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[3] See P. Limon *et al.*, NAL Report No. NAL-Pub-73/66-EXP (to be published). During most of the data taking hadrons having a mean energy of 140 GeV were selected, which resulted in a neutrino energy spectrum with a mean energy of 53 GeV and a spread of ± 20 GeV.

[4] To take into account very-large-angle muons it is necessary to make a small correction to the angular distribution data to obtain the detection efficiencies given in Table I. This correction depends on the form of the distribution in the scaling variable $y = E_h/E_\nu$ for events with muons. For antineutrinos the y distribution is not yet definitively determined by our data, but preliminary results suggest that at higher energies the antineutrino distribution is similar to that for neutrinos. Accordingly, we have used the same correction for neutrinos and antineutrinos in conjunction with the measured angular distributions to find the detection efficiencies in the last two rows of Table I. The effect is less than the error assigned to the detection deficiencies in computing the final values of R^ν and $R^{\bar{\nu}}$ and their errors.

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Direct Electron Pair Production by High-Energy Muons

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By following 280.11 m of track length of 15.8-GeV/c negative muons in nuclear emulsion, twenty direct electron pairs were observed. For these pairs we have analyzed (i) the total energy distribution, (ii) the energy partition between the two members, (iii) the angular divergence, (iv) the transverse momentum distribution, and (v) the invariant mass of the electron pairs. The experimental results are compared with the present theories.

Many experiments have been performed for the measurements of the direct pair-production cross section with electron primaries,[1] the so-called trident process, but relatively little data are available for the electron pair production through the muon primary.[2] Among these, a few experimental results agree [2,3] and others disagree[4] with theories[3,5,6] for the observed value of the direct pair-production cross section. Most of the experiments producing electron pairs by either primary electron[1] or muon[2] have been performed using cosmic-ray particles. These inherit 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. Experiments with primary muons have several advantages over those with electrons. For electron primaries, bremsstrahlung is the dominant process, and bremsstrahlung followed by conversion of the photon (pseudotrident) cannot easily be distinguished from a direct pair. But for a muon with the same Lorentz factor as an electron, bremsstrahlung is reduced roughly by a factor of $(m_e/m_\mu)^2$ for large $E/m_\mu c^2$.

In order to overcome the shortcomings of previous experimental techniques and also to look into the previous controversial experimental results, we used a monoenergetic beam of 15.8-GeV/c negative muons[7,8] in nuclear emulsion which provides a great deal of spatial resolution. In order to consider a muon producing an electron pair in the field of an emulsion nucleus with an effective charge $Z=21.4$, i.e., $\mu+Z\to\mu+Z+e^+ +e^-$, we used a small stack of Ilford G-5 nuclear emulsion which was exposed to a negative muon[7,8] beam with a flux density of 1×10^4 particles/cm^2 parallel to the emulsion plane. The contamination of the pions in the muon beams was less than 10^{-7}. The scanning was done by an along-the-track technique where the incident muons were picked up at a distance of 0.5 cm from the edge of the plate and at about half-way up from the bottom of the pellicle. These tracks were followed through the emulsion by using a constant oscillation of the Z-axis control to facilitate observation of events with dip angles greater than 0°. The average scanning speed was about 25 cm/h. Whenever an interaction was observed, the parent track was rechecked for its parallelism with the other neighboring beam tracks. A total of 280.11 m of track length was followed. We find that the total inelastic cross section [7,8] of 15.8-GeV/c muons in nuclear emulsion, after correcting for scanning bias, is $\sigma_{\text{inel}}=9.63\pm1.7$ μb/nucleon. The mean free path of a knock-on electron[8] was found to be $\lambda_{\text{knock}}=3.25\pm0.29$ m. All the apparent knock-on electrons which did not satisfy the energy-angle relationship for a two-body process were examined very carefully for a second low-energy track for a possible electron trident. After separating the three-pronged events (tridents), the vertex of each trident was carefully checked to eliminate spurious events. These coincidence pairs, called pseudotrident events, are produced either by bremsstrahlung conversion or by conversion of γ rays from the decay of a neutral particle like $\pi^0\to\gamma+e^++e^-$ (Daltiz decay) which occurs only 1/80 of the time. The calculated background was <1%.

For an interaction to be accepted for measurement as a possible electron pair, it had to satisfy the following stringent criteria: (i) There should be an apparent vertex coincident with the primary track, (ii) the secondary track has to be straight for at least one field of view (eliminating Auger electrons), (iii) the vertex (apart from an incoming particle) has to be a vertex with three outgoing particles (without any recoil of a nucleus), (iv) the outgoing secondary (pair) tracks should be on opposite sides of the primary and nearly coplanar, and (v) the two secondary tracks of interest should indeed be caused by "electrons." This determination was made when the secondary tracks were followed for scattering and ionization-density measurements. The selected events were further checked for energy-momentum balance. The errors in the angles were carefully calculated from[8]

$$\begin{aligned}(\Delta\theta)^2&=ct/p^2\beta^2+c_1/t^2,\\(\Delta\varphi)^2&=ct/p^2\beta^2+c_2/t^2,\end{aligned}\qquad(1)$$

where θ and φ are the projected and the dip angles, respectively. The first term is the multiple-Coulomb-scattering contribution to the angle error where t is the length of the cell size used, p is the particle energy, and c is a constant for the cell length t. The second term contains the error due to measurements. The constants c_1 and c_2 contain the noise contribution 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 angles separately, we calculated the error in the space angles to be less than 5%.

By scanning a total length of 280.11 m of track length we found twenty direct (electron-positron) pairs. The scanning efficiency for direct pairs was more than 98%, thus giving a mean free path for pair production in nuclear emulsion $\lambda_{\text{pair}}=14.0\pm3.1$ m and $\sigma_{\text{pair}}=9.0\pm1.9$ mb, while for 200-GeV protons, we obtained[10] $\lambda_{\text{pair}}=17.8\pm2.9$ m and $\sigma_{\text{pair}}=7.1\pm1.1$ mb. In Fig. 1(a) we show the experimental histogram of the total energy transferred to the eighteen electron pairs, with a scattering measurement error of 10%. The energy values were corrected for all other observed experimental errors.[7] Because of unsuitable physical conditions in the emulsion in the vicinity of the electron pairs, the energy determination of either one or both of the tracks from two of the electron events was not dependable and hence these events are excluded from our discussion. In the energy spectrum distribution, about 75% of the events were produced with $E_0\leq76.4$ MeV, where E_0

$=E_1+E_2$, the total energy of the electron pair ($E_1<E_2$): $E_0<mc^2\gamma=76.4$ MeV. In Fig. 1(b) the histogram shows the electron-pair energy up to 75 MeV, and this is compared with the theoretical curve given by the modified Bhabha's theory[3] for $2mc^2<E_0<\gamma mc^2$, where $\gamma=149.45$ for our experiment and mc^2 is the rest mass of an electron. The theory does not fit very well with the observed data. All the theoretical curves in this paper are normalized to our experimental data. The total cross section calculated by this theory for the range $E_0\leq 76.4$ MeV is 19 mb, which is more than twice as large as the experimental value for this observed range of E_0. In Fig. 1(c) we evaluated the angular divergence ω of the electron pair in terms of Borsellino's characteristic angle[11] $\omega_0=E_0mc^2/E_1E_2$. The calculated error in the space angle, as given by Eq. (1), is less than 5%. The theoretical curve is calculated from Eq. (14) of Ref. 11 in which we used from our experiment the overall average value $\langle E_0\rangle=57$ MeV and the imbalance ratio $\langle R\rangle=0.24$. The theoretical curve reproduces very approximately the shape of the experimental histogram. In Fig. 1(d) in the histogram we show the invariant mass $Q=(E_0^2-p^2)^{1/2}$ distribution for the electron pairs in units of $2mc^2$, where p is the total momentum of the pair. It is interesting to compare the value $\langle Q\rangle_{\text{pair}}=4.3\pm1.0$ MeV for the present experiment and $\langle Q\rangle_{\text{pair}}=4.8\pm0.8$ MeV for 200-GeV protons.[10] More than 50% of the events have $Q\leq 3$ MeV. The theoretical curve was fitted to this distribution for $E_0=57$ MeV. We see a very sharp peak in the theoretical curve at a very small value of Q. Figure 1(e) shows the experimental histogram of the imbalance ratio $R=E_1/E_0$ for all events with a theoretical curve which was calculated from Eq. (31) of Bethe and Heitler[12] for $E_0=60$ MeV. In Fig. 1(f) is shown the net p_t distribution of each electron pair. The value $\langle p_t\rangle_{\text{pair}}=3.6\pm0.8$ MeV/c may be compared with the value $\langle p_t\rangle_{\text{pair}}=4.9\pm0.8$ MeV/c for the 200-GeV proton beam. More than 50% of the events fall in the region of $p_t<3$ MeV/c.

In conclusion, the theoretical predictions on the cross section, the energy spectrum, the angular divergence, and the invariant-mass distribution of the electron pairs do not explain very well the observed experimental results. The total cross section for direct pair production by muons at 15.8 GeV/c ($\gamma\sim150$) indicates a discrepancy of approximately twice Bhabha's modified cross section, while for 200-GeV protons ($\gamma\sim200$) the discrepancy was greater than 5 times

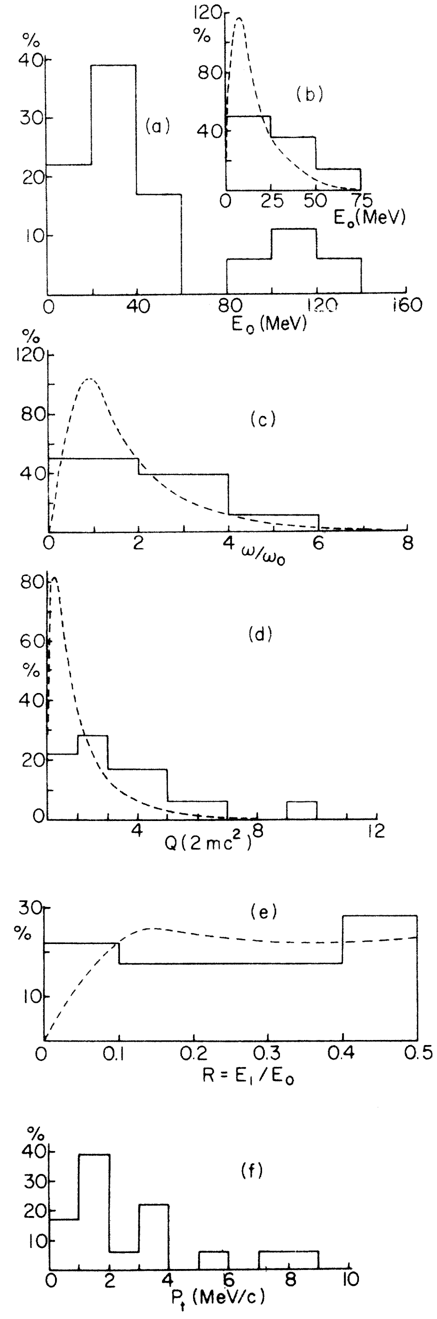

FIG. 1. (a) Energy distribution of the electron pairs. (b) Energy distribution of the electron pair with $E_0\leq mc^2\gamma=76.4$ MeV and the theoretical curve given by Ref. 3. All the theoretical curves in the present paper are normalized to the experimental data. (c) Angular divergence ω for electron pairs in terms of Borsellino's angle ω_0. The theoretical curve is given by Ref. 11. (d) Invariant mass Q distribution for all events in units of $2mc^2$. The theoretical curve is for electron pairs with $E_0=76$ MeV. (e) Experimental and theoretical (Ref. 12) distributions for $R=E_1/E_0$. (f) p_t distribution for all electron events.

Bhabha's modified cross section. The total cross section given by Racah[6] is in close agreement with it. But the theory of Murota, Weda, and Tanaka[6] gives a slightly higher cross section than the modified Bhabha's theory for a given primary energy in the same region of transferred energy. In all these theories the total electron-pair-production cross section depends on the ratio γ $(=E/m)$ and not on E and m separately or on the type of incoming particle. It is very interesting that although the γ factor in both our experiments (p and μ) are of the same order of magnitude, the cross section values vary by a factor of more than 2.5 for the small regions of E_0 and Q. We may point out that all these theories have been computed using perturbation theory and have neglected both nuclear recoil and the finite size and structure of the particles, which might be essential to include at such high energies. Nuclear emulsion has a large detection efficiency for low-energy particles and here we have been able to detect electrons with a kinetic energy of 0.07 MeV. We feel that the present experimental observations will be useful to theoreticians and that these discrepancies should be investigated very seriously.

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φ-Meson Production in π^-p and K^-p Interactions from 3 to 6 GeV/c*

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Cross sections and density-matrix elements for $\pi^-p\to\varphi n$ have been measured for $-t \lesssim 1.5$ GeV^2 at 3, 4, 5, and 6 GeV/c, using the Argonne effective-mass spectrometer to observe the decay $\varphi(1019)\to K^+K^-$. This is the first observation of the reaction in this energy range. The remarkably flat differential cross section at 4 GeV/c and the strong energy dependence suggest a production mechanism not normally seen at these energies. Data on $K^-p\to\varphi\Lambda$ and $K^-p\to\varphi\Sigma^0$ from the same experiment are also presented.

In an experiment to study $\pi^-p\to K^+K^-n$ with the Argonne effective-mass spectrometer, we have observed simultaneously the reactions

$$\pi^-p\to\varphi n, \tag{1}$$

$$K^-p\to\varphi\Lambda, \tag{2}$$

$$K^-p\to\varphi\Sigma^0. \tag{3}$$

Data were taken at 4, 5, and 6 GeV/c for all re-