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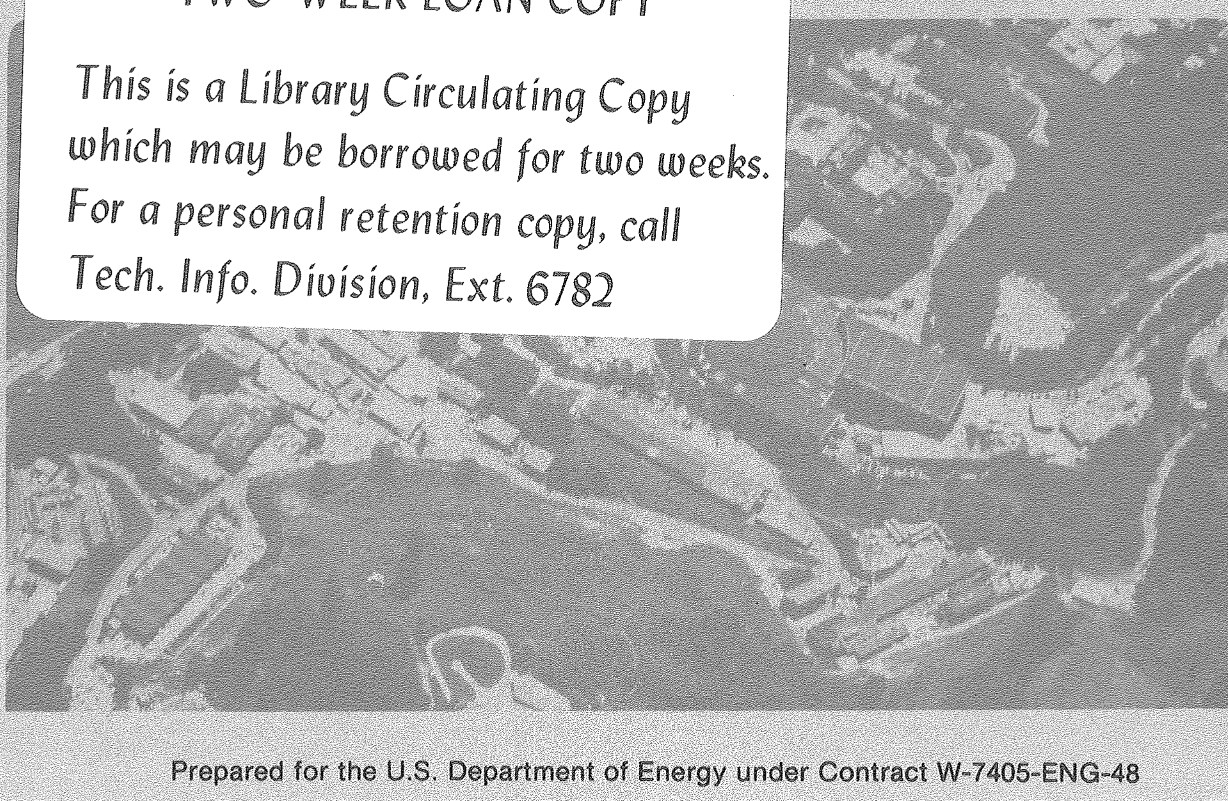

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Abstract

Interactions of 209-GeV muons in the Multimuon Spectrometer at Fermilab have yielded 20072 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}_{-130}) nb, too small to explain the high-energy rise in the photon-nucleon total cross section.

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

One model-dependent measurement of the charm muoproduction cross-section at 275 GeV has been previously reported[4] as 3±1 nb. Wide-band photon-beam experiments have measured cross sections at ~100 GeV of 720±290 nb for $D^0\bar{D}^0$ pair production[5] and 492±267 nb for inclusive D^0 production[6]. In no case have the statistics permitted discrimination between charm-production models.

This experiment identifies charmed states by their $\geq$ 3-body decays into muons. Particular charmed hadrons are unresolved. These states appear in our sample in proportion to their production rate and leptonic branching ratio. Although not suited to a first observation of charmed states, this continuum charm signature is the only reasonable explanation for 81±10% of the 20072 single-extra-muon final states reported here. These high statistics, coupled with the unambiguous determination of virtual-photon four-momenta, make possible the study of charm-production mechanisms.

The solid-iron-dipole spectrometer and the reconstruction algorithms used here have been described earlier[7]. The 2μ trigger required a $\gtrsim$ 20 GeV hadronic shower $\gtrsim$2m upstream of $\geq$ 2 hits in each of three consecutive trigger hodoscopes. Full tracking capability in an area including the beam region produced a high, nearly Q^2-independent acceptance. Data are reported from 1.4×10^{11} positive and 2.9×10^{10} 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 applied to $\mu^+\mu^-$ final states as a check.

Regions of rapidly varying acceptance are excluded by requiring daughter muon energies to exceed 15 GeV, reconstructed vertices to lie in the upstream 60% of the target volume, and shower energies to exceed 36 GeV. To avoid contamination from low-mass muon tridents, the daughter muon is required to possess at least 0.45 GeV/c momentum transverse to the scattered muon.

The spectrometer is modeled by a Monte Carlo (MC) simulation similar to that discussed in Ref. 7. Pairs of charmed quarks ($c\bar{c}$) of mass 1.5 GeV are generated according to a γGF model with a distribution $3(1-x)^5/x$ in gluon momentum fraction x. The strong coupling constant is taken as $1.5/\ell n(4m^2_{c\bar{c}})$. Quark pairs carrying the full photon energy are transformed to D mesons using a fragmentation function[8] $\mathcal{D}(z)=(1-z)^{0.4}$; z is $2\bar{E}_D/m_{c\bar{c}}$, where $\bar{E}_D$ 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 $(D \rightarrow K\mu\nu):(D \rightarrow K^*\mu\nu)$ ratio is taken[10] as 0.61:0.39. Other charmed states and decays are not explicitly simulated. The diffractive and shadowing parameters which are used to describe incoherent and coherent charm production are the same as those adopted in our ψ analysis[7]. If instead we ignore nuclear coherence and shadowing, the reported free nucleon cross sections increase by 9.4%.

Decay in flight of muoproduced π and K mesons is the major background.

It is simulated using inelastic structure functions[11] and $\pi^{\pm}$, $K^{\pm}$ production data[12] taken from another muon experiment. Bubble chamber data[13] are used to parameterize secondary meson-nucleon interactions. This use of experimental input makes the simulated background independent of hadron production models. Comparison of the quantities in Table I rules out any possibility that π and K decay explain the data. On average, the differences between means of data and Monte Carlo distributions are 3.7 times smaller for charm than for the background.

Excluding data with $\nu < 75$ GeV further improves the signal-to-background ratio. With this cut, the absolutely normalized π, K-decay calculation accounts for only 19% of the sample.

Contamination from partially reconstructed muon tridents is calculated[14] to be less than 5% because of the shower energy requirement. As an additional check, the two most energetic muons in all 3μ final state events were subjected to the 2μ analysis. Events surviving this partial reconstruction numbered only 3.9% of the true dimuon sample. This is the expected rate from double charm decay to muons. Backgrounds from $\tau\bar{\tau}$ and bottom quark pair production are negligible[14].

Figure 1(a)-(f) compares the background-subtracted charm signal with the γGF prediction. The data are modeled precisely in ν 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%; however, this variable is sensitive to diffractive slope and charm decay parameters which are not part of the γGF model. Overall, the charm MC is a sound basis for acceptance calculation.

We assign a 50% error to the size of the π, K-decay background fraction. This error is estimated in part by representing the data as different combinations of decay and γGF Monte Carlos after various cuts. The error includes the uncertainty in the measured K/π ratio[12].

The spectrometer acceptance is by far most sensitive to the energy spectrum of produced muons. Since the experimental ν distribution already is faithfully simulated, that sensitivity is best studied by varying the fragmentation function. Remodeling with $\mathcal{D}(z)=(1-z)^3$ and $\mathcal{D}(z)=(1-\min(z,0.99))^{-1.5}$ 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 $>5\sigma$ 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 π, K-decay normalization uncertainty and the fragmentation-induced changes in acceptance. As another check, the corrected opposite-sign to same-sign ratio for background-subtracted events is 1.066 ± 0.028 (±0.055). The last figure is the systematic error in the 26% relative acceptance correction. Other results cited herein are also independent of the produced muon's charge.

The measured cross section for diffractive charm production is

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

where the error is systematic. "Diffractive production" refers to creation of $c\bar{c}$ pairs which carry off most of the laboratory energy of the virtual photon, as in the γGF and VMD models. With the present cuts our data are insensitive to other possible mechanisms producing charm nearly at rest in the virtual photon-nucleon center of mass. The measured cross section is 37% higher than the 5.0 nb γGF prediction calculated with the parameters mentioned above. Corrected by x1.45 for the different beam energy, it is ~3 times the cross section reported by Michigan State-Fermilab[4].

The muon cross section is expressed as an effective photon cross section σ_{eff} by factoring out the equivalent flux[15] of transversely polarized virtual photons. The extrapolation of σ_{eff} to $Q^2=0$ using a VMD propagator $(1+Q^2/\Lambda^2)^{-2}$ is shown in Fig. 2(a), (b). The best fit propagator masses are $\Lambda=3.3\pm0.2$ and $\Lambda=2.9\pm0.2$ GeV/c^2 for $\nu=178$ and 100 GeV, and the intercepts at $Q^2=0$ are 750^{+180}_{-130} and 560^{+200}_{-120} nb, respectively[16]. The rise of 190^{+34}_{-52} nb in the charm photoproduction cross section is significant, while the difference of 0.39 ± 0.18 GeV/c^2 in propagator masses suggests some ν-dependence in the Q^2 shape[3]. In all cases except the last, the error is largely systematic. Figure 2(c) emphasizes that the diffractive charm production rate is too small to saturate the rise[17] of the total γN cross section above 50 GeV.

Using SPEAR data[10] one may very roughly estimate the neutral D:charged D:F:Λ_c ratio to be 2:1:1:1 at $m_{c\bar{c}}$ ~4-5 GeV/c^2. Applied to the average of the D^0 photoproduction cross sections cited above[5,6], this estimate implies a total charm photoproduction cross section of ~1500 nb, with substantial uncertainty. This exceeds but may be marginally compatible with extrapolation of this experiment's data to $Q^2=0$. The model used in the analysis of Refs. 5 and 6 assumes diffractive charm production with $\mathcal{D}(z)=1$ and no dependence on photon energy above 50 GeV. The dashed curve in Fig. 1(a) shows that the muon data do not support these assumptions.

We have published results corresponding to a 25±8 nb elastic ψ photoproduction cross section at 100 GeV[7]. The results reported here fix the ratio of elastic ψ to diffractive charm photoproduction at 0.045±0.022, ~2.5 times the VMD prediction of Ref. 1. In that particular picture this result suggests that *non*-diffractive charm production accounts for a significant fraction of the total charm-photoproduction cross section. Independent of VMD, these data and the analysis of Ref. 1 produce the lower limit

$$\sigma_{total}(\psi N) \geq 0.9 \text{ mb (90\% confidence)}.$$

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TABLE I. Mean values of six reconstructed kinematic quantities for data before background subtraction, for charm MC, and for π, K-decay MC. The inelasticity is defined as $1 - E(\text{daughter } \mu)/\nu$. Errors are statistical.

Reconstructed kinematic quantity	Data	Monte Carlo Charm	Monte Carlo $\pi, K \to \mu$
$\langle\nu\rangle$ (GeV)	127.0 ± 0.2	132.7 ± 0.3	109.8 ± 1.0
Geometric mean Q^2 $(\text{GeV}/c)^2$	0.767 ±.004	0.875 ±.006	0.562 ±.011
$\langle$Daughter μ energy$\rangle$ (GeV)	25.63 ±0.07	26.05 ±0.08	22.87 ±0.21
$\langle$Inelasticity$\rangle$	0.785 ±.001	0.794 ±.001	0.773 ±.003
$\langle$Missing energy$\rangle$ (GeV)	14.03 ±0.14	13.60 ±0.18	2.25 ±0.53
$\langle p(\text{daughter}) \perp \text{ to } \gamma_V\rangle$ (GeV/c)	0.750 ±.003	0.677 ±.003	0.618 ±.008

Figure Captions

FIG. 1. Reconstructed distributions in (a) energy transfer, (b) momentum-transfer-squared, (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 π, K-decay background, absolutely normalized to the integrated beam flux. Erect histograms exhibit data after subtraction of this background; statistical errors are shown. The curves, normalized to the subtracted data, are the photon-gluon-fusion charm calculation. The dashed curve in (a) represents an alternate model in which $D\bar{D}$ pairs carrying the full photon energy are produced with a probability independent of ν. Events in (c) have $\nu > 150$ GeV. The horizontal brackets exhibit typical apparatus resolution (rms). The arrow in (e) shows the shift caused by a ±2.5% excursion in calorimeter calibration.

FIG. 2. Diffractive charm photoproduction cross sections and the rise of the photon-nucleon total cross-section. Parts (a) and (b) exhibit the extrapolation of the effective cross-section for diffractive charm photoproduction to $Q^2=0$ at $\nu =$ (a) 178 and (b) 100 GeV. Statistical errors are shown. The solid curves are fits to $\sigma_0(1 + Q^2/\Lambda^2)^{-2}$ with $\Lambda=$ (a) 3.3 and (b) 2.9 GeV/c; the arrows labelled "NOM" exhibit σ_0. Systematic errors are parameterized by (1) decreasing, (2) increasing by 50% the subtracted π, K-decay background, and by recalculating the acceptance with a (3) softer, (4) harder quark fragmentation function as described in the text. Systematic effects on σ_0 are indicated by numbered arrows and effects on Λ are indicated by dashed curves, normalized to the same σ_0. Part (c) compares the extrapolated cross-

sections for diffractive charm production by real photons (data points, right scale) with a fit (see Ref. 17) to half the total photon-deuteron cross-section (curve, left scale). Systematic uncertainties dominate the errors.

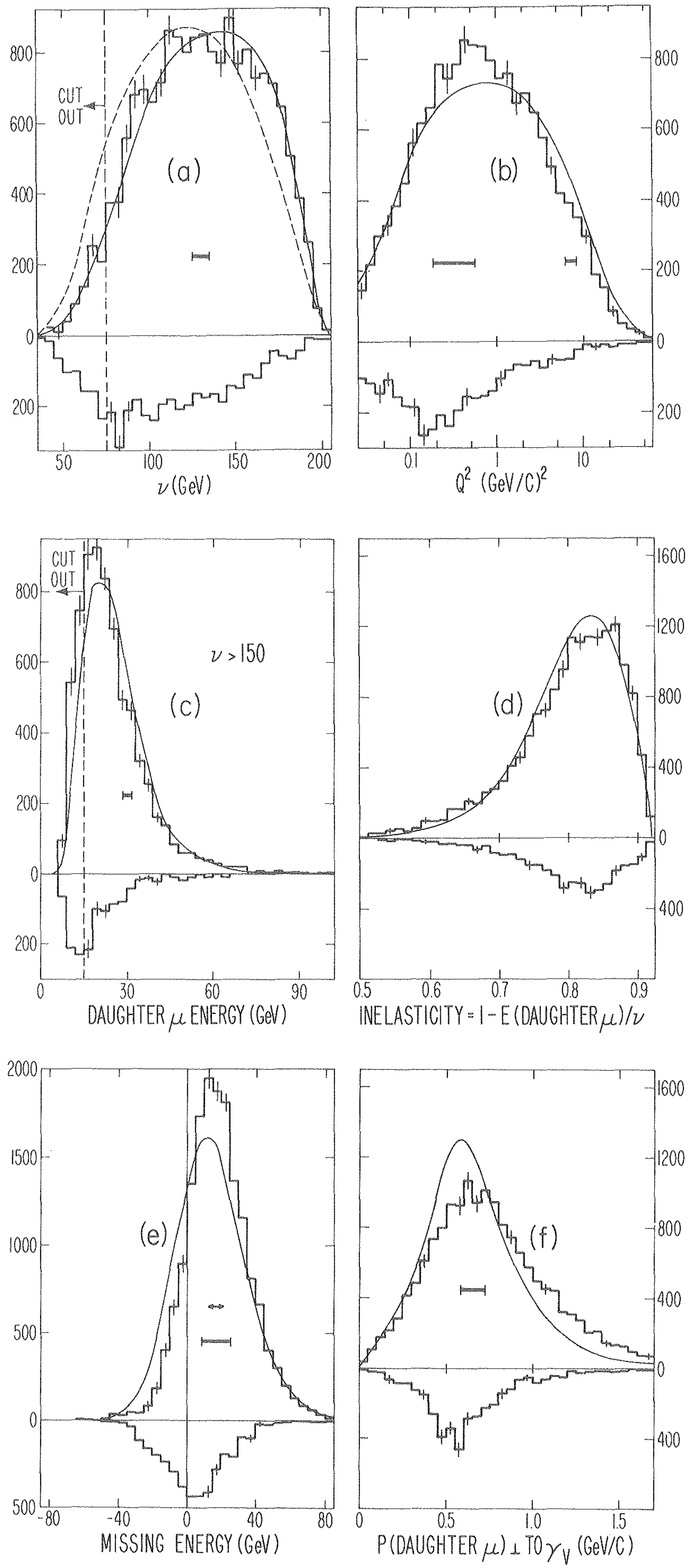

FIG. 1

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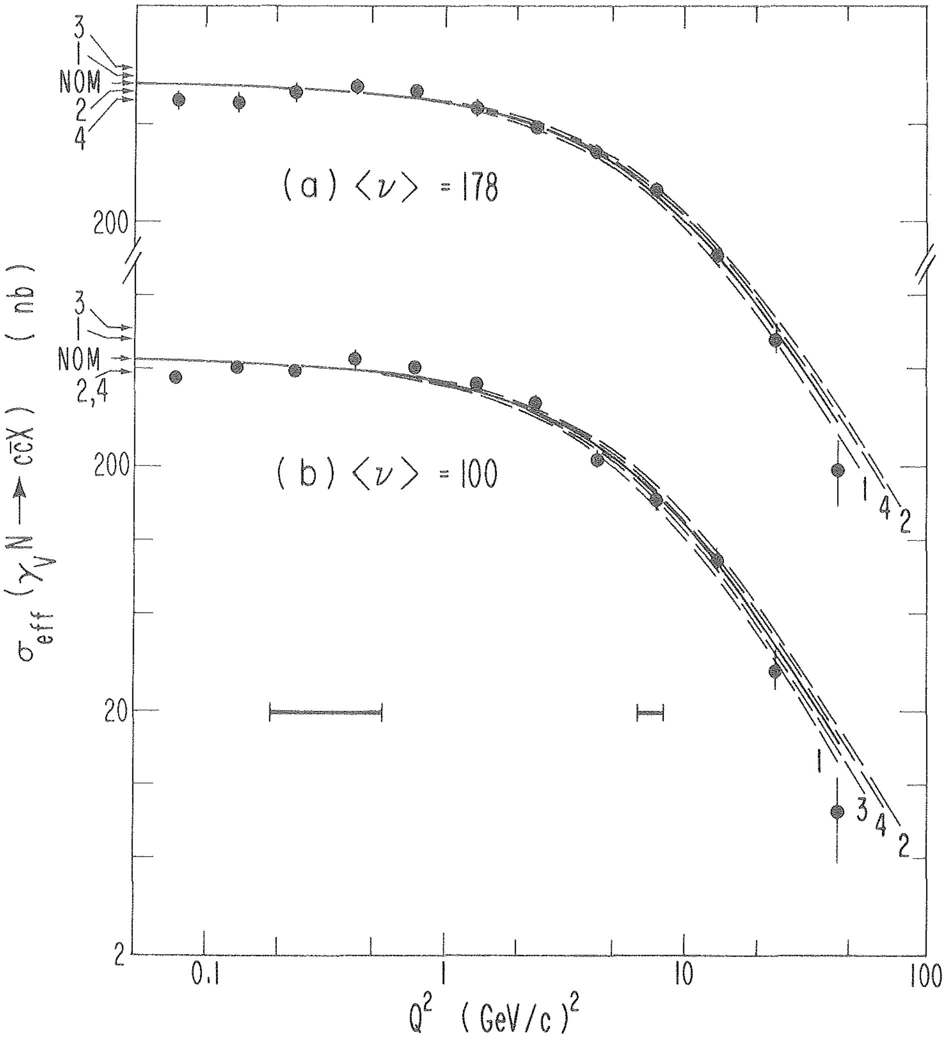

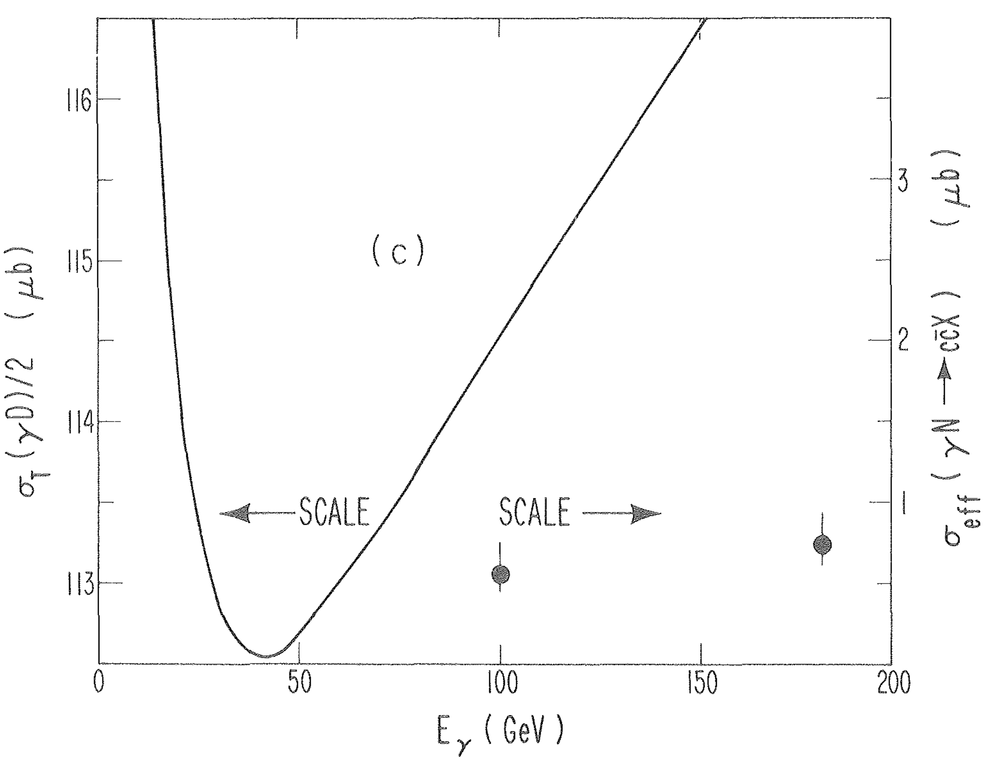

FIG. 2

XBL 803-8732