# PARTICLE YIELDS AT THE STANFORD TWO-MILE ELECTRON ACCELERATOR*

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The $\pi^\pm$, $K^\pm$, $p^\pm$, and $e^\pm$ yields at 2 and 3 deg from 16- and 18-GeV electrons on a 0.3-radiation-length beryllium target have been measured at the Stanford two-mile electron accelerator.

It was early realized that one of the most intriguing questions associated with the creation of the 20-GeV Stanford two-mile electron accelerator related to the possibility of copious production of strongly interacting particles. In 1960, Drell calculated the amplitudes for a particular set of photon-induced peripheral processes which produced strongly interacting particles.[1] These calculations were used to predict yields that were large enough to be experimentally useful.[2,3] This Letter largely confirms that prediction.

The $\pi^\pm$, $K^\pm$, $p^\pm$, and $e^\pm$ yields from 16- and 18-GeV electrons on a 0.3-radiation-length Be target have been measured at the Stanford two-mile accelerator and are reported here. The measurements were carried out at production angles of 2 and 3 deg, and at various secondary momenta between 4 and 14 GeV/$c$.

Figure 1(a) shows diagramatically the beam layout. Electron pulses, each approximately 1.5 $\mu$sec long, were delivered to a 10- by 0.6- by 0.6-cm Be target, with a typical current of 1 mA within each pulse, giving about $10^{10}$ electrons per pulse. The pulse repetition rate was normally 180 per second. The primary beam-momentum spread was <1%. After traversing the target, the electron beam was stopped in a well-shielded, water-cooled beam dump.

A quadrupole doublet midway between target and detector in the secondary beam served to focus particles of the desired momentum onto the detector array. A 1% momentum resolution was obtained by use of a bending magnet, which deflected the beam by 3 deg. The system accepted a solid angle of ~10 $\mu$sr. Figure 1(b) diagrams the detector array, which was located 220 ft from the target.

The acceptance of the counter telescope was determined by two $\frac{3}{8}$-in.-diam plastic scintillators $S_2$ and $S_3$ near the beam focus, and a $\frac{3}{4}$-in. scintillator $S_1$ that defined an angular aperture of ~7 mrad. $C_1$ and $C_2$ were, respective-

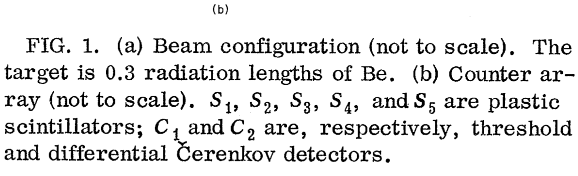


FIG. 1. (a) Beam configuration (not to scale). The target is 0.3 radiation lengths of Be. (b) Counter array (not to scale). $S_1$, $S_2$, $S_3$, $S_4$, and $S_5$ are plastic scintillators; $C_1$ and $C_2$ are, respectively, threshold and differential Čerenkov detectors.

ly, threshold and differential gas Čerenkov cells for mass identification. The pressure in $C_1$ was normally set below the threshold for $K$'s. The coincidence counts of $S_1S_2S_3$ and $S_1S_2S_3C_2$ (or $S_1S_2S_3\bar{C}_1C_2$) were recorded as a function of $C_2$ pressure. At all secondary momenta the fast particles ($\pi$, $\mu$, $e$), $K$'s, and $p$'s (or $\bar{p}$'s) were well separated in pressure. The scintillator $S_4$ was used to detect showers produced by electrons interacting in the preceding lead. The thickness of this lead was experimentally adjusted to be near the shower maximum for each momentum studied, and the discriminator on $S_4$ was set to reject single particles and accept only electron showers. Finally, the scintillator $S_5$ together with iron absorbers placed in front were used to measure the $\mu$ fraction of the beam.

The absolute magnitude of the electron-beam current was measured with calibrated toroids accurate within ±5%. The beam on target was monitored relatively by measuring the net charge emitted from the electrically insulated target. This charge amounted to about 1.2 electrons per primary beam electron, due mainly to delta rays, Compton electron emission, and positron annihilation.

All results obtained with the Be target are shown in Table I. A systematic correction for interactions and scattering losses in the detec-

Table I. Particle yields in particles $sr^{-1}$ $(GeV/c)^{-1}$ per $10^7$ incident electrons on a 0.3-radiation-length Be target. The errors reported here are the algebraic sums of the statistical errors and nonstatistical fluctuations as described in the text. The over-all normalization of the data is believed to be accurate to ±15%. All yields are at the target, i.e., they have been corrected for decay. The muon fraction was measured at a few momenta and was found to be <1% of the total yield.

| Primary electron energy (GeV) | Production angle (deg) | Charge and secondary momentum (GeV/c) | Yield | | | |
|---|---|---|---|---|---|---|
| | | | Electron | Pion | Kaon | Proton |
| 18[a] | 2 | - 4 | 2780±120 | 2520±150 | 114±10 | |
| | | - 6 | 1280± 80 | 2050±100 | 103±11 | 7.1±1.3 |
| | | - 8 | 970± 60 | 1680± 80 | 49± 5 | 5.1±1.0 |
| | | -10 | 970± 50 | 820± 50 | 22.5±2.5 | 2.9±0.7 |
| | | -12 | 930± 40 | 280± 30 | 8.3 ±0.9 | 1.2±0.4 |
| | | -14 | 1060± 40 | 74± 26 | 4.5 ±0.7 | |
| | | + 4 | 440± 40 | 2330±100 | 230±30 | 260±80 |
| | | + 6 | 98± 12 | 2130± 60 | 166±21 | 84±10 |
| | | + 8 | | 1630± 40 | 86±11 | 49± 4 |
| | | +10 | | 900± 20 | 56± 3 | 23.2±1.7 |
| | | +12[c] | | 304± 7 | 31± 3 | 9.8±0.8 |
| | | +14 | | 76± 2 | 14.6±1.5 | 3.5±0.6 |
| 18[a] | 3 | + 6 | | 1480± 60 | 103±15 | 126±30 |
| | | +10 | | 186± 8 | 35± 3 | 15.1±1.8 |
| | | +12 | | 64± 3 | 14.2±1.7 | 8.0±0.9 |
| | | -12 | 164± 5 | 52± 3 | 4.3±0.5 | 0.26±0.07 |
| 16[b] | 3 | +10 | | 148± 6 | 26± 3 | 10.7±1.7 |
| | | +12 | | 35.2±1.6 | 10.7±1.2 | 3.2±0.3 |
| | | -10 | 252± 12 | 156± 11 | 10.7±1.2 | 1.1±0.2 |
| | | -12 | 299± 9 | 37± 4 | 2.8±0.4 | 0.17±0.10 |

[a]17.85 ± 0.15 GeV.
[b]16.0 ± 0.08 GeV.
[c]Deuterons here were found to be less than 3% of the protons.

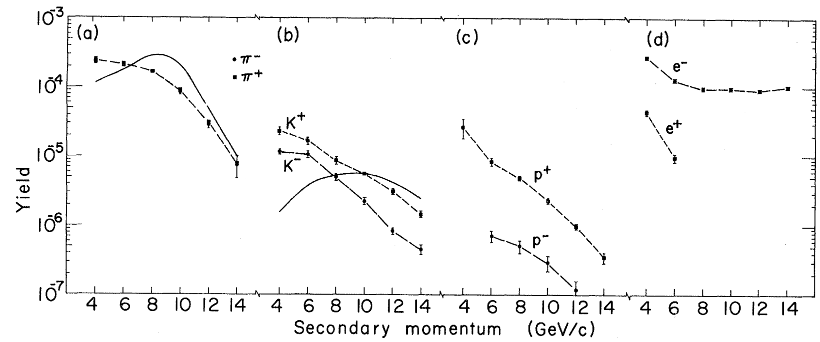


FIG. 2. Experimental yields of (a) $\pi^\pm$, (b) $K^\pm$, (c) $p^\pm$, and (d) $e^\pm$ for a 2-deg production angle and 18-GeV primary energy. All yields are in units of particles $\mathrm{sr}^{-1}$ $(\mathrm{GeV}/c)^{-1}$ per incident electron on a 0.3-radiation-length Be target. Errors shown on the graphs are the algebraic sums of the statistical errors and nonstatistical fluctuations as described in the text. The over-all normalization of the data is believed to be accurate to ±15%. The error bars on the $\pi^+$ data have been suppressed for clarity; they range from 2 to 4% (see Table I). The continuous curves in (a) and (b) are, respectively, the combined pion yields from the Drell process and from $\rho$ production, and the $K^+$ yields from the Drell process, as calculated by Y. S. Tsai and V. Whitis, private communication.

tor array, which depends on gas pressure in $C_1$ and $C_2$ as well as on momentum, has been applied to the data. This correction is typically 15%. To the statistical error we have added algebraically an error of ≈2%, which reflects nonstatistical fluctuations in the ratio of $S_1S_2S_3$ to monitor current. This combined error is quoted in Table I. The over-all normalization of the data is believed to be accurate to ±15%.

The 2-deg yields at 18-GeV primary energy are shown in Fig. 2. Figure 3 shows representative angular distributions at 18 GeV. The 0.5- and 1-deg data were taken from Boyarski et al.[4] It was necessary to correct their data from 16- to 18-GeV primary energy as well as to correct for a different target length (0.6 radiation lengths). Comparison with the 0-deg data of Barna et al.[5] is not shown, since rather large and uncertain normalization factors would be needed to convert their 1.8-radiation-length data to 0.3 radiation lengths.

It is generally believed that production of strongly interacting particles by an electron beam is a two-step process, with the electrons forming real photons by bremsstrahlung, followed by the interaction of the photons with the target nuclei. The Drell mechanism provides a quantitative estimate of the photon-nucleus interaction. However, once the strongly interacting particle is produced it may still undergo further interactions in the target, or even within the same nucleus. This difficulty, as well as the complication of going through the intermediate step of bremsstrahlung production, makes detailed comparison of the yields with theoretical production models difficult. Nevertheless, the following qualitative observations can be made:

(1) The ratio of the yields of $\pi^+$ to $\pi^-$ [Fig. 2(a)] is unity for all secondary momenta. Calculations of the combined yields of pions from the Drell process and from $\rho$ production, performed by Tsai and Whitis,[6] give order-of-magnitude agreement with the experimentally observed $\pi^\pm$ yields, and, at production angles ≥2 deg, give a decrease in yield with angle comparable to that seen in Fig. 3(a).

(2) The $K^+/K^-$ ratio [Fig. 2(b)] is greater than 1.3, which would be expected from the Drell mechanism alone.[7] The order of magnitude of the yields is consistent with such a mechanism. Associated production of $K^+$ with $\Lambda$

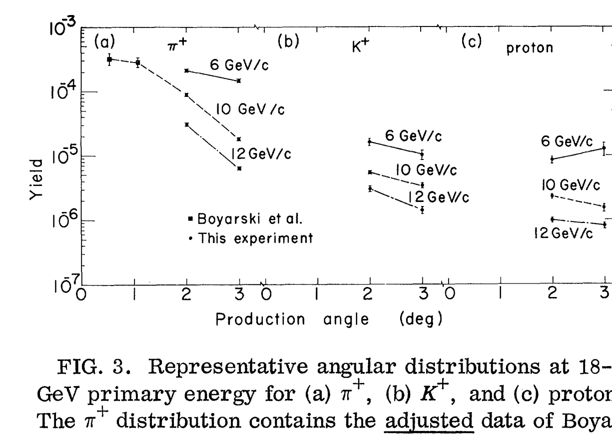


FIG. 3. Representative angular distributions at 18-GeV primary energy for (a) $\pi^+$, (b) $K^+$, and (c) protons. The $\pi^+$ distribution contains the adjusted data of Boyarski et al., Ref. 4 (see text). The units of the yields and the significance of the error bars are given in Fig. 2. The over-all normalization of the data is believed to be accurate to ±15%.

or Σ by photons, however, which could produce an excess of $K^+$ over $K^-$, has been calculated to be 2 to 3 orders of magnitude lower.[7,8] The decrease of the cross section at small angles predicted by an unmodified (no final-state interaction) Drell mechanism is not seen in the $K^+$ or $K^-$ angular distributions (Fig. 3, Table I, and Ref. 5).

(3) The large ratio of protons to antiprotons observed in Fig. 2(c) indicates that quite different mechanisms are operative. Drell has suggested that photodisintegration of the Be nucleus with direct emission of target protons may be responsible for the large proton yield.[9] The proton angular distributions of Fig. 3(c) are somewhat flatter than predicted for direct proton ejection.

A search was also made at a secondary momentum of 12 GeV/$c$ for deuterons. The yield was found to be <3 % of that of the protons.

(4) Large-angle production of $e^-$ and $e^+$ (2 or 3 deg) can occur most simply by bremsstrahlung or pair production accompanied by a single scatter in the target. Calculations using elastic scattering gave results too small to account for the observations of Table I. Inelastic scattering is probably dominant, and is difficult to calculate.

(5) The general trend of all yields to fall rapidly at high secondary momenta is, at least in part, a result of the smaller number of bremsstrahlung photons capable of producing these secondaries.

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

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[6]Y. S. Tsai and V. Whitis, private communication.

[7]Y. S. Tsai, Stanford Linear Accelerator Center Users Handbook (unpublished).

[8]The possibility of associated production by the pions within the same nucleus cannot be excluded. Analysis of data taken with an iron target, which has bearing on this question, is under way and will be reported elsewhere.

[9]S. D. Drell, private communication.

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## NEARLY MONOENERGETIC ELECTRON FLUXES DETECTED DURING A VISIBLE AURORA*

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Low-energy (3-70 keV) electron spectra were measured recently during a visible aurora at Fort Churchill, Manitoba, using a relatively high-resolution electrostatic spectrometer as part of the payload of a Nike-Tomahawk rocket. Measurements of spectra in this energy region have been of considerable interest since the 1958 experiments of McIlwain[1] in which electrons below 10 keV appeared to be the main source of auroral production. Although there have been many experimental studies of auroral radiation phenomena since then, relatively few were designed to explore the predominant low-energy (<10 keV) region, and those that did suffered from not having enough energy resolution[2] and low-energy response to define clearly the most essential features of the electron spectrum.