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SECONDARY PARTICLE PRODUCTION IN HIGH-ENERGY MUON-NUCLEON INTERACTIONS

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Secondary particles produced by muon-nucleon interactions at 10.1 GeV/c (positive) and 14.6 GeV/c (negative muons) have been identified in nuclear emulsions. The energy spectrum and angular distribution (in c.m. system) is given for pion, kaon, and proton along with their partial cross sections. Yang's hypothesis of limiting fragmentation in high-energy lepton-hadron collision is compared with our results which tend to support it.

Recently a number of experiments[1-6] have been performed studying the inelastic lepton-hadron scattering at high energies to obtain detailed information about the structure and about any fundamental constituents of hadrons. Most of the data that have been available from Stanford Linear Accelerator Center, Cambridge Electron Accelerator, Brookhaven, and Deutsches Elektronen-Synchrotron were taken where one detects only the final scattered lepton at a predetermined laboratory angle. In these experiments the arrangement was such that they did not detect the secondary particle produced in these interactions. In the present report we give our preliminary results of the measurements of the secondary particles produced in 10.1- and 14.6-GeV/c positive and negative muon-nucleon inelastic interactions, respectively. The results at 5 GeV/c were presented earlier.[7]

Two large stacks, each of 70 Ilford G-5 pellicles, were exposed to 10.1- and 14.6-GeV/c positive and negative muons, respectively, with a flux density of $5\times10^5/\text{cm}^2$ at the Brookhaven alternating-gradient synchrotron. The beam was parallel to the plane of the emulsion. The pion contamination in the beams was measured[8] and the ratio of pions to muons was found to be less than 10^{-6}. We also took another precaution by placing an extra filter just before the emulsion stack so the contamination was considered to be negligible.[9] The processed emulsions were area scanned for all possible events produced by each muon beam. Using 70 pellicles from both the exposures, we observed about 7000 stars, and under very stringent selection criteria[9] discarded the background events produced either by cosmic rays or by the secondary tracks produced in other interactions. About 2500 events passed through all the required tests. All (1+1) type[10] events were checked for coplanarity and the elastic events were removed from all calculations.

In the selected events, the grain density g_s and the product of the three-momentum and velocity $\bar{p}\beta c$ was measured for all the grey and light secondary tracks[11] with dip angles less than 30°. The grain density g_0 of the primary track was measured separately for each event in order to eliminate any error due to nonuniformity of the blob density from place to place in the emulsion stack. The blob count was performed over a length of 5000 μ for the primary and for at least 1000 μ for the secondary track. A Koristka scattering microscope, attached to which was a filar micrometer that could be read to an accuracy of 0.02 μ, was used for the measurements of $\bar{p}\beta c$. The shower particles were identified by a well-known g^*-$\bar{p}\beta c$ technique.[9,12] Whenever it was considered desirable, the secondary tracks were followed from pellicle to pellicle until they stopped in the emulsion. Thus the track-following technique gave us an independent way of identifying the secondary particles (π, K, p, and Y) uniquely and thus their energy values were determined from their ranges. The theoretical curves for $g^*=g_s/g_0$ vs $\bar{p}\beta c$ were drawn for each beam for different particles (μ, π, K, p, etc.) produced in muon-nucleon interactions. The projected and dip angles that the shower particles made with the directions of the incident muons were measured very carefully[13] for the determination of their space angles.

In all, 1300 events were used for the results presented in this Letter. Single photopion production has been shown to be principally through (3, 3) resonance. The production of pions is predominantly in the backward direction in the c.m. system at all energies corresponding to this resonance.[14] There is also a backward enhancement in the angular distribution in the c.m. system of pions produced by virtual photons which are associated with the incoming muons. The angular distribution of pions was compared with photopion production experiments,[15,16] and with theory.[17] The general form was found to be the same within the statistics. This distribution of pions along with kaons and high-energy protons ($E_p > 25$ MeV) is shown in Figs. 1(a) and 1(b) for 10.1- and 14.6-GeV/c muons, respectively, with almost equal number of total secondary tracks. The spread towards the lower values of the angular distribution of pions is more with 14.6-GeV/c than with the 10.1-GeV/c muon beam. The angular distributions of kaons and protons are peaked towards backward directions and none of them were found with angles less than 140° in the c.m. system.

The energy spectrum of pions, kaons, and protons for 10.1- and 14.6-GeV/c muons is shown in Figs. 1(c) and 1(d), respectively. The pion spectrum extends up to 1.6 and 2.5 GeV/c for positive- and negative-muon beams. Fowler and Wolfendale[18] have calculated the energy spectrum

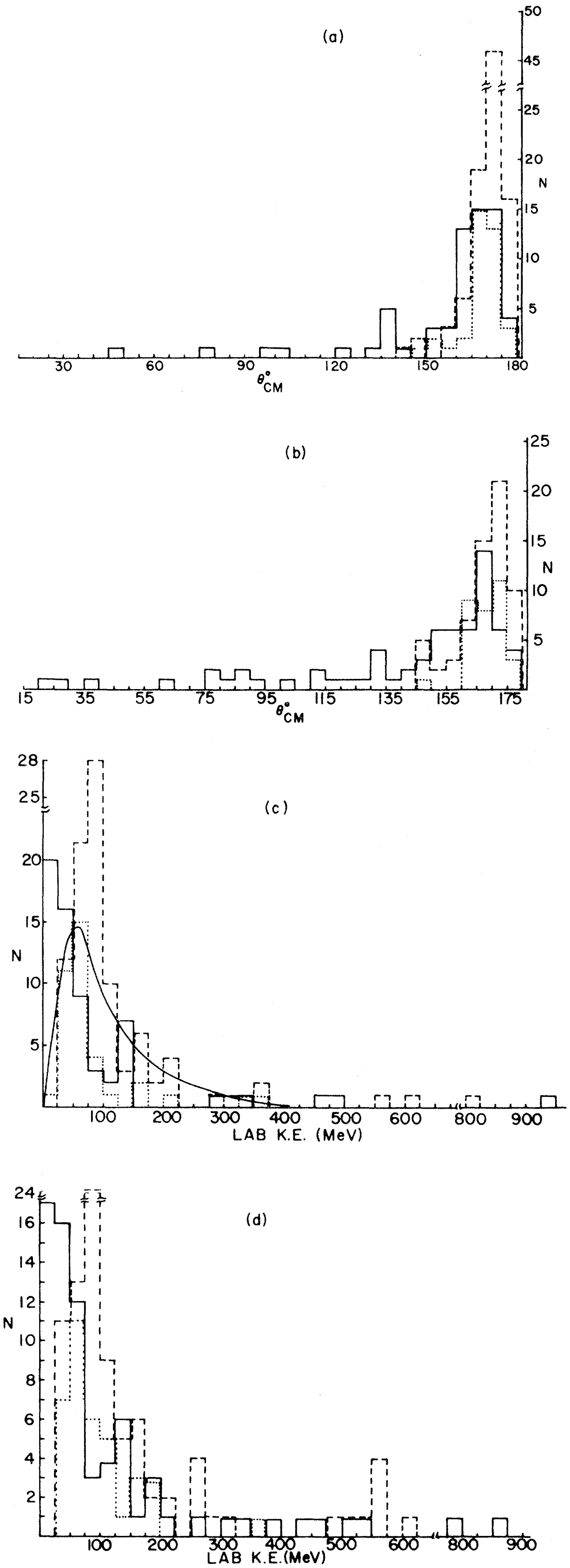

FIG. 1. (a) Angular distribution of shower particles produced in 10.1-GeV/c positive-muon–nucleon interactions in their c.m. system. Pions, kaons, and protons are represented by solid line, dotted line, and broken line, respectively. (b) Angular distribution of shower particles produced in 14.6-GeV/c negative-muon–nucleon interactions in their c.m. system. Pions, kaons, and protons are represented by solid line, dotted line, and broken line, respectively. (c) Energy spectrum of pions, kaons, and protons produced from the interaction of 10.1-GeV/c positive muons with nucleons. Pions, kaons, and protons are represented by solid, dotted, and broken line histograms, respectively. In the calculated curve for pions, the effect of pion absorption and nucleon motion was taken into consideration. Two pion events >1 GeV are not shown here. (d) Energy spectrum of pions, kaons, and protons produced from the interaction of 14.6-GeV/c negative muons with nucleons. Pions, kaons, and protons are represented by solid-, dotted-, and broken-line histograms, respectively. Nine pion events >1 GeV are not shown.

Table I. Cross-section values for muons on nucleons. All values are corrected for scanning bias.

Process	σ (μb/nucleon) 5.0 GeV/c	10.1 GeV/c	14.6 GeV/c
Total inelastic muon nucleon	3.6 ±0.3	6.67 ±0.45	9.1 ±0.56
Charged pion production	0.7 ±0.18	1.07 ±0.35	1.19 ±0.35
Charged strange-particle production	0.18 ±0.15	0.49 ±0.15	0.50 ±0.17

of single pions produced by 10-GeV/c muons for a nucleus with $A = 90$. For these calculations he combined the data of Watson et al.[15] in the total charged photon-meson cross section with the methods of Dalitz and Yennie.[19] He also considered the effect of initial nucleon momentum distribution averaged over pion angles in his calculations along with the effect of pion absorption in the same nucleus. The calculated curve shown in Fig. 1(e) has a general agreement with the experiment. The same kind of relation holds with the negative-muon beam. The kaon spectrum extends to 375 MeV/c for both beams and the proton spectrum extends to 815 and 600 MeV/c for positive and negative beams, respectively. The discussion for the production of $N^*(1238)$ and "Roper" meson (1470) which should be prominent at extremely low-momentum transfer will be presented elsewhere.[20,21]

To calculate the total inelastic cross section, we took into account the scanning bias and the scanning efficiency, and the results are shown in Table I. Also shown in Table I are the partial cross sections for the production of the secondary particles, and here we had to make a geometric correction (resulting from a dip-angle cutoff) besides the scanning corrections. The correction factor for the number of tracks of different particles produced but not used due to the stringent selection criteria of dip angles of secondary tracks is given by $(\pi/2)/\sin^{-1}(\sin\delta_{max}/\sin\theta_L)$ for $\theta_L \geq \delta_{max}$ where δ_{max} is the maximum dip angle and θ_L is the space angle measured with respect to the primary particle. For the calculation of the partial cross sections, we did not take into consideration any nuclear effects, although the data in Table I indicate a large absorption of secondary particles. The cross section for ρ^0 production was very small ($\sim 7 \times 10^{-32}$ cm^2/nucleon).

From the measurements of $\bar{p}\beta c$ and the scattering angle of the emerging muons, the energy transferred $\epsilon = E - E'$ and the square of four-momentum transfer $q^2 = 2EE'(1-\cos\theta_L)$ were calculated for each event where E and E' are the initial and the final laboratory lepton energies. For inelastic interactions, with the target approximated to be at rest in the laboratory system relative to the incident muon, we define

$$W = [M_p^2 + 2M_p(E-E') - q^2]^{1/2}. \qquad (1)$$

M_p is the mass of the proton and W is the invariant mass of the final hadronic state. Recently Benecke et al.[22] have defined a hypothesis of limiting fragmentations of the target and of the projectile in a high-energy lepton-hadron collision. They predicted that the average multiplicity $\langle n\rangle$ of shower particles increases with q^2 at a fixed value of W and approaches a limiting value. Since there were no data available prior to the present one for lepton-hadron multiplicities, we present here our results for muon-nucleon interactions at 10.1 and 14.6 GeV/c to test approximately this hypothesis of limiting fragmentations. For this analysis we used events with only one black prong but with different grey- and light-track multiplicities so that the interaction of the incoming muon is most probably with a single nucleon. The largest multiplicity observed for light and grey tracks after removal of evaporation prong is (8) and (10) for 10.1- and 14.6-GeV/c muons. Figure 2(a) shows the multiplicity of charged particles $\langle n\rangle$ as a function of q^2 for $W < 1.8$ and $W \geq 1.8$ for positive-muon beam. We see that the $\langle n\rangle$ value is almost constant for all q^2 values, and is about 1.7 for $W<1.8$. The value of $\langle n\rangle$ increases from 1.5 at $q^2 = 10^{-4}$ to 3.3 at $q^2 = 10^{-4}$ for $W \geq 1.8$. But for $q^2 > 10^{-1}$, the $\langle n\rangle$ seems to be leveling off in accordance with the above predictions. In Fig. 2(b) are shown the results for 14.5-GeV/c negative-muon beam where the average multiplicity at $W<1.8$ is about 2 for all q^2 values less than 0.5. But for $W \geq 1.8$ $\langle n\rangle$ rises from 3 to 4 as q^2 goes up and it has not yet

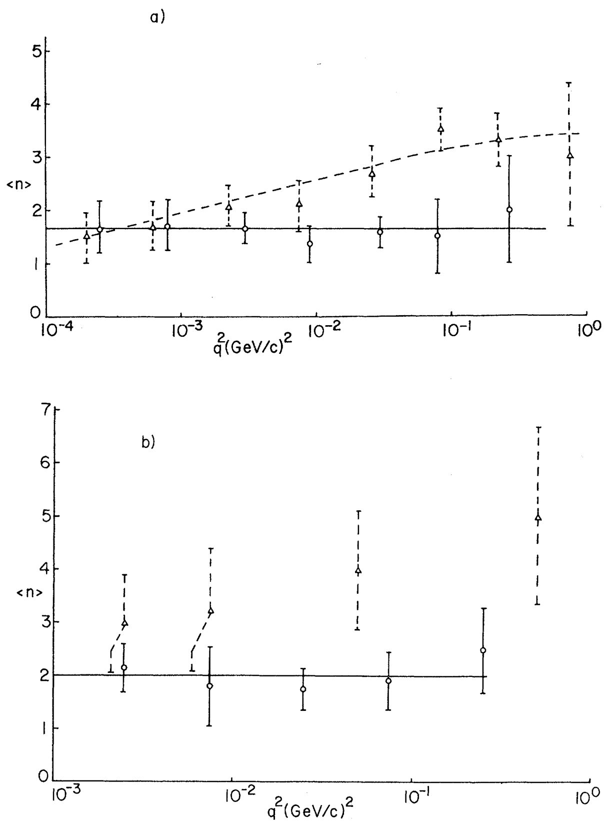

FIG. 2. (a) The average multiplicity for charged particles $\langle n\rangle$ as a function of q^2 for $W<1.8$ (solid line) and for $W\geq 1.8$ (broken line) for 10.1-GeV/c positive-muon beam. The line through the points is drawn by freehand. (b) The average multiplicity for charged particles $\langle n\rangle$ as a function of q^2 for $W<1.8$ (solid line) and for $W\geq 1.8$ (broken line) for 14.6-GeV/c negative-muon beam. The line through the points is drawn by freehand.

reached its saturation point. We may mention that the number of events with $W\geq 1.8$ is much less than for $W<1.8$. Thus our experimental results on lepton-hadronic interactions at 10.1 GeV/c seem to give the first evidence in favor of the hypothesis of limiting fragmentations.

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