has $\langle\sigma_{\vec{0}}\sigma_{\vec{r}}\rangle = D_0 r^{-1/4}[1 + C_0 (a/r)^2 + \ldots]$ [see M. E. Fisher, Physica (Utrecht) 25, 521 (1959); J. Stephenson, J. Math. Phys. 5, 1009 (1964)]. The amplitude $C_0$ might, therefore, be related to $a$ regarded as an irrelevant variable.

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# Cross-Section Measurements for Charm Production by 209-GeV Muons

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Interactions of 209-GeV muons in the multimuon spectrometer at Fermilab have yielded 20 072 dimuon final states, with (81 ± 10)% attributed to production of charmed states decaying to muons. The cross section for diffractive charm muoproduction is $6.9^{+1.9}_{-1.4}$ nb. Extrapolated to $Q^2 = 0$, the effective cross section for 178- (100-) GeV photons is $750^{+180}_{-130}$ ($560^{+200}_{-120}$) nb.

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Real- and virtual-photon beams are able to elucidate charm production in hadron reactions because they substitute charge for color coupling at one vertex. Charm and forward-$\psi$ photoproduction rates limit the $\psi N$ total cross section without assuming vector-meson dominance (VMD), and within VMD yield the ratio of elastic to inelastic $\psi N$ scattering.[1] Charm muoproduction data directly test the photon-gluon-fusion ($\gamma$GF) model,[2] which uses elements of quantum chromodynamics. This Letter presents charm-production cross sections which impose significant model constraints. Differential spectra appear in a second paper.[3]

One model-dependent measurement of the charm-muoproduction cross section at 270 GeV has been reported[4] as 3 ± 1 nb. Wide-band photon-beam experiments have measured cross sections for inclusive $D^0$ production averaged from 50 to 200 GeV of 464 ± 207 nb[5] and 295 ± 130 nb.[6] In no case has discrimination between charm-production models been attempted.

This experiment identifies charmed states by their $n$-body ($n \geqslant 3$) decays into muons. Unresolved charmed hadrons contribute in proportion to their production rate and leptonic branching ratio. While unsuited to a first observation of charmed states, this continuum charm signature is the only reasonable explanation for (81 ± 10)% of the 20 072 single-extra-muon events reported here. These high statistics, coupled with full determination of virtual-photon four-momenta, permit the study of charm-production mechanisms.

The spectrometer has been described earlier.[7] The $\geqslant 2\mu$ trigger required a $\gtrsim$ 20-GeV hadronic shower $\gtrsim$ 2 m upstream of $\geqslant$ 2 hits in each of three consecutive trigger hodoscopes. Full tracking capability in an area including the beam produced a high, nearly $Q^2$-independent acceptance. Data are reported from $1.4\times10^{11}$ positive and $0.3\times10^{11}$ negative Fermilab beam muons at 209 GeV. For $\mu^+\mu^+$ or $\mu^-\mu^-$ final states, the scattered muon is chosen to be the more energetic muon. This algorithm is 91% successful when checked using $\mu^+\mu^-$ events. Regions of rapidly varying acceptance are excluded by requiring daughter muon energies to exceed 15 GeV, vertices to lie in the upstream 60% of the target, and shower energies to exceed 36 GeV. Muon trident contamination is reduced by requiring the daughter muon to possess $\geqslant$ 0.45 GeV/$c$ momentum transverse to the scattered muon.

In a Monte Carlo (MC) simulation like that discussed in Ref. 7, pairs of charmed quarks ($c\bar{c}$) of mass 1.5 GeV/$c^2$ are generated using a $\gamma$GF model with a distribution $3(1-x)^5/x$ in gluon momentum fraction $x$, and with $\alpha_s = 1.5/\ln(4m_{c\bar{c}}^{-2})$. Quark pairs carrying the full photon energy become $D$ mesons via a fragmentation function[8] $D(z) = (1-z)^{0.4}$; $z$ is $2E_D/m_{c\bar{c}}$, where $E_D$ is the $D$ energy in the $c\bar{c}$ rest frame. Neutral and charged $D$'s are generated in a 2:1 ratio[8] and decay to muons[9] with 4% and 20% branching fractions, respectively.[10] The $(D \to K\mu\nu):(D \to K^*\mu\nu)$ ratio[10] is 0.61:0.39. Other charmed states are not simulated. The diffractive and shadowing parameters used to describe incoherent and coherent charm production are those adopted in our $\psi$ analysis.[7] Ignoring nuclear coherence and shadowing would raise the reported free-nucleon cross sections by 9.4%.

A model-independent simulation of the major background, $\pi$ and $K$ decay, is based upon structure functions[11] and $\pi, K$ production data[12] from another muon experiment, and upon bubble-chamber data[13] for $\pi, K$-$N$ interactions. Comparison of the mean values in Table I rules out any possibility that $\pi$ and $K$ decay explain the data. Excluding data with $\nu < 75$ GeV, the absolutely normalized $\pi, K$-decay rates account for only 19% of the sample. To this fraction we assign a 50% error, estimated by representing the data as different combinations of decay and $\gamma$GF MC events, and including the uncertainty in the measured $K/\pi$ ratio.[12]

Contamination from partially reconstructed muon tridents is calculated[14] to be < 5% because of the shower-energy requirement. As a check, the two most energetic muons in the $3\mu$ events were subjected to the $2\mu$ analysis. The surviving events numbered only 3.9% of the true dimuon sample, the fraction expected from double charm decay to muons. Backgrounds from $\tau\bar{\tau}$ and $b$-quark pairs are negligible.[14]

Figures 1(a)–1(f) compare the background-subtracted charm signal with the $\gamma$GF prediction. The data are modeled precisely in $\nu$ and adequately in $Q^2$, daughter-muon energy, and inelasticity. The missing energies are different at the level of the systematic uncertainty in calorimeter calibration. The daughter-muon $p_\perp$ is higher in the data by 15%, but is sensitive to diffractive-slope and charm-decay parameters which are not part of the $\gamma$GF model.

The spectrometer acceptance is by far most sensitive to the energy spectrum of produced muons. Since the experimental $\nu$ distribution already is faithfully simulated, that sensitivity is best studied by varying the fragmentation function. Remodeling with $D(z) = (1-z)^3$ and $D(z) = [1 - \min(z, 0.99)]^{-1.5}$ changes the detector acceptance by $-19\%$ and $+20\%$, respectively. The "too soft (hard)" fragmentation predicts a mean daughter energy which is smaller (larger) than that of background-subtracted data by more than 5 standard deviations and spoils the agreement in other distributions. The systematic errors quoted below are obtained by taking the sum in quadrature of excursions caused by the $\pi, K$ normalization uncertainty and the fragmentation-induced changes in acceptance. After a $(26 \pm 5)\%$ relative acceptance correction, the opposite-sign to same-sign ratio for background-subtracted events is $1.07 \pm 0.06$.

The measured cross section for diffractive charm production is

$$\sigma_{\text{diff}}(\mu N \to \mu c\bar{c}x) = 6.9^{+1.9}_{-1.4} \text{ nb},$$

where the error is systematic. "Diffractive production" refers to creation of $c\bar{c}$ pairs carrying most of the laboratory energy of the virtual photon, as in the $\gamma$GF and VMD models. This analysis is insensitive to other mechanisms producing charm nearly at rest in the $\gamma N$ center of mass. The measured cross section is 37% higher than

TABLE I. Mean values of reconstructed quantities for data before background subtraction, for charm MC, and for $\pi, K$-decay MC. Errors are statistical.

| Reconstructed kinematic quantity | Data | Monte Carlo Charm | Monte Carlo $\pi, K \to \mu$ |
|---|---|---|---|
| $\langle\nu\rangle$ (GeV) | $127.0 \pm 0.2$ | $132.7 \pm 0.3$ | $109.8 \pm 1.0$ |
| Geometric mean $Q^2$ [(GeV/$c$)$^2$] | $0.767 \pm 0.004$ | $0.875 \pm 0.006$ | $0.562 \pm 0.011$ |
| $\langle$Daughter-$\mu$ energy$\rangle$ (GeV) | $25.63 \pm 0.07$ | $26.05 \pm 0.08$ | $22.87 \pm 0.21$ |
| $\langle$Missing energy$\rangle$ (GeV) | $14.03 \pm 0.14$ | $13.60 \pm 0.18$ | $2.25 \pm 0.53$ |

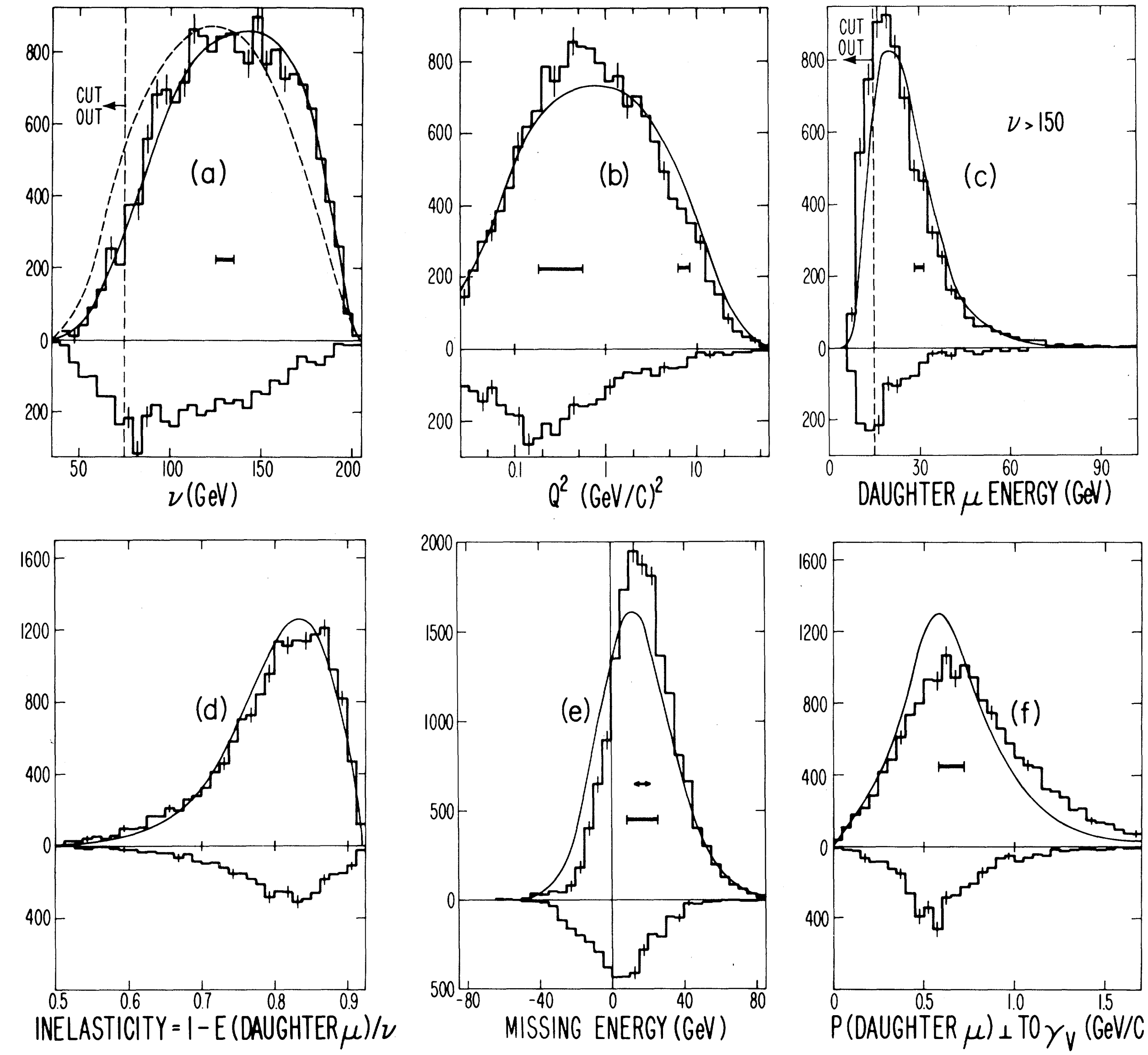


FIG. 1. Distributions in (a) energy transfer, (b) square of momentum transfer, (c) daughter-muon energy, (d) inelasticity, (e) missing (neutrino) energy, (f) daughter-muon $p_\perp$. The ordinates are events per bin with acceptance not unfolded. Inverted histograms show the simulated $\pi$, K-decay background, normalized to the beam flux. Erect histograms exhibit background-subtracted data. Errors are statistical. The curves, normalized to these data, are the photon-gluon-fusion charm calculation. The dashed curve in (a) represents an alternative model (Refs. 5 and 6) in which $D\overline{D}$ pairs are produced with $\nu$-independent probability. Events in (c) have $\nu$ > 150 GeV. Horizontal brackets exhibit typical rms resolution. The arrow in (e) shows the shift caused by a ± 2.5% excursion in calorimeter calibration.

the 5.0-nb $\gamma$GF prediction. Corrected by 1.45× for the different beam energy, it is ~3 times the cross section reported in Ref. 4.

The effective photon cross section $\sigma_{\rm eff}$ is obtained by factoring out the equivalent flux[15] of transversely polarized virtual photons. The extrapolation of $\sigma_{\rm eff}$ to $Q^2 = 0$ using a VMD propagator $(1 + Q^2/\Lambda^2)^{-2}$ is shown in Figs. 2(a) and 2(b). The best fits to $\Lambda$ are $3.3 \pm 0.2$ and $2.9 \pm 0.2$ GeV/$c^2$ for $\nu = 178$ and 100 GeV, and the $Q^2 = 0$ intercepts are $750^{+180}_{-130}$ and $560^{+200}_{-120}$ nb, respectively.[16] The increase of $190^{+34}_{-52}$ nb in the charm photoproduction cross section is significant; the difference of $0.39 \pm 0.18$ GeV/$c^2$ in $\Lambda$ suggests some $\nu$ dependence in the $Q^2$ shape.[3] Except in the last case, the errors are largely systematic. The diffrac-

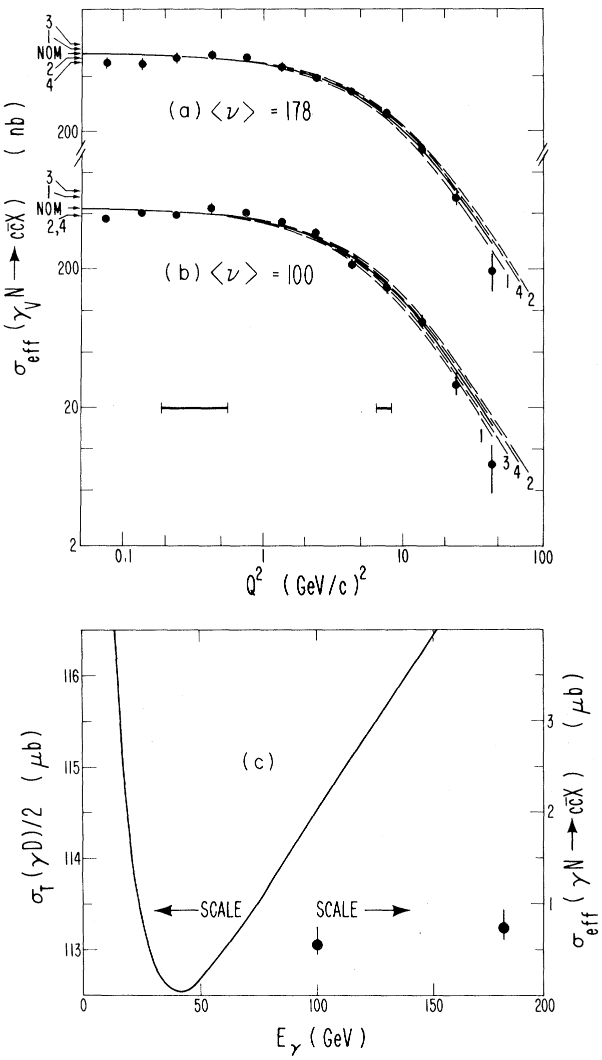


FIG. 2. Diffractive charm-photoproduction cross sections and the rise of the $\gamma N$ total cross section. Parts (a) and (b) show the extrapolation of the effective cross section to $Q^2=0$ at (a) $\nu=178$ and (b) $\nu=100$ GeV. Errors are statistical. The solid curves are fits to $\sigma_0(1+Q^2/\Lambda^2)^{-2}$, with (a) $\Lambda=3.3$ and (b) $\Lambda=2.9$ GeV/$c^2$; the arrows labeled "NOM" exhibit $\sigma_0$. Systematic errors are parametrized by (1) decreasing, (2) increasing by 50% the subtracted $\pi, K$-decay background, and by recalculating the acceptance with a (3) softer, (4) harder quark fragmentation function as described in the text. The effects on $\sigma_0$ are indicated by numbered arrows and the effects on $\Lambda$ are indicated by dashed curves, normalized to the same $\sigma_0$. Part (c) compares $\sigma_0$ (data points, right scale) with a fit (Ref. 17) to half the total photon-deuteron cross section (curve, left scale). Systematic uncertainties dominate the errors.

tive charm production rate is too small to saturate the rise[17] of the total $\gamma N$ cross section above 50 GeV [Fig. 2(c)].

Using SPEAR data,[10] one may crudely estimate the (neutral $D$):(charged $D$):$F$:$\Lambda_c$ ratio to be 2:1:1:1 at $m_{c\bar{c}} \sim 4$–5 GeV/$c^2$. Applied to the $D^0$ cross sections cited above,[5,6] this estimate yields $\approx 0.5$–1.2 $\mu$b of total charm photoproduction. This is compatible with our $Q^2 \to 0$ result. The model used to evaluate the acceptance for data reported in Refs. 5 and 6 assumes diffractive charm production with $D(z)=\delta(z-1)$ and no energy dependence above $\nu=50$ GeV. The muon data do not support these assumptions [Fig. 1(a)].

We have published results corresponding to a $25 \pm 8$ nb elastic-$\psi$-photoproduction cross section at 100 GeV.[7] The data reported here fix the ratio of elastic $\psi$ to diffractive charm production at $0.045 \pm 0.022$, $\sim 2.5$ times the VMD prediction.[1] In that picture this result suggests that *non*diffractive production is a significant fraction of the total charm-photoproduction cross section. Independent of VMD, our data and the analysis of Ref. 1 produce the limit $\sigma_{\text{total}}(\psi N) \geq 0.9$ mb (at 90% confidence level).

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## Limit on Υ Muoproduction at 209 GeV

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We present the dimuon mass spectrum from 102 678 three-muon final states produced by muon interactions within a magnetized steel calorimeter. The data place a 90%-confidence-level upper limit on the production of Υ states by muons: $\sigma(\mu N \to \mu \Upsilon X) B(\Upsilon \to \mu^+\mu^-) < 22 \times 10^{-39}$ cm$^2$, consistent with a photon-gluon-fusion model calculation.

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We report a limit on Υ production by 209-GeV muons in the Berkeley-Fermilab-Princeton multimuon spectrometer at Fermilab.[1] An integrated luminosity of $0.78 \times 10^{39}$ cm$^{-2}$, corresponding to 75% of the full data sample, has yielded 102 678 trimuon final states, including $6693 \pm 355$ examples of $J/\psi$ and $\psi'$ production. In every event, all three outgoing muons are fully momentum analyzed and are subjected to an energy-conserving one-constraint fit using calorimetric measurement of the associated shower energy.

No limit on Υ production by real or virtual photons has been published. A conference report[2] based on results from the Bologna-CERN-Dubna-Munich-Saclay (BCDMS) experiment presents the limit $\sigma(\mu N \to \Upsilon X) B(\Upsilon \to \mu^+\mu^-) < (6 \pm 3) \times 10^{-39}$ cm$^2$ (at 90% confidence level) for ~275-GeV muons, where the error is systematic. This limit is based on 761 multimuon events corresponding to an integrated luminosity[2] of $0.7 \times 10^{39}$ cm$^{-2}$. A third muon was observed in 11% of these events. No calorimetric information was available. With 48% Υ acceptance, the BCDMS limit corresponds to ≤2 Υ candidates (at 90% confidence level). In total, the experiment observed 24 events between 8 and 12 GeV/$c^2$ in dimuon mass. These were compared to a calculated background of 30 electromagnetic tridents in the same region.

We have calculated the expected Υ rates using a photon-gluon-fusion ($\gamma$GF) model[3] which accounts[4] for most of the published features[1] of $\psi$ muoproduction. It uses a Bethe-Heitler diagram for heavy-quark–pair production with the nuclear photon replaced by a gluon. Additional soft-gluon exchanges needed to conserve color are assumed not to affect the kinematics. With a distribution $G(x) = 3(1-x)^5/x$ in gluon momentum fraction $x$, a bottom quark mass $m_b = 4.7$ GeV/$c^2$, a bottom quark charge $|q_b| = \frac{1}{3}$, and a strong-coupling constant $\alpha_s = 1.5/\ln(4m_{b\bar{b}}^{-2})$, where $m_{b\bar{b}}$ is the mass in GeV/$c^2$ of the produced quark pair, the model predicts Υ muoproduction cross sections of $0.13 \times 10^{-36}$ cm$^2$ at 209 GeV and $0.28 \times 10^{-36}$ cm$^2$ at 275 GeV. With $B(\Upsilon \to \mu^+\mu^-) = (3.1 \pm 0.9)\%$,[5] the expected values of $B\sigma$ are $(4.0 \pm 1.2) \times 10^{-39}$ and $(8.7 \pm 2.5) \times 10^{-39}$ cm$^2$, respectively. The BCDMS upper limit is $(70 \pm 40)\%$ of the latter cross section.

Figure 1 displays the spectrum in dimuon mass $M_{\mu^+\mu^-}$ from this experiment. Events below 5 GeV/$c^2$ in $M_{\mu^+\mu^-}$ are reconstructed and momentum fitted as described in Ref. 1. Above 5 GeV/

 