SECONDARY PARTICLE YIELDS AT 0° FROM THE NEW STANFORD ELECTRON ACCELERATOR*

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We have measured the yields of secondary particles produced at zero degrees to the direction of the incident beam in a beryllium target bombarded by 16-GeV/c electrons from the new Stanford linear electron accelerator. The target was 1.8 radiation lengths thick. We had three purposes in making these measurements. First, we believed that the most intense secondary particle beams could be obtained at or near zero degrees, where the flux per unit solid angle would be at or near maximum, and where a thick production target (several radiation lengths) can be used without broadening the effective source. Our second purpose was to see if a zero-degree, secondary beam of strongly interacting particles could be useful in view of the fact that in such a beam there are millions of electrons or positrons for every pion. Our third purpose was to provide results to complement the work of others at nonzero angles.[1,2]

The measurements were made as part of a program of building and testing a high-energy muon beam at the Stanford Linear Accelerator Center, during tests of equipment and methods to be used in making a search for new particles.

The beam has three sections. The first is a momentum-analysis section in which an image of the target is formed in both planes at the momentum slit. In the second state, momenta are recombined to give a dispersion-free image in both planes at the second focus. The final state consists of a pair of quadrupoles which form a third double image, 90 m from the target. The measurements were made at the third focus.

Electron contamination was removed by placing a lead radiator, typically 5 radiation lengths thick, at the first focus. Electrons which lose an amount of energy greater than the momentum resolution of the beam, in this case less than one percent, are removed from the beam by the bending magnets in the second state. From the Bethe-Heitler straggling formula, and the thick-target bremsstrahlung calculations of Tsai and Whitis,[3] it can be shown that rejection factors of the required order of magnitude (10^7 to 10^8) can be obtained with radiators of 3 to 5 radiation length thickness.

At the end of the beam were placed, in order, a differential Cherenkov counter of the type described by Kycia and Jenkins,[4] filled with CO_2, a lead-Lucite sandwich shower counter,[5] and scintillation counters placed at depths up to 1.6 m in an iron absorber. The telescope which defined the incident beam for all of these consisted of two scintillation counters, one several meters upstream of the Cherenkov counter, and the second about one meter downstream of the Cherenkov, immediately in front of the shower counter.

Measurements of beam composition were made at 12.0, 8.0, and 5.5 GeV/c, for both positive and negative particles. At each momentum, the electron contamination was measured by means of the shower counter. Except for one measurement at 5.5 GeV/c, where it was 2%, the proportion of electrons in the beam was always less than one percent. The $K/(\pi+\mu+e)$ and $p/(\pi+\mu+e)$ ratios were measured by the number of particles which penetrated the 1.6-m thick iron absorber. Particle production ratios obtained in this manner are given in Table I, corrected for decay and for absorption in the counters and the lead radiator.

In addition to measurements of relative abundance, the muon flux was measured at 5.5 and 8.0 GeV/c relative to 12 GeV/c, and absolute measurements were made at 12 GeV/c. The flux was measured with large counters in the iron absorber which intercepted the whole beam. In order to avoid excessive counting rates, it was necessary to operate at a level of electron current in the accelerator too low to be measured accurately by the electron-beam-current toroid monitor. The flux measurements were therefore referred to a small monitor telescope placed behind the iron absorber at the end of

Table I. Particle production ratios at 0°. Target, 1.8 radiation lengths of beryllium; electron energy, 16 GeV; beam acceptance,[a] ±6.3 mr vertical, ±3.8 mr horizontal.

Momentum (GeV/c)	π^-/μ^-	π^+/μ^+	K^-/μ^-	K^+/μ^+	$\bar{p}/\mu^-$	p/μ^+	$\mu^\pm$ flux per GeV/c relative to 12 GeV/c
5.5	5.6 ± 0.8	5.5 ± 0.8	0.48 ± 0.07	0.90 ± 0.13	$(0.90\pm0.13)\times10^{-2}$	0.23 ± 0.03	2.9 ± 0.5
8.0	4.1 ± 0.4	4.0 ± 0.4	0.21 ± 0.02	0.41 ± 0.04	$(0.82\pm0.16)\times10^{-2}$	0.11 ± 0.01	2.6 ± 0.3
12.0	3.1 ± 0.3	3.0 ± 0.3	0.024 ± 0.005	0.10 ± 0.01	$\leq 2\times10^{-3}$	0.036 ± 0.006	1.0

[a]All results in this table are averages over the angular acceptance of the beam. See text.

the beam. This intermediate monitor was calibrated for each measurement against the toroid monitor at high current.

The loss of particles from the beam due to Coulomb scattering in the radiator was taken into account in the case of the relative flux measurements by changing the radiator thickness to give approximately the same Coulomb scattering at each momentum. Small corrections, based on the variation of yield with radiator thickness at 12 GeV/c, were made to obtain the fluxes for equal Coulomb scattering. Corrections were made for the presence of muons from π decay. The relative muon yields measured in this way are given on the last line of Table I. No difference in the yields of positive and negative muons was observed.

The absolute flux of muons at 12 GeV/c was obtained by reducing the radiator thickness in steps from 23.6 to 2.7 radiation lengths, and extrapolating to 0 thickness. Calculations of the loss due to scattering in the radiator are in good agreement with the observed variation of counting rate with radiator thickness. The counting rate at 12 GeV/c for a 2.7-radiation-length radiator must be multiplied by a factor of 1.5 to arrive at the rate for 0 radiator. The combined uncertainty in the extrapolation and in the beam acceptance with no radiator is estimated to be ±30%. All other sources of error are small in comparison. Our result for the 12-GeV/c muon yield is $(1.0\pm0.3)\times10^{-4}$ $\mu^\pm$/sr (GeV/c) per incident electron, averaged over the acceptance of the beam.[6,7] The complete results are shown in Fig. 1, normalized to the experimental point at 12 GeV/c.

We have compared our results with calculations made by Tsai and Whitis[8] of the muon yields at small angles from a 1.8-radiation-length target. When we averaged their results over the acceptance of the beam and made small corrections for energy loss and multiple scattering in the target (about 3% each), we obtained a value of $(1.1\pm0.1)\times10^{-4}$/sr GeV/c per electron for the muon flux expected at 12 GeV/c compared with our experimental result of $(1.0\pm0.3)\times10^{-4}$. The agreement with the energy variation we observe is good. From the expected variation of muon yield with angle we find that our yields at 12.0, 8.0, and 5.5 GeV/c should be multiplied by factors of 1.43, 1.15, and 1.06, respectively, to obtain the yield which would be observed in an infinitesimal solid angle.

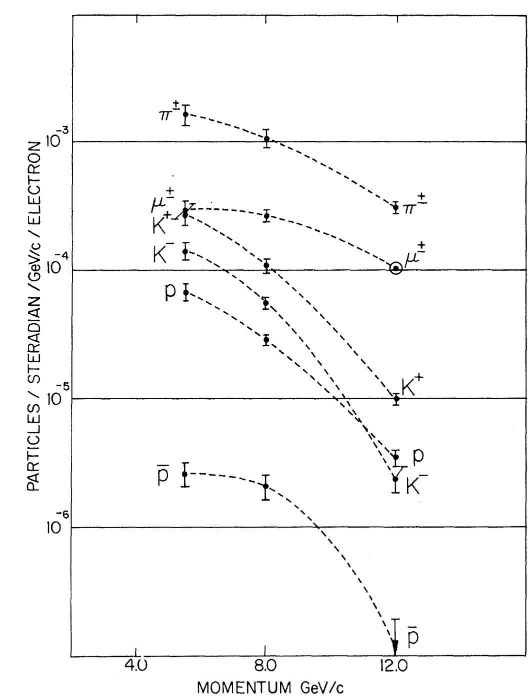

FIG. 1. Complete results at 0° for 16-GeV/c electrons incident on a 1.8-radiation-length beryllium target. Fluxes are averages over the acceptance of the beam (see text). The results are normalized to the observed muon flux at 12 GeV/c. The normalization is uncertain by ±30%. Error bars on the muon flux are uncertainties relative to the 12-GeV/c point. Other error bars are uncertainties relative to the muon flux at the same momentum. The curves are freehand through the points.

The yields of the strongly interacting particles are also averaged over the acceptance of the beam, and the correction to the pion yields will depend on the angular distribution.

In order to compare our measurements at 0° from 16-GeV/c electrons incident on 1.8 radiation lengths of beryllium with those of Flatté et al.[1] at 2° and 3° from 18-GeV/c electrons on a 0.3-radiation-length target and of Boyarski et al.[2] at 1° and 0.5° from 16-GeV/c electrons on a 0.6-radiation-length target, it is necessary to make some assumption about the yield as a function of photon energy, and to correct for the appropriate photon track length, and for absorption in our much thicker target. These corrections have ±30% uncertainties. We feel, however, that an even greater difficulty is the separate normalization for the three different experiments, and that there is no common point at which to test the relative normalizations. Therefore, comparisons demanding more precision than a factor of 2 should not be made.

With this in mind we made the following conclusions: (1) The secondary particle flux at zero degrees is, within a factor of 2, the maximum obtainable at the Stanford Linear Accelerator Center.[9] (2) Secondary beams at zero degrees from thick (or thin) targets can be used at this accelerator because the electrons or positrons can be removed without seriously affecting the secondary beam quality.

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[1]S. M. Flatté, R. A. Gearhart, T. Hauser, J. J. Murray, S. J. Wojcicki, R. Morgado, M. Peters, P. R. Klein, and L. H. Johnston, second following Letter [Phys. Rev. Letters 18, 366 (1967)].

[2]A. Boyarski, F. Bulos, W. Busza, D. Coward, R. Diebold, J. Litt, A. Minten, B. Richter, and R. Taylor, following Letter [Phys. Rev. Letters 18, 363 (1967)].

[3]Y. S. Tsai and Van Whitis, Stanford Linear Accelerator Center Report No. SLAC-PUB 184, 1966 (unpublished); and private communication.

[4]T. F. Kycia and E. W. Jenkins, in Proceedings of the Conference on Nuclear Electronics, Belgrade, 1961 (International Atomic Energy Agency, Vienna, 1962), Vol. I, p. 63.

[5]Kindly lent by C. Heusch.

[6]The beam acceptance is ±6.3 mr in the vertical plane, ±3.8 mr in the horizontal plane, and ±1.2% in momentum.

[7]Measurements were also made of the muon flux at 12 GeV/c with a small counter telescope, with all quadrupoles turn off. In this case, the electron contamination had to be removed by placing 20 radiation lengths of lead close to the target. The resulting corrections for the additional muon production in lead were made using the results of Tsai and Whitis (Ref. 8). Corrections also have to be made for multiple scattering in the lead. These results are also consistent with the predictions of Tsai and Whitis within similar limits of error.

[8]Y. S. Tsai and Van Whitis, private communication. The muon-pair production cross sections used in this calculation were obtained from the formulas given by Y. S. Tsai, in Proceedings of the International Conference on Nucleon Structure at Stanford University, 1963, edited by R. Hofstadter and L. I. Schiff (Stanford University Press, Stanford, California, 1964), p. 221, by the application of the substitution rule. The thick-target bremsstrahlung spectrum was obtained from the work described in Ref. 3.

[9]The Stanford linear accelerator is designed to give about 2×10^{14} electrons per second. Peak electron currents corresponding to about 7×10^{13} electrons per second at full repetition rate have been obtained in its initial operation [G. A. Loew, in Proceedings of the 1966 International Conference on Instrumentation for High Energy Physics, Stanford, 1966 (International Union of Pure and Applied Physics and U. S. Atomic Energy Commission, Washington, D. C., 1966), p. 365]. However, practical considerations of target shielding and the absorption of the power in the electron beam may limit the current which can be used in any specific case. More details may be obtained from the Stanford Linear Accelerator Center Users Handbook.