihilation into three or more hadrons, with at least two charged particles in the final state, at 5 GeV center-of-mass energy. We find a model-independent lower limit of $\sigma > 9.1 \pm 1.0$ nb; assuming invariant phase-space production of pions, we calculate the detection efficiency of our detector to be $(45\pm 11)\%$, yielding a cross section $\sigma = 21 \pm 5$ nb. The average charged hadron multiplicity is found to be $\bar{n} = 4.3 \pm 0.6$.

We have extended our previous electron-positron colliding-beam studies[1,2] at the Cambridge Electron Accelerator to a center-of-mass energy of 5 GeV. We report here results on the production of three or more hadrons, with a least two charged particles in the final state.

Electrons and positrons of energy $E = 2.5$ GeV collided head on (the electron beam direction defines the z direction). As before, the interaction products were observed in the nonmagnetic detector BOLD[1,3] which covers 2π sr with four quadrants, each consisting of spark chambers, counters, and radiators. BOLD detects charged particles and photons emitted in the angular range $45^\circ < \theta < 135^\circ$, with a φ coverage of 73% of 2π. In the 5-GeV experiment, two-counter telescopes covered the remainder of the φ range and, as will be explained below, they permit a useful check of the detection-efficiency calculation. The luminosity was measured using the double-bremsstrahlung process.[4] The detector was triggered by the presence in at least two of the quadrants of charged particles, either with a minimum range corresponding to 95-MeV pions or with showers of energy greater than 800 MeV. A total of 2.3×10^6 triggers were recorded.

A first scan yielded 115 multibody events which satisfied the following five criteria:

(1) Two or more charged-particle tracks have to come from a volume centered around the interaction region and must penetrate a perpendicular thickness equivalent to 10.7 g/cm^2 of iron.

(2) If an event has only two tracks, they have to be (a) noncollinear with an angle in space $\Delta\alpha$ between them given by $\Delta\alpha < 160^\circ$; and (b) noncoplanar with the beam line with the difference in azimuthal angle $\Delta\varphi$ given by $|\Delta\varphi| < 160^\circ$ ($\Delta\varphi$ is defined in the range $-180^\circ < \Delta\varphi < +180^\circ$).

(3) The vertex point of all the tracks lies in a fiducial volume $\Delta x\times\Delta y\times\Delta z = 4.0\times4.0\times9.4$ cm^3. This volume is determined from the measured length of the beam overlap region, the origin of Bhabha scattering events,[4] multiple scattering of charged particles, and the precision of reconstruction.

(4) Tracks are not electromagnetic. The shower spark chambers and the shower counters identify electrons and positrons with good efficiency down to energies of 600 MeV. This criterion eliminates eight events, five of which are identified as coming from $e^+e^- \to e^+e^-\gamma$; another possible source of such events involves π^0 decaying with Dalitz pair emission.

(5) Events cannot be accompanied by a large number of background sparks and tracks. This eliminates four events, which most likely are initiated by cosmic rays passing through the time-of-flight veto and which are so complex

TABLE I. Experimental multiplicity distribution of multiprong events.

Number of charged tracks	Fiducial sample	Gas background	Contamination	Event number N_p
2	45 ± 6.6	7 ± 2.6	2 ± 1	36 ± 7.3
3	32 ± 5.7	2 ± 1.4	0	30 ± 5.8
4	28 ± 5.3	0	0	28 ± 5.3
5	7 ± 2.6	0	0	7 ± 2.6
6	2 ± 1.4	0	0	2 ± 1.4
7	1 ± 1	0	0	1 ± 1
8	1 ± 1	0	0	1 ± 1
Σ	116 ± 11	9 ± 3.0	2 ± 1	105 ± 11

that tracks that obey the previous criteria are reconstructed.

In a rescan of 95% of the data one additional event was found. Table I lists the distribution of the 116 events according to N_p, the number of charged particles detected in the four BOLD quadrants.

There are two sources of background not associated with e^+e^- interactions: cosmic-ray and beam-gas scattering events. Cosmic-ray vertices are expected to have a uniform spatial distribution. Increasing the fiducial volume in the x and y directions by a factor of 5 adds no additional events, indicating negligible cosmic-ray background.

Beam-gas scattering vertices are expected to be distributed along the beam (z) direction: Increasing the z fiducial length by a factor of 2.1 while keeping all other criteria the sames adds nine events, indicating a significant background from beam-gas scattering which must be subtracted.[5]

The distributions in charged-particle multiplicity and vertex-point coordinates of beam-gas scattering events were measured in runs with single e^+e^- beams at increased gas pressure such that the integral of beam current times gas pressure was equivalent to ~17 times that corresponding to the data run. This information leads to the nine-event background subtraction of column 3, Table I.

We want to obtain from the sample of observed multibody events the cross section σ for e^+e^- one-photon annihilation into three or more hadrons with at least two charged particles. The main contamination comes from the process $e^+e^- \rightarrow e^+e^-X^0$, where $X^0 = e^+e^-$, $\mu^+\mu^-$, $\pi^+\pi^-$, in which two nearly real photons collide to produce X^0 and the electron and positron are scattered forward with reduced energy.[6] The rates for these processes have been computed[7] using the equivalent photon approximation: 2 ± 1 two-prong events are found to be included by the BOLD geometry and the acceptance criteria.[8] This contamination is subtracted as shown in Table I. An upper limit of 1.5 events has been obtained[7] for the contamination from $e^+e^- \rightarrow e^+e^-M^0$, where $M^0 = [\eta'(958)$, hadrons$]$ using $T_{\gamma\gamma\rightarrow\eta'} < 40$ keV and $\sigma_{\gamma\gamma\rightarrow \text{hadrons}} = 0.3\ \mu\text{b}$. No correction has been made for this source of contamination.

We have also obtained some experimental support for the absence of substantial contamination from events due to the collision of two nearly real photons from observations with a limited tagging system.[9]

The remaining 105 ± 11 multibody events are believed to be hadronic. This is supported by the number of observed interactions of the 360 tracks, and the 126 showers (from π or η decays) pointing back to the interaction region. Some contamination from strange, unexpected, multibody leptonic events cannot be eliminated experimentally.

If we assume 100% detection efficiency, the 105 ± 11 events determine a model-independent lower limit of $L_i\sigma$, where L_i is the time-integrated luminosity. The value of $L_i = (1.14 \pm 0.06) \times 10^{34}$ cm^{-2} has been obtained as outlined in Ref. 3. Since $L_i\sigma > 105 \pm 11$, $\sigma > (9.2 \pm 1.0) \times 10^{-33}\ \text{cm}^2$.

To find the value of σ, the lower limit must be divided by the average detection efficiency ϵ_T whose calculation is model dependent since it corrects for particles emitted outside the solid angle subtended by the detector. The efficiency calculation is based on the following:

(1) All particles are assumed to be pions produced according to an invariant phase-space dis-

tribution. This model determines the values of $\epsilon(p,q,m)$, the detection efficiencies in BOLD for e^+e^- annihilation into (1) q charged particles of which p are detected and (2) m neutral particles none of which are counted.

(2) Because of the relatively large solid angle subtended by BOLD, the efficiency $\epsilon(p,q,m)$ depends only weakly on m. We use therefore $\epsilon(p,q)$ which represents the average of $\epsilon(p,q,m)$ over m.

(3) To explain the observed multiplicities (Table I), reactions $e^+e^- \to q\pi^\pm + m\pi^0$, with $q+m \leq 16$, $m \leq 4$, and $q = 2, 4, \ldots, 16$, are taken into account. The following eight simultaneous equations are solved for σ_q, the partial cross sections for the emission of q charged particles: $N_p = L_i \sum_q \epsilon(p,q) \times \sigma_q$, with $p = 2, 3, \ldots, 9$ and $q = 2, 4, \ldots, 16$.

(4) The cross section $\sigma = \sum_q \sigma_q$, the average detection efficiency $\epsilon_T = 105/L_i\sigma$, and the averaged charged multiplicity $\bar{n} = \sum_q q\sigma_q/\sigma$ are then calculated as described in Ref. 7 in a manner similar but not identical to the one used in the analysis of the 4-GeV data.[2] While partial cross-section values have large uncertainties, the summed cross section σ is quite well determined.

The validity of the use of an invariant phase-space model has been tested in two different ways. Figure 1 shows the distribution of the cosines of the angles between any two tracks for observed events with at least three charged tracks in BOLD (two-track events are not used, to eliminate the problem of beam-gas subtraction). This experimental distribution is very similar to Monte Carlo program-calculated distributions for 4π and 6π phase-space events shown in Fig. 1 as distributions (b) and (c). If multipion events were the result of decays from two-body production, we would expect the distribution to be more peaked near $\cos\theta = -1$ and $+1$; this has been verified to be the case in a calculation of the channel $e^+e^- \to A_1^+A_1^- \to (\pi^+\rho^0) + (\pi^-\rho^0) \to (\pi^+\pi^+\pi^-) + (\pi^+\pi^+\pi^-)$. A second test involves the use of the four two-counter telescopes (with 3.2 g/cm^2 of lead absorber between the counters) which cover the φ space taken up by the four quadrant supports of BOLD. The use of these counters results in a considerable increase of the solid-angle coverage of the detector, from 2.0π to 2.8π sr. When the information from the four telescopes is included in the analysis of the 116-event sample, the multiplicity distribution is significantly changed toward higher average multiplicity from the distribution of Table I. It must be noted, however, that the origin and nature of particles that trigger these two-counter telescopes are less certain than of those observed in the quadrants; the distribution obtained with the expanded geometry is thus sensitive to the presence of noise particles and is less reliable than the distribution of Table I. Nevertheless the value of $L_i\sigma$ calculated using the expanded geometry differs by less than the quoted statistical error from the value obtained with the standard geometry, thus further supporting the use of an invariant phase-space model.

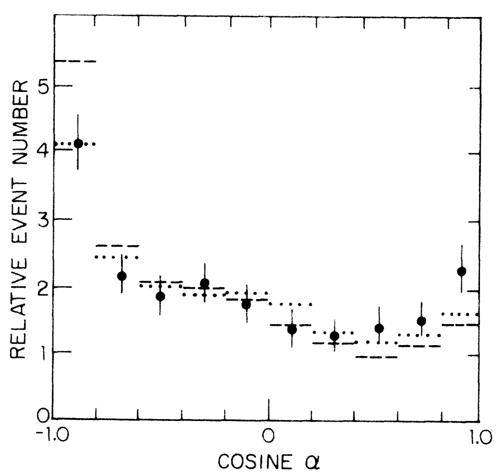

FIG. 1. Distribution of the cosine of the angle α between any two tracks for events with three or more tracks inside BOLD: solid circles, experimental data points; dashes, Monte Carlo generated events for the $2\pi^+2\pi^-$ final state (invariant phase space); dots, Monte Carlo generated events for the $3\pi^+3\pi^-$ final state (invariant phase space).

Employing the multiplicity distribution of Table I, we calculate $\sigma(5\text{ GeV}) = (21 \pm 5) \times 10^{-33}$ cm^2; $\bar{n} = 4.3 \pm 0.6$; $\epsilon_T = (45 \pm 11)\%$. The ratio R of the cross section to the theoretical cross section $\sigma_{\mu\mu}$ for the reaction $e^+e^- \to \mu^+\mu^-$ at 5 GeV has the value $R(5\text{ GeV}) = 6.0 \pm 1.5$. The quoted errors are statistical and reflect primarily the statistical uncertainties in the values N_p. Various internal checks (of which the use of the expanded geometry is one) suggest that known systematic uncertainties do not increase these errors significantly.

The corresponding 4-GeV results reported previously are $\sigma(4\text{ GeV}) = (26 \pm 6) \times 10^{-33}$ cm^{-2}; $R(4\text{ GeV}) = 4.7 \pm 1.1$, and $\bar{n} = 4.2 \pm 0.6$. Our new results indicate that multihadron production in e^+e^- annihilation remains as surprisingly large at 5 GeV as it was at 4 GeV. When compared with lower energy results[10] as is done in Fig. 2, the value of σ is constant above 2 GeV within the present fairly large errors. This is to be contrasted

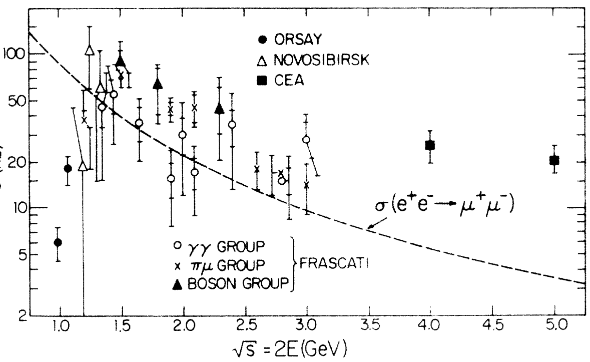

FIG. 2. Results of the measurements of $\sigma(e^+e^- \to \text{multihadrons})$. For the double error bars, the first limit indicates the quoted systematic error; the second limit represents the statistical uncertainty linearly added to the systematic error.

with the $1/E^2$ dependence of the cross section for the production of pairs of point particles such as $e^+e^- \to \mu^+\mu^-$. A preliminary analysis of the first hadron production experiment carried out at the Stanford electron-positron colliding-beam facility is in good agreement with our 4- and 5-GeV results.[11]

This experiment has been made possible by the outstanding efforts of the staff of the Cambridge Electron Accelerator Laboratory, in particular G.-A. Voss, R. Averill, A. Hofmann, H. Mieras, and H. Winick. They raised the beam energy from 2.0 to 2.5 GeV and then ran the colliding-beam system for our experiment under difficult circumstances. We are also indebted to G. Hanson, J. Koch, A. Litke, R. Madaras, and J. M. Paterson, all collaborators in our previous colliding beam experiments, for their very great contributions to the entire BOLD system. The help of the Harvard Cyclotron Laboratory staff is gratefully acknowledged.

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[8]The majority of $e^+e^- \to e^+e^-X^0$ events are rejected by the $|\Delta\varphi| < 160°$ requirement.

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