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Columbia University, New York, New York 10027

and

B. C. Brown, J.-M. Gaillard, and T. Yamanouchi
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

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J. M. Weiss, J. K. Yoh
Columbia University, N. Y., N. Y. 10027‡
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B. C. Brown, J.-M. Gaillard*, T. Yamanouchi
Fermi National Accelerator Laboratory, Batavia, Ill. 60510

ABSTRACT

Direct production of electrons and muons is observed in 300 GeV p-Be collisions. The yields are much higher than predicted by current models. Data are consistent with charge symmetry and universality.

We describe here the observation of high transverse momentum electrons and muons produced directly in proton-beryllium collisions at 300 GeV.[1] The primary motivation for this measurement is the search for the parents of "direct" leptons.[2] Candidates for the parents include (i) virtual massive photons, (ii) vector mesons (ρ, ω, ϕ ...) produced with large transverse momentum, (iii) intermediate bosons ($W^{\pm}$, Z^{0} ...), (iv) charmed particles, (v) heavy leptons.

Electron detection has the virtue of high resolution in energy and angle. This is important in maintaining sensitivity to "bumps" which would be generated by the two-body decay of one of the above parents with discrete mass M produced with small transverse momentum. A peak would appear in the lepton transverse momentum spectrum at a value of $P_{\perp} = M/2$. Muon detection has the complementary advantage of having backgrounds (π and K decay) which are lower by a factor of ~4.

DIRECT ELECTRON OBSERVATION

The electron experiment is performed with the apparatus already described.[3] A magnetic momentum analysis followed by shower detection in a lead glass spectrometer provides hadron rejection of a factor of $\sim 10^{5}$. Efficiencies for electron detection are determined by studying the effect of cuts on an electron enriched sample of events. A ready source of calibration electrons is obtained by inserting a

1 radiation length converter into the intense γ flux from the target.

Two important backgrounds are the γ conversion in the minimum of material in the secondary beam and the π^o Dalitz decays. Both of these can be subtracted with high precision by the following method. A series of foils of known thicknesses are inserted into the secondary beam and the electron yield is plotted as a function of foil thickness (Fig. 3a of the previous Letter). This permits us to extrapolate back (0.7% of a radiation length at 83 mr and 0.9% at 50 mr, including target thickness) to zero matter in the secondary beam. This leaves an electron signal due only to short lived sources. The contribution of Dalitz pairs is also known since they are derived from the same parent π^o spectrum measured by the slope of the foil conversion curve (with a small correction for the finite mass of the Dalitz pair). Other background sources, listed in Table I, are negligible.

The residue after subtractions is the direct electron signal, statistically significant to better than 10 standard deviations. This signal, at a consistent level of $\sim 10^{-4}$ of the π^o's, persists in spite of a large series of critical tests for spurious sources: collimator wall conversions, hadron background, extrapolation non-linearities, air contamination of the He in the target region and dependence on the viewing angle.

The extrapolation is done in bins of transverse momentum for both electrons and positrons. The charge asymmetries of the directly produced electrons are given in Fig. 1a. The two charges have equal yields and are averaged to give the invariant cross sections in Fig. 1b. The plotted errors are statistical only. While overall normalization uncertainties may be as high as 50%, the ratio of direct electrons to π^o's is quite well measured by comparing the signal with the slope of the foil conversion curve in each transverse momentum bin. The variation in this ratio with $P_\perp$ is shown in Fig. 1c.

The cross sections are seen to fall smoothly over 4 decades with no evidence of bumps. It should be noted that the acceptance is relatively flat out to $P_\perp \sim 11$ GeV/c, the kinematic limit. A run with 5 cm of lead at 6 m from the target demonstrates experimentally that the source of the electrons must have a lifetime less than 10^{-9} M sec, where M is the mass of the parent in GeV/c^2.

DIRECT MUON OBSERVATION

To detect muons, we add to our apparatus (1) x and y hodoscopes at 10 m from the target to improve background rejection and (2) a hadron absorber, 0.9 m of heavimet on a movable sled. The face of the absorber can be placed as close as 32 cm from the center of the target and its position is varied in order to change the decay-in-flight path of π's and K's. The absorber subtends at least 35 mr beyond the actual acceptance so that all but an insignificant number of particles must traverse the entire absorber in order to be accepted. Two additional absorbers (2 m of graphite and 0.5 m of polyethylene) are permanently mounted downstream. These additional absorbers do not significantly affect the multiple scattering and together with the heavimet absorber reduce the flux of hadrons traversing our apparatus by a factor of 10^4. The remaining hadrons (~ 1/2 of the particle flux) are identified with a hadron calorimeter.[3]

Extrapolation of the muon yield to zero decay path for hadron decay results in the "direct production" muon signal. Fig. 2a shows a sample of the data plotted as a function of the available decay path (including the 15 ± 3 cm mean decay path in the heavimet). A clear signal, equivalent to ~ 50 cm of π and K decay path, is seen. The signal corresponds to ~ 10^{-4} of the pion production. Backgrounds, such as long lived hadronic sources, muon leakage around the absorber and target out events, are all negligible.

Multiple scattering effects, the critical corrections in this type of experiment, are evaluated by Monte Carlo calculations. Since all the absorbers are always in the path of the accepted particles, the change in acceptance is due to the change in lever arm in the multiple scattering and amounts to less than 30% for $P_\perp > 2.5$ GeV/c. The effect of the energy loss in the absorbers is simply to shift the spectrum in $P_\perp$ by a well known amount.

Figure 2b shows our preliminary results for $p + Be \rightarrow \mu +$ anything. Again, μ^+/μ^- is consistent with 1. Although the muon invariant cross section is, at present, lower than the electron cross section, our absolute normalization uncertainty of 50% could account for the difference.

CONCLUSIONS

In seeking to interpret these results, we can tentatively exclude W's as the parents since these would produce a peak and the charged variety should show a +/- asymmetry. Charmed particles may also show a charge asymmetry. Only a double arm experiment[4] can establish whether we are observing single leptons from the decay of forward massive virtual photons or the leptonic decay of high $P_\perp$ low mass particles (e.g. vector mesons). Table II lists the standard vector mesons and their relative contributions to the direct lepton signal, assuming the spectrum of each vector meson is the same as the observed spectrum of neutral pions.[3]

An explanation of the lepton flux, consistent with the equality of the three pion charge states and not violating the K/π ratio, is $\rho^{\pm} = \rho^{o} = \omega^{o} = \phi^{o} \sim 4$ times the direct (i.e., not from vector meson) π^{o} production. The direct leptons then arise primarily from the ϕ^{o}. The constancy of the ratio of leptons to pions vs. $P_\perp$ tends to favor this hypothesis. An overwhelming production of vector mesons in close hadron collisions, if confirmed, may have profound implications for the strong interactions. For reference, we note that the lepton yields observed here are 1-2 orders of magnitude higher than the predictions of parton annihilation models.[5] We are aware of two other searches for muons[6,7] and one for electrons[8] which give similar results.

Assuming that three events within a resolution bin (± 3% for electrons) would have been observed with a 95% confidence level, we set a limit on the production of leptons with $P_{\perp} >$ 4.5 GeV/c of $\sigma < 10^{-34}$ cm^2. To make more incisive statements on the production of W's, etc., one requires plausible models for production and decay, a commodity in rare supply these days. Data on massive photon production would be even more useful.[4]

It is a pleasure to thank the staff of the Fermi National Accelerator Laboratory and especially of the Proton Section for their efforts. We are also deeply indebted to Messrs. T. E. Nurczyk, F. H. Pearsall and S. J. Upton and the Nevis Laboratories for their help in the design and implementation of the apparatus.

FOOTNOTES AND REFERENCES

*Permanent address: Laboratoire de l'Accélérateur Linéaire, Orsay, France

†Present address: Rutherford High Energy Laboratory, Chilton, Didcot, Berkshire, England

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[1]A preliminary report of this work has been given: H. P. Paar et al., Bull. Am. Phys. Soc. 19, 446 (1974).

[2]L. M. Lederman and D. H. Saxon, Nucl. Phys. B63, 313 (1973).

[3]J. A. Appel et al., preceeding Letter.

[4]Such an experiment is scheduled to run at FermiLab (E-288) in late 1974.

[5]See for example G. R. Farrar, California Institute of Technology preprint CALT-68-422 (1974), H. P. Paar and E. A. Paschos, FermiLab preprint, NAL-Pub-74/29 THY, to be published in Physical Review and R. Savit and M. B. Einhorn, FermiLab preprint NAL-Pub-74/35 THY, to be published in Physical Review.

[6]J. P. Boymond et al., post-deadline paper, Bull. Am. Phys. Soc. 19, (1974) and Phys. Rev. Letters 33, 112 (1974).

[7]D. Bintinger et al., post-deadline paper, Bull. Am. Phys. Soc. 19, (1974).

[8]CERN-Columbia-Rockefeller-Saclay Group, ISR, private communication.

TABLE I

Electron yield, Normalized to π^0 Yield[a]

$1.9 < P_\perp < 4$ GeV/c

$\left.\begin{matrix}\pi^0\\ \eta^0\end{matrix}\right\} \to \gamma + e^+ + e^-$	$\dfrac{[1.6 + 0.8\ \eta^0/\pi^0] \times 10^{-4}}{(1 + 0.38\ \eta^0/\pi^0)}$
$\mu^- \to e\nu\bar{\nu}$	10^{-8}
$\bar{\pi} \to e\nu$	10^{-7}
$K^- \to \pi^0 e^- \bar{\nu}$	3×10^{-6}
$K_L^0 \to \pi^+ e^- \bar{\nu}$	2×10^{-6}
Hyperons	$3 \times 10^{-6} x(\text{hyperon}/\pi)$
Signal	$\sim 1 \times 10^{-4}$

a) We assume in the paper that γ's arise from π^0's. If η^0 production were to equal π^0 production there would result a 7% increase in the Dalitz subtraction.

TABLE II

Direct Lepton Sources

$\langle P_\perp \rangle \sim 3$ GeV/c

Source	N_ℓ/N_{π^0}	
$\rho^0 \rightarrow \ell^+ \ell^-$	5×10^{-6}	Assuming $N_V = N_{\pi^0}$
$\phi^0 \rightarrow \ell^+ \ell^-$	3×10^{-5}	
$\omega^0 \rightarrow \ell^+ \ell^-$	7×10^{-6}	
$q\bar{q} \rightarrow \ell^+ \ell^-$ (Drell-Yan)	$\sim 5 \times 10^{-6}$	
Signal	$\sim 1 \times 10^{-4}$	

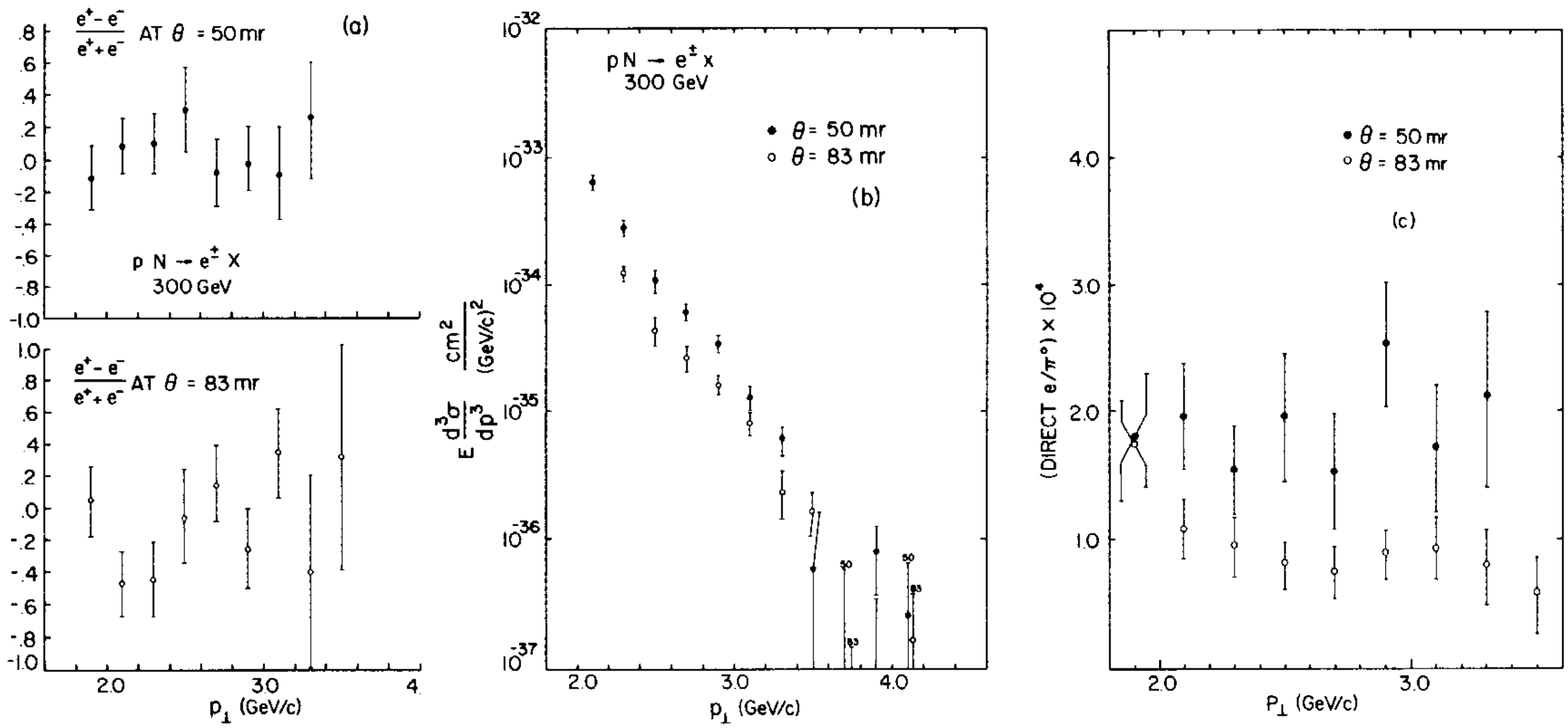
Figure 1: a) Comparison of positive and negative direct electrons at 50 mr and 83 mr (corresponding to 65^{o} and 93^{o} in the p-nucleon center of mass system).

b) Invariant cross sections per nucleon for direct electrons.

c) Direct electron to π^{o} ratios.

Figure 2: a) Muon yield vs. decay path. The slope gives the contributions of pions and kaons. $(2.0 \leq P \leq 2.6$ GeV/c). The corrections are for multiple scattering effects.

b) Invariant cross section per nucleon for direct muons near 90^{o} in the center of mass system.



$\frac{e^+ - e^-}{e^+ + e^-}$ AT θ = 50 mr
(a)
p N → e± X
300 GeV
$\frac{e^+ - e^-}{e^+ + e^-}$ AT θ = 83 mr
$p_\perp$ (GeV/c)
p N → e± X
300 GeV
• θ = 50 mr
○ θ = 83 mr
(b)
$E \frac{d^3\sigma}{dp^3}$ $\frac{cm^2}{(GeV/c)^2}$
$p_\perp$ (GeV/c)
• θ = 50 mr
○ θ = 83 mr
(c)
(DIRECT e/π^0) × 10^4
$P_\perp$ (GeV/c)

Fig. 1

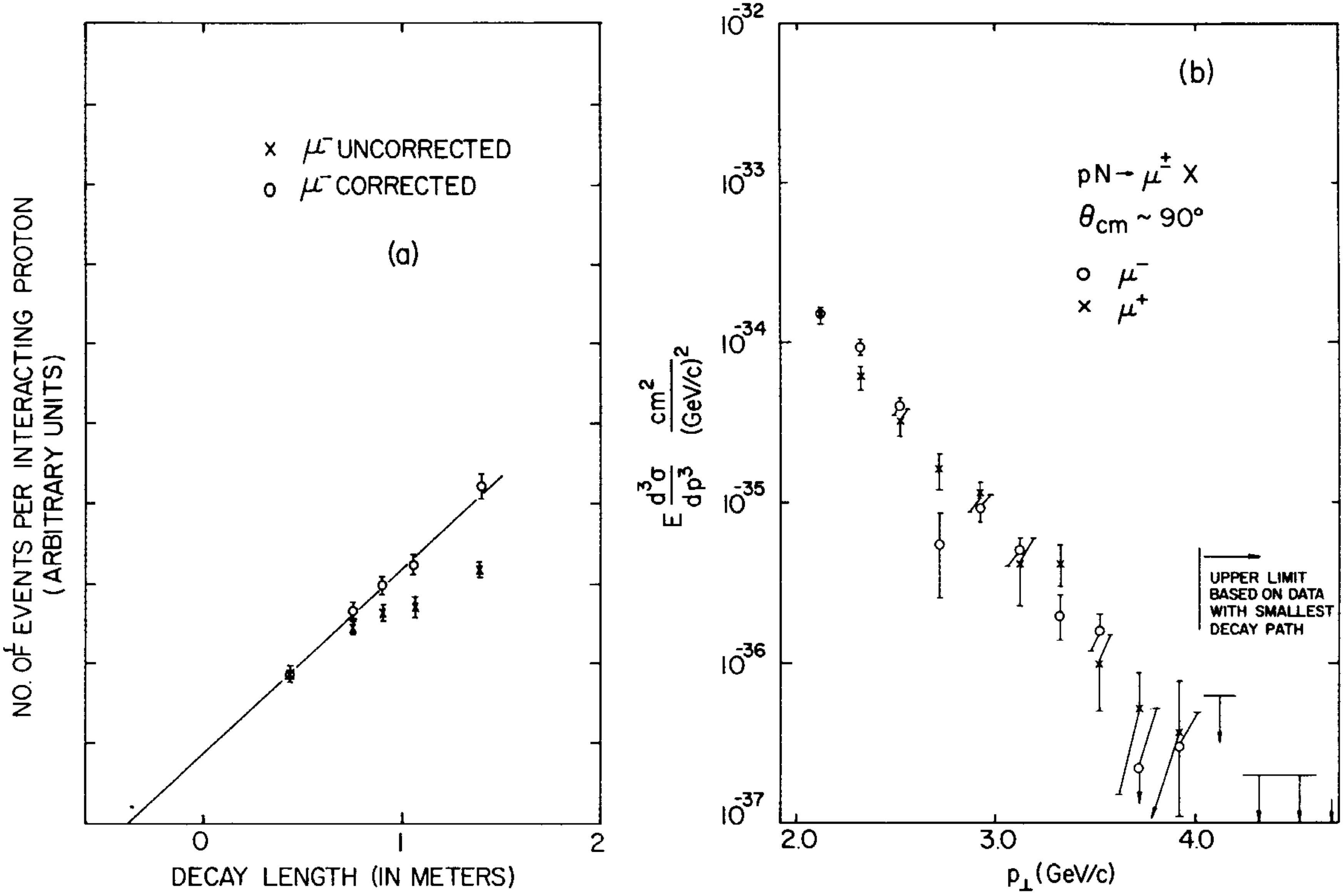

NO. OF EVENTS PER INTERACTING PROTON
(ARBITRARY UNITS)
x μ⁻ UNCORRECTED
o μ⁻ CORRECTED
(a)
0
1
2
DECAY LENGTH (IN METERS)
(b)
pN → μ± X
θcm ~ 90°
o μ⁻
x μ⁺
E d³σ/dp³ cm²/(GeV/c)²
10⁻³²
10⁻³³
10⁻³⁴
10⁻³⁵
10⁻³⁶
10⁻³⁷
UPPER LIMIT
BASED ON DATA
WITH SMALLEST
DECAY PATH
2.0
3.0
4.0
p⊥ (GeV/c)

Fig. 2