SCATTERING OF HIGH-ENERGY POSITIVE AND NEGATIVE MUONS ON ELECTRONS

P. L. Jain and N. J. Wixon*
Department of Physics, State University of New York at Buffalo, Buffalo, New York 14214
(Received 16 July 1969)

The elastic interaction of 10.1-GeV/c positive and 14.5-GeV/c negative muons with electrons in nuclear emulsion has been studied. Energies of the knock-on electrons calculated from scattering measurements were comparable with those obtained from their ejection angles. In the case of both positive and negative muon-electron elastic scattering we did not observe any departure of the muon from a Dirac-type particle with transferred energies up to 1.4 and 3 GeV, respectively. This is in contradiction with some of the previous results.

During the past few years a number of experiments[1-5] were performed with cosmic rays to measure the muon-electron elastic interactions. Most of these experiments have shown an anomalously large number of events in the region of 1 GeV energy transfer to the electron, while one other[4] has shown a larger cross section for positive than for negative muons at the higher momentum-transfer values. These experimental results for the cross section are in disagreement with the theoretical calculations for the interaction of nonidentical point fermions which has been derived by Bhabha.[6] The overall situation with the cosmic-ray experiments is still confused and complicated. All the cosmic-ray experiments possess a common set of difficulties, for example: (i) The pion background is uncertain, (ii) the muons in a particular experiment are not monoenergetic, and (iii) the use of thick targets necessitates serious corrections for multiple-scattering and radiation processes.

There are other experiments[7] which used accelerator-produced negative muons with momenta peaked at 8.5 GeV/c; and positive and negative muons[8] at 5.5 and 10.5 GeV/c, respectively. In both cases thick targets were used and thus one has to take into account multiple processes which also include the ionization loss of the μ meson. For 8.5-GeV/c negative muons, the calculated and the measured value of the cross section showed a better agreement than in the case of a later experiment with 5.5 and 10.5 GeV/c in which the agreement was ~30%.

In order to overcome the shortcomings of the previous experimental techniques and also to look into the previous controversial experimental results, we used monoenergetic muon beams of 10.1-GeV/c positive muons and 14.1-GeV/c negative muons in nuclear emulsions which have a great deal of spatial resolution. The maximum kinetic energy transferrable to the electron is 4.8 and 8.3 GeV from positive and negative muons, respectively.

Two small stacks of Ilford G-5 nuclear emulsions were exposed to muon beams of primary momenta 10.1 and 14.5 GeV/c at the Brookhaven alternating-gradient synchrotron with a flux density of 1×10^4 muons/cm^2. The contamination of pions in the muon beam was less than 10^{-7}. The scanning was done by the "along the track" technique where the incident muon was followed along its path through the emulsion. Beam tracks whose projection and dip angles were less than three degrees from the "general" beam direction and which were in the central two-thirds of the emulsion thickness were chosen for scanning. The track thus chosen was then aligned parallel to the X motion of the Koristka microscope stage and scanned along its length using a constant oscillation of the Z control to facilitate observation of events with dip angles greater than 0°. As we were only interested in the high-energy knock-on electron events, we confined our scanning to the scattered events whose projection angles were less than 10°. In order to save scanning time, we used a special eyepiece which has a cross hair of the desired projection angle. This permitted stopping from scanning only for the events which obviously fell within the desired angle and thus increased our scanning speed to half a meter per hour. For an interaction to be accepted for measurement as a possible knock-on electron event, it had to satisfy the following stringent criteria: (i) There should be an apparent vertex coincident with the primary track; (ii) the secondary has to be straight for at least one field of view and sharp scatters were not included (eliminating Auger electrons); (iii) the vertex has to be a three-particle vertex (without any recoil of nucleus); and (iv) the projected angle has to be less than some predetermined cutoff angle (~10°).

The next criterion applied to each of the events was the determination that the secondary track of interest was indeed due to an electron. This determination was made during the measurements of the event, when the electron track was followed for scattering measurements. The events satisfying the above criteria for analysis also have to satisfy criteria for being an elastic muon-electron interaction, as the knock-on process is a two-body process. The selected events were further checked for coplanarity and energy-momentum balance.

Since most of the controversy in the previous experiments arises for knock-on electrons with energy ≥ 1 GeV, accuracy in the measurements of the small angles was highly desirable. Consequently a coordinate method suitable to our needs was developed and was used for all the angle measurements. The error in the angle was carefully calculated from

$$(\sigma_\theta)^2 = ct/p^2\beta^2 + c_1/t^2,$$
$$(\sigma_\varphi)^2 = ct/p^2\beta^2 + c_2/t^2,$$

where θ and φ are the projected and dip angles. The first term is the multiple-Coulomb-scattering contribution to the angle error where t is the length of the cell size used, $p\beta$ the particle energy, and c is a constant that contains K the scattering constant for the cell length t. The optimum cell size used for different energy ranges of knock-on electrons varied from 50 to 250 μ. The second term contains the error due to measurements. The constants c_1 and c_2 contain the noise contributions as determined by the methods of Biswas, Peters, and Rama[9]; c_2 also contains the effects of finite depth of focus and shrinkage-factor uncertainties. From the measurement of errors in the projection and the dip angle separately, we calculated the error in the space angles which was less than 5%. Energies of the secondary electrons were carefully measured using the technique of multiple Coulomb scattering and they were corrected for all experimental observed errors. The statistical error in the scattering was calculated by the method developed by Bonnetti, Dilworth, and Scarsi.[10]

By scanning a total length of about 83.14 and 280 m for positive and negative muons we found about 39 and 86 events for 10.1- and 14.5-GeV/c muon beams, respectively. In each case data were separately plotted for projection and dip angles and from these distributions we find that the dip-angle histograms show a definite tendency to peak at small angles whereas the projected-angle histograms exhibit a paucity of events in the central region and more uniform distribution for the larger projected angles. In Figs. 1(a) and 1(b) are shown the combined angular distributions for 10.1- and 14.5-GeV/c muons for dip and projected angles, respectively. These distributions indicate that the scanning technique used was most efficient for events with small-magnitude dip angles and becomes less and less efficient as the dip angles increase. Loss in scanning efficiency was calculated and was used in the final calculations. It was found that no corrections were needed for events with energy transfer greater than 100 MeV.

For both the beams, we plotted the energy derived from the scattering technique against the calculated space angle of the electron from the angle measurements. We found that most of the experimental points lie within one standard deviation of the kinematical curve. There are a few events (two in the positive and five in the negative muon beam) that fall below the kinematical curve. They have been carefully scrutinized and have passed all the validity tests within our criteria for event acceptance except the fit to this curve. It is found, however, that the track of each of

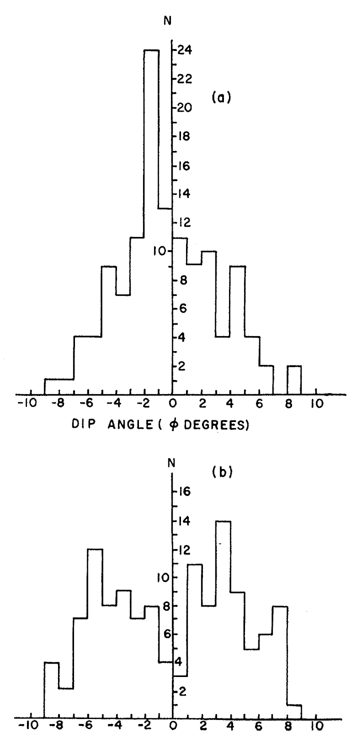

FIG. 1. The combined (a) dip-angle and (b) projection-angle distribution for knock-on electrons from 10.1- and 14.5-GeV/c positive and negative muons, respectively.

these seven events passes through a certain point along its trajectory where there is a definite change in the multiple-scattering behavior. The change indicates an energy loss greater than the average expected amount in the length of the track used in the scattering measurement. This behavior has been attributed to a catastrophic bremsstrahlung loss. We know that electrons can radiate large amounts of energy in small distances and these few events have suffered radiative collisions with energy losses great enough to be detected by the scattering technique. To correct for these effects and to ultimately minimize the uncertainty in the secondary-electron energy, for the final analysis the energy used was that from the measured ejection angles. This technique gave us an average uncertainty of 15% in the electron energy with a maximum uncertainty of ~20%. Thus the energy loss due to radiation for these few events was corrected and the integral spectrum of the number of events was plotted against the energy of the knock-on electron. In Fig. 2(a) are shown the experimental data for 10.1-GeV/c positive muons. The largest value of the kinetic energy transferred to the knock-on electron observed in this beam is 1.5 GeV. The solid vertical error bars represent the statistical error due to the number of events considered, derived from the Poisson distribution. The dashed extensions to the statistical error bars are the scanning-bias corrections as discussed earlier for large dip-angle events. The solid curve was calculated from Bhabha's formula for the cross section and this was uncorrected for the radiative processes which are only 5-6%. This small correction will be unnoticeable on the scale of these plots and indeed not detectable within the precision of this experiment. The absolute cross sections as predicted by Bhabha for transferred energies greater than 250 MeV are in excellent agreement with the data. The present experimental results reflect no anomalous scattering of positive muon on electrons up to $t = 1.8\times10^{-3}$ (GeV/c)^2. If we consider these results in comparison with the results of Backenstoss et al.[7] at 8 GeV/c for negative muons, we get no indication of charge asymmetry in the scattering. In Fig. 2(b) are shown the results of 14.5-GeV/c negative muons, where the highest energy transferred to the knock-on electron was observed to be 3.25 GeV. Once again the fit to the unnormalized Bhabha cross section for transferred energies above 250 MeV is excellent. The data reflect no anomalous scattering and no structural effects of negative muons on electrons up to $t = 3.3\times10^{-3}$(GeV/c)^2.

Thus we see that the present results show that in negative muon-electron scattering there is no deviation from the Bhabha cross section up to

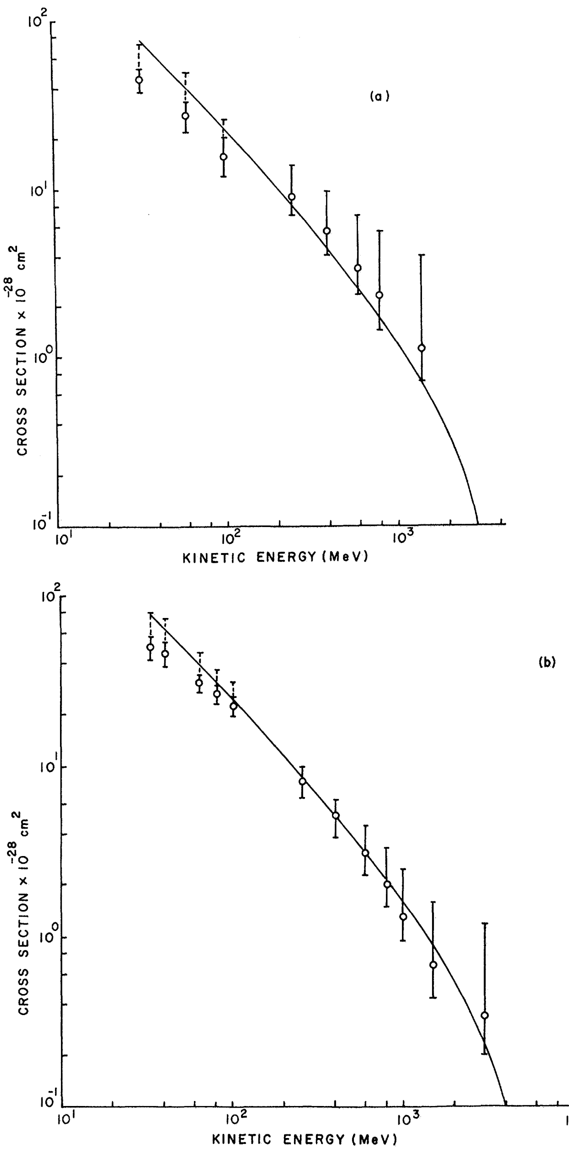

FIG. 2. Integral cross section versus knock-on electron energy from (a) 10.1-GeV/c positive and (b) 14.5-GeV/c negative muons. The solid error flags on the experimental points represent the statistical error in the cross section:

$$\sigma = \sigma_0 \pm \sigma_0/N^{1/2}, \quad N > 10;$$

$$\sigma = \sigma_0 \pm \sigma_0/(N+1)^{1/2} \text{ for } N \leq 10.$$

The dashed error flags are due to the scanning efficiency for larger dip-angle events. The solid curve is based on knock-on process from Bhabha's calculation.

transferred energies in the region of 3 GeV. This is in contradiction to some of the cosmic-ray experiments which reported deviation from the Bhabha cross section. Our results for the scattering of positive muons on electrons up to transferred energies in the region of 1.5 GeV also show agreement with Bhabha cross section. This is in contradiction to some extent to the charge-asymmetry results of Kotzer and Neddermeyer.[4]

Thus we believe that to the best of our knowledge this is the first muon-beam experiment in nuclear emulsion in which a systematical study was made for the pure knock-on process. We are checking the results at 5-GeV/c negative muon momenta and also extending our observations to a 10.1-GeV/c positive-muon beam.

We are very grateful to the late Professor J. Hornbostel for making the arrangement for the exposure; to the Brookhaven, Columbia, and Rochester Group for letting us use their beam for our emulsions. The Research Foundation of the State University of New York is gratefully acknowledged for awarding one of the authors (P.L.J.) a Joint-Award, Faculty Fellowship that was used in part in the research work presented here. The other author (N.J.W.) would like to thank T. Fecteau and D. Phillips for their kind help in scanning and measuring a part of the data presented here and to his other colleagues in the high-energy group for their assistance.

*An account of this research is submitted by N. J. Wixon in partial fulfillment of the requirement for Ph. D. thesis to the Department of Physics, State University of New York at Buffalo. Now at Cornell Aeronautical Laboratory Inc. of Cornell University, Buffalo, N. Y.

[1]W. Walker, Phys. Rev. 90, 234 (1952); I. McDiarmid and M. Wilson, Can. J. Phys. 40, 698 (1962).

[2]P. Kearney and W. Hazen, Phys. Rev. 138, B173 (1965).

[3]R. Deery and S. Neddermeyer, Phys. Rev. 121, 1803 (1961); N. Chaudhuri and M. Sinha, Nuovo Cimento 35, 13 (1965).

[4]P. Kotzer and S. Neddermeyer, Bull. Am. Phys. Soc. 10, 80 (1965), and 12, 916 (1967).

[5]W. R. Binns and P. D. Kearney, Bull. Am. Phys. Soc. 14, 500 (1969).

[6]H. Bhabha, Proc. Roy. Soc. (London), Ser. A 154, 195 (1936), and 152, 559 (1935).

[7]G. Backenstoss, B. Hyams, G. Knop, P. Martin, and U. Stierlin, Phys. Rev. 129, 2759 (1963).

[8]T. Kirk and S. Neddermeyer, Phys. Rev. 171, 1412 (1968).

[9]S. Biswas, B. Peters, and F. Rama, Proc. Indian Acad. Sci., Sec. A 41, 154 (1955).

[10]A. Bonnetti, C. Dilworth, and L. Scarsi, Nuclear Emulsions (George Newnes, Ltd., London, England, 1958).

SEARCH FOR MESONS SUGGESTED BY THE VENEZIANO MODEL*

G. McClellan, N. Mistry, P. Mostek, H. Ogren, A. Osborne, A. Silverman, J. Swartz, and R. Talman
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14850

and

G. Diambrini-Palazzi
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14850,
and Istituto di Fisica dell'Università de Genova, Genova, Italy
(Received 11 July 1969)

Recent Regge-pole models have predicted the existence of particles of well-defined mass lying on daughter trajectories of such known particles as the ρ. A search for the coherent photoproduction of these mesons from carbon has been made. None was found. We conclude that in the mass range 1.0–1.8 GeV such mesons are coupled to the photon or the nucleus, at least two orders of magnitude more weakly than is the ρ.

A common feature of various Regge-pole models is the existence of daughter trajectories.[1] In particular, the Veneziano[2] model leads to families of particles lying on parallel, linearly rising trajectories. Thus, each particle on the ρ trajectory is degenerate in mass with particles of lower spin lying on daughter trajectories. We report here a search for the 1^- daughters of the 2^+ and 3^- mesons of the ρ trajectory. Henceforth, we shall refer to these 1^- mesons as the ρ' and ρ'', respectively. Shapiro,[3] applying the Veneziano model to $\pi\pi$ scattering, obtains the following values for the masses and 2π decay widths of the ρ' and ρ'': $m_{\rho'} = 1300$ MeV and