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Pion-electron scattering at 16 GeV

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A measurement of the absolute differential cross section for pion-electron scattering is reported. Measurements were made in a nuclear emulsion exposed at CERN to 16.2-GeV/c negative pions. Good agreement with point-particle predictions is obtained.

I. INTRODUCTION

One of the simplest and the most readily observable electromagnetic interactions of the pion is pion-electron scattering. Studies of this scattering process at sufficiently high energies should provide direct information on the form factor of charged pions. The point-particle cross section for this process was calculated many years ago in the first Born approximation by Bhabha[1] and later by Salecker[2] who obtained similar results in a lowest-order quantum-electrodynamics calculation. More recently, contributions of the higher-order Feynman diagrams have been calculated.[3] Any differences between these predictions and experimental results are expected to result from an extended pion charge distribution.[4]

The pion-electron scattering cross section at high energies has been studied experimentally by Allan *et al.*[5] in a hydrogen bubble chamber using 16-GeV/c negative pions. Reasonable agreement was found with the theoretical point-particle predictions at small energy transfers, but at large energy transfers a possible deviation from point-particle predictions was seen. Although the results suggested an extended charge distribution for the pion, small statistics at large energy transfers prohibited definite conclusions about the charge structure. Recently, Adylov *et al.*[4] reported results of an experiment designed to measure the pion radius. This experiment used a magnetostrictive spark-chamber spectrometer to measure the relative cross section at large energy transfers.

The present experiment investigates the pion-electron scattering process at a pion energy of 16 GeV, but in nuclear emulsion. Because this thin-target technique permits a microscopic investigation of each interaction at its origin, many of the uncertainties involved in bubble-chamber and spark-chamber experiments for studying processes involving secondary electrons are overcome. In particular, the high spatial resolution of nuclear emulsion permits reliable differention between pion-electron scattering and other potentially confusing interactions such as high-disparity electron pair production or bremsstrahlung-induced electron pair production. Effects of bremsstrahlung losses on measurements of the energy of the secondary electrons are minimized. In the present experiment an absolute measurement of the pion-electron scattering cross section is made. Good agreement is found between the experimental results and point-particle theoretical predictions at energy transfers between about 100 and 3600 MeV, which suggests that an extended pion charge distribution is not necessary to explain pion-electron scattering for energy transfers of this magnitude.

II. EXPERIMENTAL PROCEDURES

In this experiment the cross section for the scattering of high-energy pions on electrons has been measured using data obtained from a stack of Ilford K-5 nuclear emulsion pellicles which were exposed to the 16.2 ± 0.64-GeV/c negative-pion beam at CERN. The beam contained approximately 90% negative pions. Because the contamination consisted chiefly of negative muons, and because the electron scattering cross sections of muons and pions are of the same order, this 10% beam contamination will produce only second-order errors in the measured pion cross sections.

The very large emulsion scanning effort reported here was undertaken for the specific purpose of studying the purely electromagnetic interactions of high-energy negative pions.[6,7] Because these interactions involve principally either two-particle (electron scattering) or three-particle (direct pair production) final states, and because all particle tracks involved are near minimum grain density, the interactions are difficult to see in emulsion. Further, the scanning difficulties are intensified by the relatively small transverse-momentum transfer in such interactions. As a result, the pion seldom undergoes a noticeable direction change. In order to maximize the detection efficiency, beam-track scanning was done at a magnification of about 800× and at a relatively slow scan rate along the track. The bulk of the scanning was done at an average along-the-track speed of 22 cm/h, although approximately 6% of the data was collected at a speed of 14 cm/h with comparable results.

In order to make accurate cross-section measurements, it is necessary to locate the desired interactions in a manner that will allow statistical determinations of their probabilities of occurrence. This was done in this experiment by careful and systematic scanning along the length of individual beam tracks. Each track was scanned from a point near its entrance into the stack to the point where the particle either first interacted or left the emulsion pellicle. All recognized interactions of any type were recorded, and any detected interaction terminated the scan of the particular beam-particle track. Using this technique, a total length of 1.83×10^5 cm of beam-pion track was scanned.

Due to the magnitude and duration of this scanning effort, ten different scanners were involved. Although this scanner multiplicity complicates any effort to determine the efficiency with which the scanners located pion-electron scattering interactions, a procedure of selective rescanning of beam tracks was developed which permitted a determination of the efficiency of each scanner for relocating previously recorded pion-electron collisions. In this procedure, approximately 25% of the beam particle tracks to be refollowed were selected because the responsible pion had interacted with an electron. Each scanner rescanned the same set of tracks. Analysis of these rescanning results indicated an average relocation efficiency for pion-electron scattering interactions of 0.79 ± 0.03.

Beam-pion tracks, which are always in the focal plane of the microscope, change direction only slightly in electron collisions—the maximum pion direction change of 12.5′ occurs at a knock-on electron energy of 4.8 GeV. Such small changes in the primary particle direction would be missed in scanning. Interactions are detected only by locating the scattered electron track. There is a general correlation between the magnitude of the total scattering angle and the difficulty in seeing

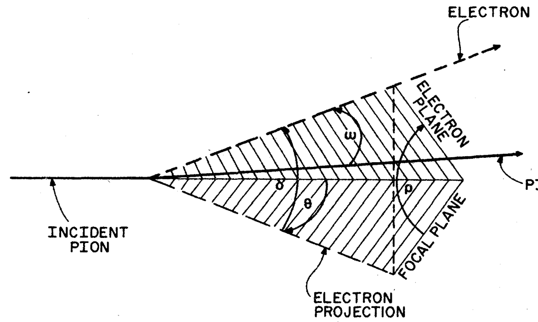

FIG. 1. Schematic of the knock-on electron process (angles exaggerated). ω is the total angle between the electron and scattered pion. ρ is the angle between the focal and electron planes. δ is the angle between the electron track and its projection on the focal plane. θ is the angle between the initial pion direction and the projection of the electron track on the focal plane.

those interactions in emulsion. This factor limits our ability to efficiently locate interactions with electron energies below about 100 MeV. Although some dependence of detection efficiency on the projected angle (θ in Fig. 1) remains at energies above 100 MeV, the difficulty in seeing secondary tracks which do not lie in the focal plane of the microscope contributes more significantly to the scanning inefficiency at these energies. Generally, the larger the angle between the electron track and the microscope focal plane ("dip" angle, δ in Fig. 1), the more difficult the interaction is to see. This dependence of the scanning efficiency on both projected and dip angles makes determination of the energy-dependent scanning efficiency difficult.

One of us (J. S.) has developed a sophisticated model for determining the scanning efficiency using the measured distributions of the angles between the plane of the interaction and the focal plane (ρ in Fig. 1). Since these angles should be distributed isotropically, the extent to which the measured distributions differ from isotropy at a given electron energy determines the scanning efficiency at that energy once the parameters in the model have been determined by best fits to the distributions at several energies. Unfortunately, the limited statistical accuracy of the experimental distributions cause results of this procedure to have large uncertainties. For this reason, a more straightforward method of detection-efficiency determination has been adopted which makes use of the measurable physical parameters that determine the visibility of a track in the emulsion. The dependence of the scanning efficiency η on the parameters H_0, which is the depth of focus of the microscope, and L_0, which is the maximum length of track which can be viewed by the eye, can be expressed in terms of the plane angle, ρ and the total scattering angle ω as (see Fig. 1)

$$\eta = \frac{L}{L_0} = \frac{H_0}{L_0}\left(\frac{1}{\sin^2\rho \sin^2\omega} - 1\right)^{1/2}.$$

Both L_0 and H_0 were measured approximately, but more accurate values were obtained by normalization of this efficiency function to the plane-angle distributions at different energies. Best-fit values of the parameters of $H_0 \sim 1.0\ \mu$ and $L_0 \sim 100\ \mu$ agree well with direct measurements of these constants. Using these values together with the obvious condition that $\eta \leq 1$, we have obtained the total scanning efficiency as shown in Fig. 2. Also included is the energy-independent efficiency of 0.79.

Another source of measurement error was found to be incorrect track recording or following. Although a systematic procedure for selecting tracks to be followed was employed, a portion of the tracks followed were found to have been either followed twice due to incorrect track identification or misfollowed due to confusion with a crossing track which had been previously scanned. This effect produced a decrease in the net track length scanned of about 5%.

Energies of knock-on electrons can be estimated either by making multiple Coulomb scattering measurements on the electron tracks, or by measuring the angle of the secondary electron relative to the beam pion direction. If the electron scattering is elastic, there is a one-to-one correspondence between the scattering angle and the true electron energy. Although no assumptions about the elasticity of the interaction need to be made in determining energies by the multiple Coulomb scattering technique, these measurements have statistical errors of at least ± 10%; radiation losses by the electrons over the path lengths required for the multiple scattering measurements produce additional uncertainties in the measured energies.

The uncertainties in the energies of elastically scattered electrons are determined by the accuracy with which the scattering angles can be measured. Over the energy range considered here, the angles can be measured with sufficient precision to give about ± 5% uncertainty in electron energies. This uncertainty is approximately energy-independent due to compensating factors in the angle measurement and in the dependence of the energy on the scattering angle.

Multiple Coulomb scattering measurements are most accurate for tracks which lie in the focal plane of the microscope. Such flat tracks provide the best comparison of the two energy-measuring techniques. Careful measurements were made on a sample of 30 such interactions to compare the two measurement techniques. In all but one case the energies measured by multiple scattering were within or slightly below the one-standard-deviation uncertainty ranges of the corresponding energies determined by measuring the scattered electron angle. This result would be expected if the interactions were elastic scatterings and if some of the

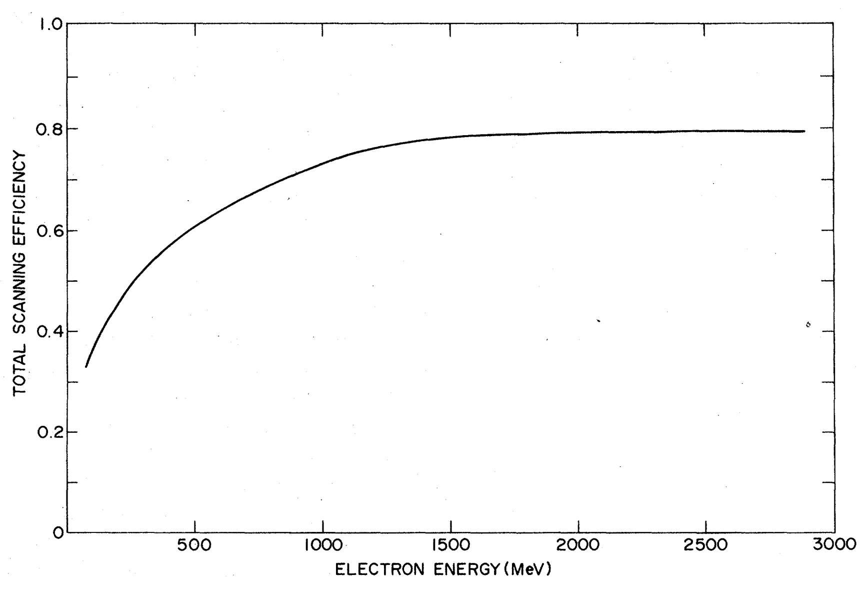

FIG. 2. Total efficiency for locating scattered electrons, as a function of electron energy. Both energy-dependent and energy-independent effects are included.

secondary electrons had lost energy by radiation over the path length of the multiple-scattering measurements. Therefore, we have chosen the electron momenta determined from angle measurements as the most accurate values.

In order to be sure that all located pion-electron scattering interactions (and only such interactions) were included in the final event sample, all interactions having two or three minimum ionizing secondary tracks were carefully analyzed. All such interactions which were determined to have only two secondary tracks were considered to be possible knock-on electrons, and multiple Coulomb scattering momentum measurements together with accurate angle measurements were made on each secondary track in such interactions. Agreement between the measured momentum and that calculated assuming elastic scattering was taken to indicate a probable knock-on electron. Any interactions in which significant disagreement existed between the two energy estimates was rejected as a knock-on electron candidate. This procedure was effective in eliminating almost all confusing interactions. An important type of confusing interaction which must be eliminated in this way is that of electron pair production in which one of the pair particles is not visible due, for example, to its very low energy, large dip angle, or to its absorption. This type of interaction amounted to about 4% of the total number of actual knock-on electrons. It should be noted that in bubble-chamber analyses this percentage would be expected to be higher due to the macroscopic nature of the viewing technique. Although the percentage of such confusing interactions in emulsion is small, their inclusion would cause significant distortions in the differential cross section at large energy transfer due to the small-angle nature of these interactions.

In order to insure that strong-interaction events were not included in the sample, the pion deflection angles were accurately measured. Strong interactions will typically produce a much greater pion deflection then will pion-electron scattering. Thus this procedure together with the above momentum vs angle check should effectively preclude the inclusion in the knock-on sample of any strong-interaction events.

III. RESULTS

A total beam-pion path length of 183 100 cm was scanned in the manner described above. In this path length, 280 knock-on electrons with >50 MeV/c momentum were determined to have been produced by 16.2-GeV beam pions; of these, 189 had energies >100 MeV. In order to interpret the measured number spectrum in terms of a scattering cross section, corrections were made for both the energy-dependent and energy-independent scanning efficiencies discussed above.

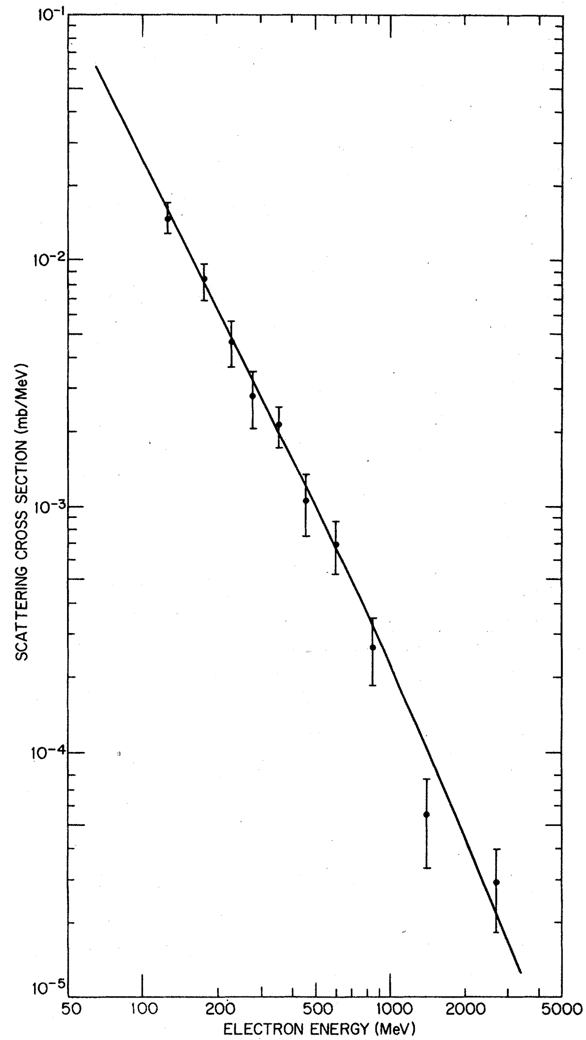

FIG. 3. Absolute differential cross section for pion-electron elastic scattering as measured in this experiment and as calculated (Ref. 1 and 2) for a point pion at 16 GeV. Uncertainties are primarily statistical.

Figure 3 gives the corrected absolute differential cross section as a function of the scattered electron's energy. Also shown is the calculated first-order cross section of Salecker,[2] although a plot of the results of the early calculation by Bhabha[1] would be indistinguishable. No normalization has been made. Good agreement is found between the results of this experiment and the first-order theory for point particles. Because scanning efficiencies increase with increasing electron energy, the higher-energy data are subject to the least experimental uncertainty. However, because the cross section decreases with increasing energy, the statistical accuracy of the measurements decreases at the higher energies.

Good agreement with the lowest-order point-particle cross section indicates that below ~3000 MeV energy transfer, at least within the accuracy of this experiment, there is no need to postulate an extended charge distribution for the pion. Further, radiation corrections to the cross section are not important at these energy transfers. This result is to be compared with that of Allan *et al.*[5] in which the measured cross section was somewhat below the theoretical predictions at similar energy transfers. Statistical limitations at large momentum transfers prevented strong conclusions in that work as it does in this one, however.

The small differences in the present results and those of Allan *et al.*[5] at large energy transfers can plausibly be explained by experimental differences. Results of the present emulsion experiment are expected to have their greatest accuracy at the highest observed electron energies, while the bubble-chamber results are likely to experience increasing uncertainty with increasing electron energies. Energy measurements on high-energy electrons tracks in thick target detectors such as bubble chambers require path lengths large enough to permit significant radiative energy loss by the electrons. Thus some of the high-energy electrons in these types of detectors will have measured energies significantly below their original value. This would result principally in a relative decrease in the measured cross section at the highest measured electron energies.

Use of the pion-electron scattering to sensitively probe the pion charge structure and to further test the validity of the theoretical cross-section calculations requires experiments with greater statistical accuracy at considerably larger energy transfers. Adylov *et al.*[4] have measured the pion radius using pion-electron scattering at large energy transfers using 50-GeV pions. This work, which measured the relative cross section and which relied on calculations and Monte Carlo simulations to correct for a number of experimental uncertainties, obtained a pion radius of $\langle r_\pi \rangle^2 = (0.61 \pm 0.15)\ \mathrm{fm}^2$. However, the 20% of their data points between their lowest measured energy transfer of ~ 13 GeV and 18 GeV are quite consistent with point-particle predictions. A rather abrupt transition to nonpointlike behavior at higher energy transfers suggests significant remaining systematic uncertainties. An independent confirmation of this measurement would be of considerable interest.

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