WIDE ANGLE PHOTOPRODUCTION OF MU PAIRS *

J. K. de Pagter
Cambridge Electron Accelerator, USA
A. Boyarski, G. Glass, J. I. Friedman, H. W. Kendall
Massachusetts Institute of Technology, USA
M. Gettner, J. F. Larrabee, Roy Weinstein
Northeastern University, USA
(Presented by J. I. FRIEDMAN)

A study has been made of the photoproduction of μ pairs carbon using a 5 GeV bremsstrahlung beam at the Cambridge Electron Accelerator. We report here the initial experimental results which when compared with theory [1, 2] provide a test of the validity of the quantum electrodynamic (QED) description of the muon propagator at squared four-momentum transfers q_m^2 up to about $8f^{-2}$.

Measurements were made of the differential cross sections in the following kinematic intervals: 1.8 Gev $\leqslant E_1, E_2 \leqslant$ 2.4 GeV, $4.5° \leqslant \theta_1, \theta_2 \leqslant 11.5°$; $-15° \leqslant \Phi_1 \leqslant 15°$; $165° \leqslant \Phi_2 \leqslant 195°$. The quantities E_1, E_2; θ_1, θ_2; and Φ_1, Φ_2 denote the total energies, the polar angles, and the azimuthal angles of the members of the pair. The μ-pair detector was a 154 counter hodoscope arranged in two similar arrays placed symmetrically on either side of the γ beam, as shown in Fig. 1. The counters nearest the target defined the polar and azimuthae angles of each member of the muon pair. The polar and azimuthal angle defining counters were placed behind 3 feet of iron in order to reduce the singles rate to an acceptable level. In each array 12 inches of iron followed the

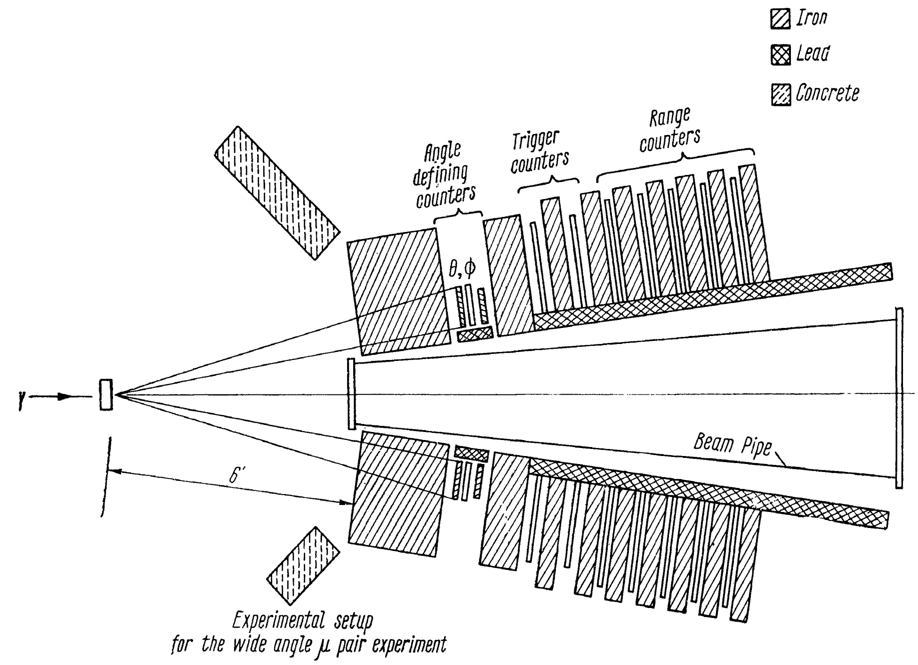

Fig. 1.

* Work supported in part by the National Science Foundation under grants NSF-G17419 and GP625 and in part by the US Atomic Energy Commission under contract AT (30-1)-2098.

angular counters and was in turn followed by a trigger array. Thus 48 inches of iron preceeded the trigger arrays in order to attenuate the pion yields. Each trigger array consisted of two layers of counters separated by 3 inches of iron. A quadruple fast coincidence of pulses from the four layers was used as a μ pair signature. This coincidence was used to gate flip flops which could store a count from each hodoscope counter. All flip flop states and additional information describing running conditions were then stored on magnetic tape after each gate pulse. Delayed coincidences used to determine the chance rate were also recorded and tagged with a distinguishing label.

In each array range counters, placed behind the trigger layers, measured the muon energies in five intervals. Consecutive layers of range counters were separated by 3 inches of iron.

Beyond 10 radiation lengths of iron, the charged particles from the target giving rise to quadruple coincidences consisted of one component which exhibited an attenuation length in iron which was in excellent agreement with measurements of π attenuation [3]. A second charged component had a distinctly different dependence on iron thickness. With the back layer of trigger counters shielded by $4-{}^1/_4$ feet or iron, this latter charged component accounted for about 95% of the detected charged particle pairs. These we identify as μ meson pairs. The yield of detectable K meson pairs (kinetic energy of each member greater than 1.8 GeV) was negligible because of the very small portion of the bremsstrahlung spectrum available for such production, and because of the relatively small production cross section.

Experimental data were corrected for rates with the target removed, chance rates, counter efficiencies, coulomb scattering losses, and backgrounds resulting from π pair production. The latter gives rise to (π, π), (π, μ), and (μ, μ) backgrounds, where the μ mesons originate from π decays in flight. Data on these backgrounds were obtained by measuring the charged particle rates behind 2 feet of iron where π pairs predominate. These measurements were made as a function of the γ end-point energy, and only the yields arising from photon energies which would permit detection of the π's or their decay μ's with our normal shielding arrangement were considered. This data gave the π pair angular distribution, which within the statistics was uniform, but did not give the energy distribution. Pessimistic but reasonable π pair energy spectra were assumed in order to include range effects in the attenuation of the π's, compute the fraction of π's decaying into π's , and make an estimate of the number of μ's with sufficient energy for detection. Except at the largest angles the backgrounds arising from π pairs were negligible. For example, for events symmetric in θ detected at about $\theta_1 \approx \theta_2 \approx 9.5°$, the percentage backgrounds compared to the μ pair rate were as follows:

$$(\pi, \pi) = 4.5\%, \ (\pi, (\mu) = 3.7\%, \ (\mu, \mu) = 6.2\%.$$

The background yields have an uncertainty of about 33% and the subsequent errors, which are included in the systematic error, are small compared to the statistical uncertainty in the final results.

The theoretical comparison with the data employed a covariant calculation of pair production in first Born approximation [4] *. The elastic form factor of carbon was taken into account by using an analytic expression for the carbon form factor that was derived from electron scattering experiments [5]. The assumption was made, as is generally done, that the form factor for scattering a virtual e or μ is the same as that for a real e or μ **. The uncertainty in the form factor is included in the systematic errors. The form factor error is a monotonically increasing function of q_N^2 (q_N is the four momentum transfer to the nucleus) starting at negligible values and rising to about 6% for the highest average values of q_N^2 that were used in obtaining the present results. This error is small compared to the statistical error in the corresponding points.

Cross sections were evaluated for all combi. nations of θ_1, θ_2, E_1, E_2, Φ_1 and Φ_2. Each cross section was calculated from a six dimensional integral over the acceptance intervals of the variables. These results were then folded with the Moliere distribution function for

* This calculation included some lepton mass dependent terms which are negligible for the electron pair production considered in (2), but not for muon pair production.

** This experiment produced sufficient data to permit investigation of the yields vs q_N^2 for various limited ranges of q_m^2. This will enable us empirically to investigate the carbon form factor for muons off the mass shell.

R vs q_m^2 for 5 selections of data in which $\theta_1 \sim \theta_2$

	$(\theta_2-\theta_1)=0.16°$		$(\theta_2-\theta_1)=0.61°$		$(\theta_2-\theta_1)=0.93°$		$(\theta_2-\theta_1)=0.42°$		$(\theta_2-\theta_1)=0.35°$		
q_m^2/fermi^{-2}	R[a]	ΔR	R	ΔR	R	ΔR	R	ΔR	R	ΔR	Systematic[b] Error
1.34	.970[c]	.166	1.252	.308	.969	.389	1.119	.133	1.201	.284	.012
1.87	1.360	.108	1.274	.127	1.277	.125	1.179	.079	1.175	.093	.014
2.48	1.253	.118	1.037	.110	1.219	.123	1.082	.094	1.053	.104	.017
3.16	1.102	.139	1.147	.138	.971	.159	1.123	.120	1.287	.121	.023
3.91	.715	.172	1.062	.182	.865	.208	1.089	.147	.894	.155	.031
4.74	1.110	.242	1.102	·251	.964	.270	1.389	.208	1.664	.366	.045
5.65	.854	.372	1.320	.340	.885	.372	1.185	.328	.958	.281	.067
6.63							1.090	.617	2.889	.673	.110
6.90	.844	.526	1.625	.477	2.216	.565					.110
7.86							1.799	.645	1.324	.717	.104

[a] $R=\sigma_{\text{exp}}/\sigma_{\text{theor}}$. ΔR is the error in R corresponding to one standard deviation.

[b] Systematic error includes error in the elastic and inelastic fom factor and the uncertainty in the π backgrond.

[c] The acceptance intervals for the yields used in obtaining the above ratios are as follows: $\Delta\Phi_1=\Delta\Phi_2=30°$, $\Delta E_1=\Delta E_2=587$ MeV, $\Delta\theta_1=\Delta\theta_2=0{,}764°$, $|\Phi_1-\Phi_2-180°|<30°$, $1820<E_1$, $E_2<2407$ MeV.

multiple coulomb scattering due to 3 feet of iron, for the target thickness, and for the finite beam size. The results were also corrected for inelastic μ pair production, with and without π production. This was done using the calculations of Drell and Walecka [6] for inelastic pair production, sum rules [7] for inelastic electron scattering, inelastic electron scattering spectra from carbon [8], and results from the electron-production of pions [9]. Inelastic pair production accounted for a negligible fraction of events at low q_m^2 and for about 8% at the highest value of q_m^2 used in the present results. The uncertainty of this yield is also included in the systematic error. Compton terms and radiative corrections are negligible and charge conjugation arguments show that interference terms between Compton and Bethe — Heitler diagrams vanish [2].

The dependence of the cross section on q_m^2 has been investigated from about $1.3\,f^{-2}$ to about $8f^{-2}$. Table shows five separate selections of data representing pair production for $|\theta_2-\theta_1| \leqslant 0.9$ degrees. This represents about half the data taken, 3736 events from a total of 8827, and was selected because of the comparatively small contamination from inelastic effects, small uncertainty in the form factor, and because q_m^2 is fairly well defined. For this data q_N^2 lies between $0.01f^{-2}$ and $1.0f^{-2}$; 95% of this data corresponds to $q_N^2 < 0.4f^{-2}$.

A least squares fit to all of the data of Table gives

$$R=(1.18\pm0.15)\,(1-[0.011\pm0.021]\,|\,q_m^2\,|)$$

where $R=\sigma_{\text{exp}}/\sigma_{\text{theory}}$. The χ^2 probability for this fit is 15%. The errors quoted correspond to one standard deviation and are combined from statistical and systematic uncertainties. The error in the slope from statistics alone is ±0.0184, whereas the major part of the uncertainty in the normalization is from systematic error which is 12%. If a breakdown model such as that proposed by Drell [1] is used, we may compare this data with the results of other experiments, although such modell are arbitrary. Following Drell we replace the rationalized muon propagator

$$1/(q_m^2-m_\mu^2)\to 1/(q_m^2-m_\mu^2)-1/(q_m^2-m^2-\Lambda_\mu^2)$$

and find that with 95% confidence $(1/\Lambda_\mu)^2 < (0.16f)^2$. For the same confidence level the Frascati measurement of muon pair production [10] yields $(1/\Lambda_\mu{}^2) < (0.23f)^2$. The g-2 experiment (11) yields $(1/\Lambda_\mu)^2 < (.1f)^2$ if all deviation from theory is entirely attributed to the muon propagator. In a model independent sense the present experiment has found agreement with the predictions of QED, both in slope and normalization, at values of q_m^2 up to about an order of magnituder larger than that previously attained in the pair production process.

REFERENCES

1. D r e l l S. D. Ann. Phys., **4**, 75 (1958); B e r e s t e t s k i i V. et al. Translation Soviet Physics JETP, **3**, 761 (1956); JETP (USSR), **30**, 788 (1956); B j o r k e n J. D., D r e l l S. D. Phys, Rev., **114**, 1368 (1959).
2. B j o r k e n J. D. et al. Phys. Rev., **112**, 1409 (1958).
3. T i n l o t J. BNL-750 (T276), (1961).
4. B j o r k e n J. D. Personal communication (1963), unpublished.
5. E h r e n b e r g H. F. et al. Phys. Rev., **28**, 214 (1956).
6. D r e l l S. D., W a l e c k a D. Personal communication (1963).
7. D r e l l S. D., S c h w a r t z C. L. Phys. Rev., **112**, 568 (1958); M c V o y K. W., V a n H o v e L. Phys. Rev., **125**, 1035 (1962).
8. L e i s s J. E., T a y l o r R. Personal communication. (We are grateful to these authors for making available their unpublished data.)
9. P a n o f s k y W. K. H., A l t o n E. A. Phys. Rev., **110**, 1155 (1958); H a n d L. N. Phys. Rev., **129**, 1834 (1963).
10. A l b e r i g i - Q u a r a n t a et al. Phys. Rev. Lett., **9**, 226 (1962).
11. C h a r p a k G. et al. Phys. Lett. **1**, 16 (1962).

DISCUSSION

B a d a l y a n

Did you analyze your data on the photoproduction of muon pairs as the result of the decay of an intermediate vector resonance, say, the ω^0 meson ?

J. I. F r i e d m an.

We have looked at the distribution of events as a function of total energy in the two muon system. In a preliminary analysis we see no bumps that could be attributed to the leptonic decays of the ρ^0 or ω^0. However, the statistics are poor at the energies corresponding to these decays.