PHYSICAL REVIEW D VOLUME 2, NUMBER 9 1 NOVEMBER 1970

Scattering of High-Energy Pions on Electrons

F. M. WATERMAN* AND P. J. MCNULTY
Physics Department, Clarkson College of Technology, Potsdam, New York 13676
(Received 17 April 1970)

A total of 50 knock-on electrons with emission angles less than or equal to 10° were located by along-the-track scanning of 105.4 m of 16.2-GeV/c negative-pion track in nuclear emulsion. The measured electron energies were found to be in agreement with kinematics. The spectrum of these high-energy δ rays is in agreement with both theory and previous bubble chamber results. A serious scanning deficiency at small angles in along-the-track scanning was found, and its implications for experiments searching for anomalous scattering on electrons are discussed.

I. INTRODUCTION

A NUMBER of groups have recently reported indications of anomalous electromagnetic interactions. Kinzer and Burwell[1] found disagreement with theory in the production of electron-positron pairs with combined energy ≥ 20 MeV by 16.2-GeV/c negative pions in nuclear emulsion. Kotzer and Neddermeyer[2] reported an anomalous cross section for scattering positive cosmic-ray muons by electrons over both theory and their negative muon-electron scattering results. No such anomaly was found in counter experiments using accelerator-produced negative muons at 8.5 GeV/c,[3] and positive and negative muons at 5.5 and 10.5 GeV/c, respectively.[4] Nor was one found in the bubble chamber study of Allan *et al.*[5] using 16.2-GeV/c negative pions.

We report here on our measurements of the absolute cross section for the production of knock-on electrons that make small angles (0°–10°) with the primary tracks of 16.2-GeV/c negative pions in nuclear emulsion. This experiment was begun in order to compare with similar muon-electron studies.[6,7] All pion-induced events other than knock-on electrons were found to be easily and safely separated by kinematics—confirming the ability of Kinzer and Burwell[1] to perform such separation with reasonable care. In Sec. III we demonstrate the existence of serious scanning biases occurring at both large dip and small projection angles. Comparison of data not lying in either of these angular regions of scanning bias with theory yielded excellent absolute agreement. Scanning biases at small projection angles have not been reported previously but must be taken into account in interpreting the results from experiments searching for anomalous muon-electron scattering at these small angles.[7]

* National Science Foundation Trainee.

[1] R. L. Kinzer and J. R. Burwell, Phys. Rev. Letters **20**, 1050 (1968).

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

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

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

[5] J. Allan, G. Eksprong, P. Sallstrom, Nuovo Cimento **32**, 1114 (1964).

[6] N. J. Wixon, P. J. McNulty, and P. L. Jain, Bull. Am. Phys. Soc. **12**, 63 (1967).

[7] P. L. Jain and N. J. Wixon, Phys. Rev. Letters **23**, 715 (1969); P. L. Jain, N. J. Wixon, D. A. Phillips, and J. T. Fecteau, Phys. Rev. D **1**, 813 (1970).

II. THEORY

A. Kinematics

Knock-on electrons are produced in quasi-elastic collisions of the primary pion with atomic electrons that have binding energies which are much smaller than the energy transfers considered in this experiment (>30 MeV). Therefore, all binding effects will be ignored and the kinematical relations for elastic collisions can be used to relate the knock-on electron's kinetic energy T to its emission angle ω:

$$T=\frac{2mP_\pi^2\cos^2\omega}{(T_\pi+m_\pi+m)^2-P_\pi^2\cos^2\omega}, \tag{1}$$

where m_π, P_π, and T_π are the mass, momentum, and kinetic energy of the incident pion and m is the electron mass.

B. Theoretical Spectra

The number of electrons produced per centimeter with kinetic energies in the interval from T to $T+dT$ by a primary particle of charge e and spin 0 passing through a substance of electron density N was first calculated by Bhabha[8] and more recently to order α^3 by Edin and Eriksson[9] as

$$\varphi(T)dT=2\pi r_e^2Nmc^2(1-\beta^2T/T_m)\times[F^2(q)+\delta]dT/\beta^2T^2, \tag{2}$$

where T_m is the maximum possible kinetic energy transferable to the knock-on electron (in this experiment 7.44 GeV), r_e is the classical electron radius, m is the electron rest mass, βc is the pion's velocity, $F(q^2)$ is the pion's form factor (=1 for this experiment), and the electron density $N=1.04\times10^{24}$ electrons/cm^3 for nuclear emulsion. The contribution from radiative corrections represented by δ has been shown by Edin and

[8] H. J. Bhabha, Proc. Roy. Soc. (London) **A164**, 257 (1938).

[9] K. A. Edin and K. E. Eriksson, Nuovo Cimento **41A**, 349 (1966).

Eriksson[9] to be less than 2% for this experiment, and will be neglected.

III. EXPERIMENTAL PROCEDURE

The pellicle of nuclear emulsion used in this investigation is one of a stack originally exposed to the negative pion beam of the CERN proton synchrotron at Geneva. The momentum of the primary beam was 16.2 ± 0.6 GeV/c. The contamination of the beam by muons, kaons, and antiprotons was less than 5%. The primary particle flux was approximately 8×10^3 particles/cm^2. The pellicles used were Ilford-type K-5 of dimensions 8.6 cm$\times$15 cm$\times$600 μ. The angular deviation in both the projection and dip angles of the pion beam was approximately ±5 mrad.

A Koristka MS2 scattering microscope was used to scan along the beam pion tracks for knock-on electrons that appeared as secondary tracks emerging in the forward direction ($<10°$ projection angle from the primary track). All primary tracks followed were located in a strip in the plane of the emulsion approximately 2 cm wide and were required to be at least 50 μ from the top or bottom pellicle surfaces. The rate of movement of the stage under the microscope objective during scanning was 25–30 cm/h. Including the time required to set a track up for scanning, perform the reiterations required by the 5-cm maximum stage displacement, and record the events, the effective scanning rate becomes 15–20 cm/h. Scanning began 1 mm in from the pellicle edge and tracks were followed to within about 2 mm of the opposite edge unless the primary track came within 10 μ of either the top or bottom surface of the pellicle, resulted in a star, or was noticably deflected ($\geq0.5°$). The average useful track length was approximately 10 cm out of a possible 14.5 cm. Approximately one-third of the tracks emerged and about one-fifth ended in stars. Only five deflections were noted in the 105.4 m scanned.

A. Scanning Criteria

Events found were subjected by the scanners to the following requirements:

(a) The event should be composed of three minimum-ionizing prongs with no visible recoil.

(b) Imaginary lines joining the grains of the primary and extending from the secondary grains should be in "good focus" at the point of intersection.

(c) The secondary makes a projection angle of less than 10° with the continuation of the primary.

(d) The pion track shows no evidence of scatters through angles greater than those allowed by kinematics or the uncertainty of the measurements ($\pm0.5°$).

(e) The pellicle was rotated by the scanner until the secondary track was parallel to the x axis of the stage motion. By following the secondary tracks back towards the vertex at rapid speeds, the event was often identified as merely a passing track with a gap in its grain density at the intersection with the primary.

(f) The immediate localities of secondaries ending abruptly at the primary were examined for a second lepton track emerging from what would then be the vertex of an electron-positron pair. All events surviving the above criteria were recorded by the scanners as possible knock-on electrons.

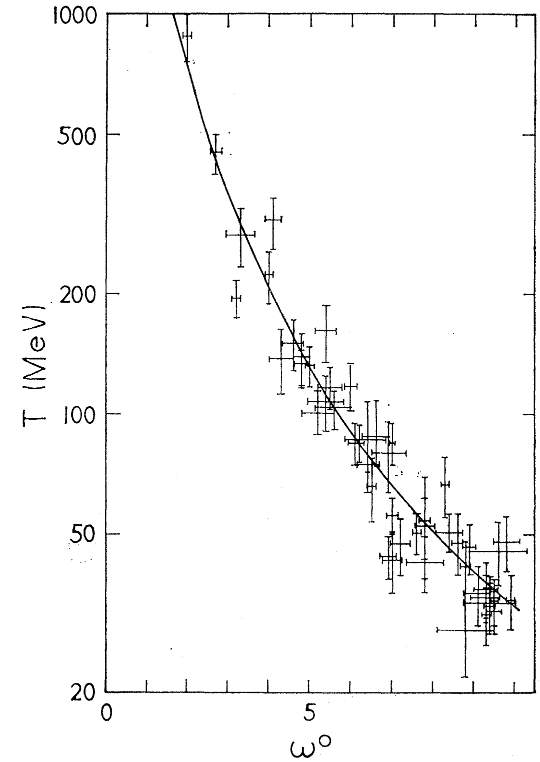

FIG. 1. Kinetic energy versus emission angle for all knock-on electrons with emission angles less than 10°.

B. Effects of Bremsstrahlung

The solid angle between the knock-on track and the initial direction of the primary was measured for all tracks that survived the scanning criteria. The energy of each knock-on electron can, of course, be determined from the scattering angle by kinematics, but an independent determination was made by scattering each track on the Koristka MS2 under a magnification of 550$\times$, using a four-times-the-mean-termination routine described elsewhere.[10]

The values of the energy and emission angle measured for each track were compared with kinematics. Seven out of the 58 events obtained by the scanners were found to be in obvious disagreement with kinematics. Upon close reexamination of the vertices, six of these tracks were shown to be members of electron-positron

[10] F. M. Waterman and P. J. McNulty, Nucl. Instr. Methods **82**, 61 (1970).

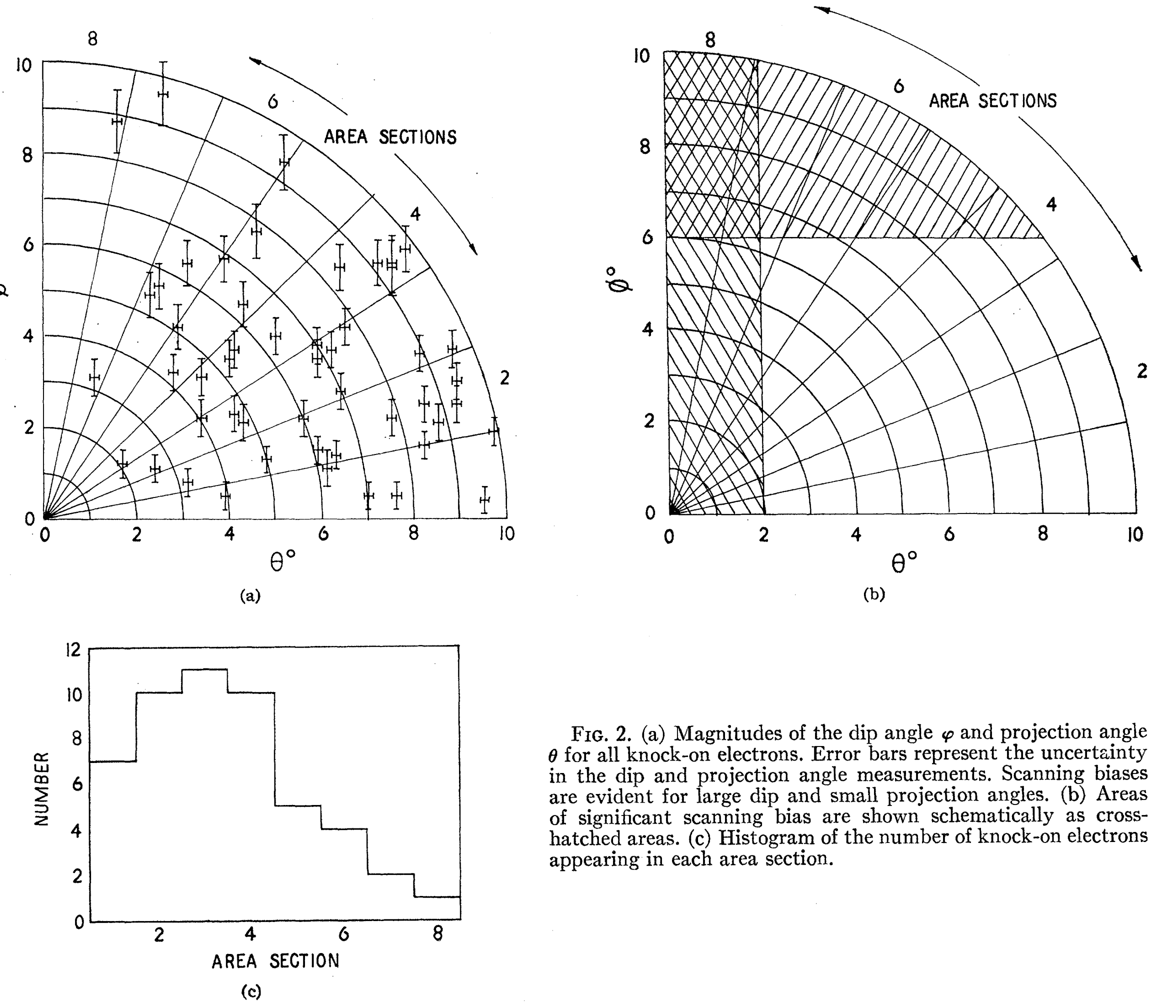

FIG. 2. (a) Magnitudes of the dip angle φ and projection angle θ for all knock-on electrons. Error bars represent the uncertainty in the dip and projection angle measurements. Scanning biases are evident for large dip and small projection angles. (b) Areas of significant scanning bias are shown schematically as cross-hatched areas. (c) Histogram of the number of knock-on electrons appearing in each area section.

pairs. The remaining anomalous event proved to be a passing track. The scattering angle of the continuation of the primary track with respect to the initial direction was measured by established techniques. In one case the scattering angle of the primary pion was found to be more than three times greater than the value expected from kinematics. Despite the apparent agreement of the energy and angle with knock-on kinematics, the event is probably due to pion production.

The measured values of the emission angle and the energy are plotted in Fig. 1 for the remaining 50 knock-on electrons. The horizontal and the vertical error bars represent the uncertainty in the angle measurements and the statistical error in the multiple-scattering measurements, respectively. Forty out of the 50 events shown in Fig. 1 are within 1 standard deviation of agreement with kinematics. No catastrophic energy losses due to bremsstrahlung were observed. The only effect of bremsstrahlung seems to have been to shift the energy spectrum toward lower energy by about 5%.

C. Scanning Efficiency

To determine the effect of dip and projection angles on the ability of the scanner to detect knock-on electrons, the magnitudes of both angles are plotted in Fig. 2(a) for each event. The vertical and horizontal error bars are the uncertainties in the dip and projection angle measurements, respectively. The probability of knocking the electron into each of the eight wedge-shaped area sections should, of course, be identical. Moreover, the theoretical distribution over the θ, φ space shown in Fig. 2 is approximately uniform above 1°. An obvious scanning bias occurs in area sections 5–8. This bias is even more clearly demonstrated in Fig. 2(c), which plots as a histogram the number of knock-on electrons found in each area section of θ, φ space. A slight bias against events occurring in area section 1 can be explained in terms of a tendency to systematically overestimate the dip measurements by roughly $\frac{1}{4}\,\mu$. In the area sections 5–8 shown in Fig. 2(a) there is an increasing bias against detection due to the large dip angles of the knock-on electron. There is also evidence

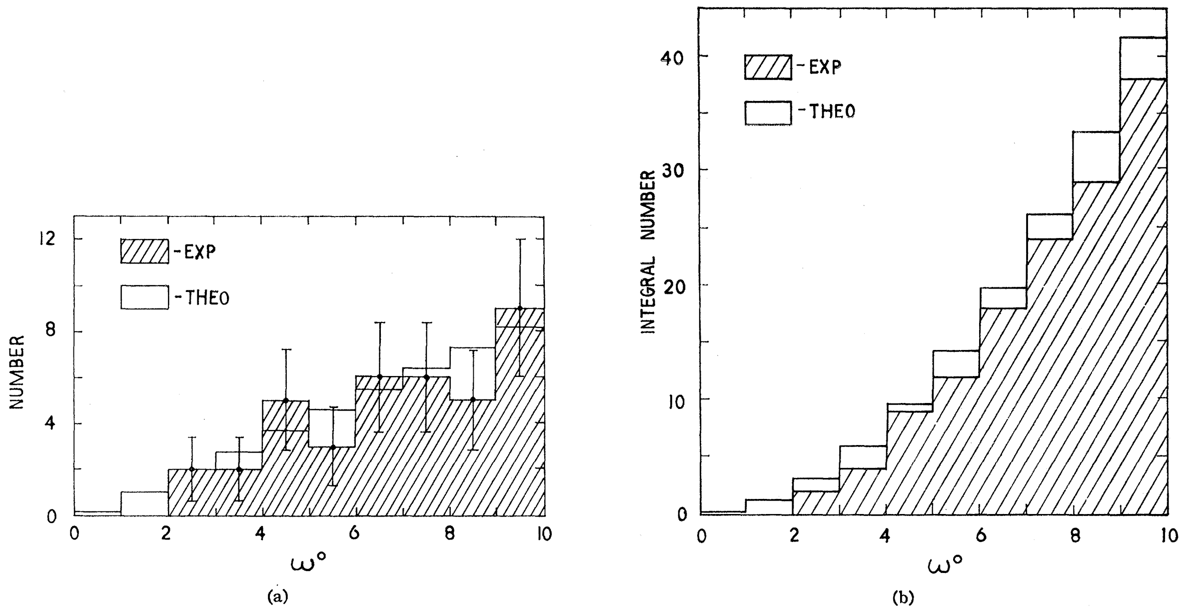

FIG. 3. (a) Differential angular distribution of knock-on electrons produced by 16.2-GeV/c pions in emulsion plotted as a hatched histogram. The theoretical distribution is plotted as an open histogram. The error bars represent statistical error. (b) Integral representation of the experimental (hatched) and theoretical (open) angular distributions of knock-on electrons in area sections 1–4.

of a substantial scanning bias, possibly exceeding 50%, against tracks that have projection angles of less than 2°. The existence of such a bias suggests that experiments searching for knock-on electrons at very small angles will require separate careful scans for these small angle events. The regions of significant scanning bias are shown as hatched areas in Fig. 2(b). Evidence of such a scanning bias at small projection angles can also be seen upon examination of Fig. 1(b) of Ref. 7. This effect would then seem to be inherent to along the track scanning in emulsions. Restricting analysis to events that lie in area sections 1–4 of Fig. 2(a) would at least limit the effect of this bias to emission angles below 2°.

IV. RESULTS AND CONCLUSIONS

Figure 3(a) is a histogram of the number of events plotted against emission angle. To avoid problems introduced by the scanning bias in dip angle, only events occurring in area sections 1–4 of Fig. 2(a) are included. The hatched histogram represents the experimental data with vertical error bars to represent statistical error. The open histogram is the theoretical angular distribution calculated by converting Eq. (2) to an angular distribution by means of Eq. (1). Figure 3(b) shows the integral spectrum of knock-on electrons (hatched) compared to theory in the form of an open histogram. Again no indication of a disagreement with the theoretical expression for the angular distribution is found.

The serious scanning deficiency at projection angles below 2° discussed above seems to be intrinsic to standard along the track scanning. Experiments on knock-on electron spectra found by this method will require a complicated geometrical correction for this effect precisely in the region of the observed anomaly.

ACKNOWLEDGMENT

We would like to thank Dr. N. J. Wixon for sending us his results prior to publication.