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Measurement of Muon-Pair Photoproduction in the Deep Inelastic Region*

J. F. Davis, S. Hayes,† R. Imlay,‡ P. C. Stein, and P. J. Wanderer
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14850
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The inclusive cross section for low-mass muon pair photoproduction has been measured in the deep inelastic region. The measured cross section is much larger than that expected for one-photon (Bethe-Heitler) processes. This result may be additional evidence for pointlike structure (partons) in nucleons. The experimental results are compared with the parton model of Bjorken and Paschos. The value of the cross section predicted by this model is too low.

Electron-scattering experiments in the deep inelastic region[1,2] have shown that the cross sections for excitation of nucleons in the continuum region scale and are large. The existence of pointlike charged particles (partons) within the nucleon has been proposed to explain these results. Bjorken and Paschos[3] have suggested that deep inelastic two-photon processes may be a test of some aspects of the parton models. Such processes include inelastic Compton scattering[4] and its analog, the inclusive photoproduction of low-mass muon pairs in the inelastic region. The latter process must be separated from the usual Bethe-Heitler production of muon pairs. Bethe-Heitler production is calculable[5] from the nucleon electromagnetic structure functions. An excess in the cross section can be attributed to the Compton diagram.

This paper reports a measurement of the photoproduction of low-mass muon pairs in the deep inelastic region. Photons produced by bremsstrahlung of 11.7-, 10-, and 8.5-GeV electrons at the Cornell University Wilson Synchrotron Laboratory were incident on a beryllium target. Targets of 9.4 and 14.1 g/cm^2 were used. The technique for the detection of the muons was similar to that employed in previous experiments.[6] It makes use of the difference between the absorption lengths of muons and other particles. Muons passed through absorber A, hodoscope H_F, twelve scintillation counters R alternated with iron, and hodoscope H_R, and stopped in a thick iron pack before reaching counters V (Fig. 1). The apparatus detected muons produced between 10° and 15° with respect to the incident beam and with energies between 2.58 and 3.49 GeV. Hodoscope H_F defined the solid-angle acceptance (0.0154 sr) of the experiment. The R counters

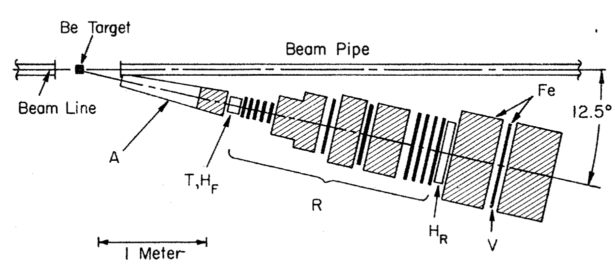

FIG. 1. Schematic diagram of the detector. Each gap in the iron contains a single R or V counter, as indicated. Lead shielding between the detector and the photon beam is not shown. The beam enters from the left.

were sufficiently larger than this solid angle so that losses due to multiple scattering were negligible. Enough iron was placed between each of these counters to ensure the statistical independence of the pulse heights of neighboring counters. The trigger required two or more particles in H_F and a single particle in R.

The output pulse from each counter was split; one of the two signals was delayed an additional 30 nsec. Both prompt and delayed signals were included in the trigger logic, so that coincident muons or muons separated by 30 nsec produced triggers. For each trigger, the pulse heights of the counters for both prompt and delayed signals were recorded. The times at which particles crossed the counters in H_F relative to a reference signal generated by counter T were also recorded. This measurement determined two-particle coincidences with a resolution of 0.9 nsec full width at half-maximum.

The single-particle pulse-height spectrum for each counter was obtained by relaxing the trigger logic for every tenth trigger so that only a single particle was required. The observed single-particle spectrum was then separated from the background due to low pulse heights. The spectrum expected for two particles was calculated by taking a convolution of two singles spectra and a background spectrum. A cut on the pulse height was established at the 1% level of this calculated two-particle spectrum which rejected, typically, $\frac{3}{4}$ of the single particles.

The analysis criteria which defined muon-pair events required that two particles pass through H_F and H_R, that the R-counter pulse heights exceed the pulse-height cuts, that the timings in H_F be coincident within ± 1.0 nsec, and that there be no particles in V. One additional cut, discussed below, was also imposed. In the final sample of data there were 275 events at 11.7 GeV, 257 events at 10 GeV, and 70 events at 8.5 GeV. The target-out rate was negligible. Corrections were made for computer dead time (typically 9%), dead time in T (6%), hodoscope inefficiency (6%), loss due to timing cuts (4%), loss due to the pulse-height cut (12%), triggering inefficiency (4%), and accidental coincidences (15%).

Checks were made of the validity of the interpretation of the pulse-height data. The statistical independence of the pulse heights of different counters was verified by calculating correlation coefficients for the observed single-particle spectra.

The pulse-height spectra of the final sample of data were compared to the calculated spectra by defining a likelihood ratio L which combined the pulse-height information from the last eight counters for each event:

$$L = \log \prod_{i=5}^{12} \frac{D_i(x_i)}{S_i(x_i)},$$

where i is the counter number, x_i is the pulse height in counter R_i, S_i is the observed single-particle pulse-height distribution, and D_i is the calculated two-particle pulse-height distribution. Figure 2 shows the distribution of L for the final sample of 10-GeV data. Also shown are the expected distributions of L for incident single particles and for incident double particles having pulse heights greater than the cut used in the experiment. This good agreement between the expected and observed distributions was obtained at each energy, indicating that the analysis criteria are sufficient and that the pulse-height spectra are well understood. The few events having $L<3.8$ were rejected.

The analysis criteria were relaxed individually to check that the observed rate was not critically dependent on the details of the experimental analysis. In one test, the magnitude of the pulse-height cuts was varied by 10%; in another test the pulse height of any one R counter was allowed to be below the cut. The change in the observed rate was negligible. In the latter test the pulse-height distribution of the counter removed from the analysis agreed with the expected two-particle distribution. The requirement of

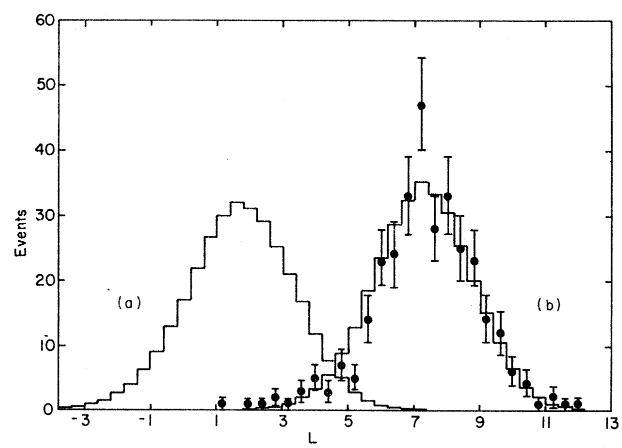

FIG. 2. The distribution of the probability ratio L for the data taken at 10 GeV is shown together with the calculated distributions of L (a) for single-particle events and (b) for double-particle events. L is defined in the text.

two particles in the rear hodoscope was dropped, and the increase in rate was consistent with expectation. Within statistical errors, data divided into high and low beam intensity runs had the same muon-pair production rate.

The expected yield for the experiment was calculated for Bethe-Heitler (BH) production[5] and for Compton production. The momentum transfer to the nucleus $[q^2=(k-p_+-p_-)^2$, where k, p_+, and p_- are the four-momenta of the photon, positive muon, and negative muon, respectively] was large for the reactions detected $[1.0\ (\mathrm{GeV}/c)^2<|q^2|<5.5\ (\mathrm{GeV}/c)^2]$. Thus, production from the beryllium nucleus was assumed to be incoherent. Fermi momentum was taken to be uniformly distributed in phase space. The effect of multiple Coulomb scattering in absorber A and in the iron was calculated using the techniques of Ref. 6. For calculations the BH production was divided into three types: elastic ($\gamma N\to N\mu^+\mu^-$, where N is a nucleon), inelastic resonance ($\gamma N\to N^*\mu^+\mu^-$, where N^* is a nucleon isobar), and inelastic continuum ($\gamma N\to X\mu^+\mu^-$, where X is any other hadronic final state). These cross sections may be written as functions of the nucleon electromagnetic structure functions $W_1(q^2,\nu)$ and $W_2(q^2,\nu)$, where $\nu=q_0$. The structure functions are determined from electron and muon scattering. In the region of q^2 and ν accepted by this experiment, reasonable estimates for W_1 and W_2 may be obtained from existing scattering data.[1,2] The expected yield due to Compton production as calculated by Bjorken and Paschos[3] may be written in the form $gW_2(q^2,\nu)(\langle\sum Q_i^4\rangle/\langle\sum Q_i^2\rangle)$, where g is a known function of the kinematic variables and $\langle\sum Q_i^n\rangle$ is derived from the average parton charge which was taken to be 1.

Table I shows the expected cross section integrated over the experimental aperture for a bremsstrahlung subtraction between $k_{max}=11.7$ and 10 GeV and between $k_{max}=10.0$ and 8.5 GeV. The invariant mass of the recoil hadron system is $W=(m_p^2+2m_p\nu+q^2)^{1/2}$. There is no contribution to the subtracted cross sections from elastic BH since in both bins $W_{min}>M_p$. The dominant contribution to the expected cross section is due to the inelastic Compton production. Table I also shows the measured cross sections. In both bins the experimental yield is much larger than that expected from the theory. This large observed cross section cannot be accounted for by the Compton process as calculated by Bjorken and Paschos.

A search was made for contributions to the observed rate due to processes other than the direct photoproduction of muon pairs in the target. An obvious source is pion pairs. While the probability for a pion to penetrate to the rear counters in the telescope is negligibly small, a pion which decays to a muon before being absorbed will simulate a muon produced in the target. This contribution can be substantially increased by lengthening the decay region following the target. Therefore, a run was made with the distance from the target to the absorber increased from 9 to 35 in. The aluminum in absorber A was replaced with iron so that the range acceptance of the telescope remained unchanged. No statistically significant increase in the cross section was observed, and an upper limit of 10% was placed on this contribution to the total observed rate.

Attempts were made to estimate the background due to other processes. The following channels were considered:

$$\gamma N\to\rho X,\quad \rho\to\mu^+\mu^-; \tag{a}$$

$$\gamma N\to\rho X,\quad \rho\to\pi^+\pi^-\to\mu^+\mu^-; \tag{b}$$

$$\gamma N\to\eta X,\quad \eta\to\gamma\mu^+\mu^-; \tag{c}$$

TABLE I. The calculated and measured cross sections for muon-pair photoproduction, integrated over the experimental apparatus. Units are picobarns per photon per beryllium nucleus. The kinematic parameters are defined in the text. The errors shown are statistical; normalization uncertainty is ~10%.

Photon energy bin (GeV)	Kinematic region	Resonance BH	Continuum BH	Inelastic Compton	Measured
10.0–8.5	$1.7\ (\mathrm{GeV}/c)^2<\lvert q^2\rvert<4.1\ (\mathrm{GeV}/c)^2$ $1.5\ \mathrm{GeV}<\nu<4.8\ \mathrm{GeV}$ $1.1\ \mathrm{GeV}<W<2.8\ \mathrm{GeV}$	0.0006	0.0128	0.0293	0.27 ± 0.06
11.7–10.0	$2.0\ (\mathrm{GeV}/c)^2<\lvert q^2\rvert<5.0\ (\mathrm{GeV}/c)^2$ $3.0\ \mathrm{GeV}<\nu<6.5\ \mathrm{GeV}$ $1.5\ \mathrm{GeV}<W<3.3\ \mathrm{GeV}$	0.0001	0.0085	0.0403	0.75 ± 0.11

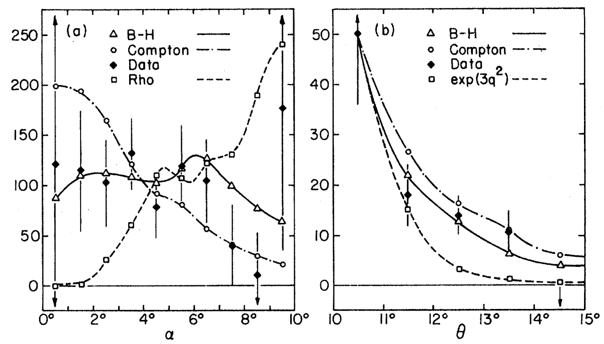

FIG. 3. Distributions (a) in muon-pair opening angle and (b) in the angle between the incident photon and the muon-pair momentum. The curves are defined in the text.

$$\gamma N \to \varphi X, \quad \varphi \to K^+K^- \to \mu^+\mu^-; \tag{d}$$

$$\gamma N \to K_S{}^0 X, \quad K_S{}^0 \to \pi^+\pi^- \to \mu^+\mu^-; \tag{e}$$

$$\gamma N \to K_L{}^0 X, \quad K_L{}^0 \to \pi\mu\nu \to \mu^+\mu^-; \tag{f}$$

where X is any final state. In addition, two mechanisms by which muon pairs might be produced in absorber A were also investigated: direct photoproduction by photons which were at large angles, or as the decay products of pions produced by pions which were at large angles. Estimates were made from generous extrapolation of known cross sections, since the appropriate inclusive hadronic cross sections for these processes are in general unknown in the region of interest to this experiment. The dominant channels were (a), (c), (d), and muon production in absorber A. The total estimated contribution of all of the above-mentioned channels was 6%, and no one channel contributed more than 2%. It should be noted that large contributions from many of the above channels are ruled out by the previously noted insensitivity of the rate to the position of absorber A.

Figure 3 shows the distributions (a) in muon-pair opening angle, and (b) in the angle between the incident photon and the muon-pair momentum. For comparison the shape of the distributions expected from inelastic BH and Compton production are indicated. Also Fig. 3(a) shows the shape expected for muon pairs from ρ decay, and Fig. 3(b) the shape expected for muon pairs produced with an exponential q^2 dependence ($d\sigma/dq^2 = Ae^{3q^2}$). As can be seen in these figures, the observed distributions are consistent with either the BH or the Compton shape. However, the observed distributions differ significantly from the expected ρ shape and from the exponential shape.

This experiment is the first measurement of lepton-pair photoproduction in the deep inelastic region. The observed cross section is much larger than that expected from BH production. The Compton production term based on the parton model of Bjorken and Paschos is too small to account for the observed results. However, these results do lend support to the idea of a direct interaction of real photons with a particulate structure within the nucleons.

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†Present address: Woods Hole Oceanographic Institute, Woods Hole, Mass. 02543.

‡Present address: Department of Physics, University of Wisconsin, Madison, Wis. 53706.

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