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Measurement of $K^\pm$ and K^0 inclusive rates in e^+e^- annihilation at 29 GeV

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We have measured the $K^0+\bar{K}^0$ inclusive cross section in e^+e^- annihilation at 29 GeV with the Mark II detector on the PEP storage ring at SLAC. We find $1.27\pm0.03\pm0.15$ $K^0+\bar{K}^0$ per hadronic event. We have also used time-of-flight particle identification to measure the $K^\pm$ rate over the momentum range 300–900 MeV/c.

We report a measurement of inclusive rates for $K^0+\bar{K}^0$ and $K^\pm$ production[1] in e^+e^- annihilation at $\sqrt{s}=29$ GeV from the Mark II experiment on the PEP storage ring at SLAC. We use charged-track information to reconstruct the decay $K_S\to\pi^+\pi^-$ for kaon momenta between 0.2 and 10.0 GeV/c. The $K^\pm$ rate is measured over the momentum range 300–900 MeV/c, in which time-of-flight kaon identification is possible.

Measurements by the TASSO collaboration[2-4] at $\sqrt{s}=34$ GeV indicate an inclusive rate of 2.0 ± 0.2 $K^\pm$ per event and 1.48 ± 0.05 $K^0+\bar{K}^0$ per event. This difference in kaon rates is not easily explained within the framework of standard fragmentation models.[4] At 29 GeV, the Time Projection Chamber (TPC) collaboration[5,6] has measured 1.35 ± 0.13 $K^\pm$ per event and 1.22 ± 0.15 $K^0+\bar{K}^0$ per event. The TPC and TASSO $K^\pm$ rates differ chiefly in the low-momentum region over which the Mark II detector can identify both $K^\pm$ and K^0.

The Mark II time-of-flight system and main cylindrical drift chamber have been described in detail elsewhere.[7] An inner high-resolution cylindrical drift chamber[8] provides impact-parameter measurements perpendicular to the beam axis with resolution

$$\sigma_r{}^2=(110/p)^2+(95)^2\ \mu\text{m}^2$$

for charged tracks, where p is in GeV/c. Both the inner and main drift chambers are used in charged-track reconstruction and provide momentum resolution of

$$(\sigma_p/p)^2=(0.025)^2+(0.010p)^2\ .$$

The time-of-flight system consists of 48 scintillation counters arranged parallel to the beam (z) axis at a radius of 1.5 m and covering 75% of 4π sr. Each scintillation counter is read out at both ends by photomultiplier tubes. For isolated particles in hadronic events, with information from both ends of the counter, the rms time resolution is 350 ps and the z position of the particle can be determined with a σ_z of 8 cm.

The data samples used in this measurement were collected by the Mark II detector over a two-and-one-half-year period and correspond to a total integrated luminosity of 205 pb^{-1}. The K^0 and $K^\pm$ rates have been determined from different subsamples of hadronic events (of 105 and 130 pb^{-1}, respectively), as the $K^\pm$ measurement depends most critically on the time-of-flight system while the K^0 measurement requires optimal charged-particle tracking.

Events with at least five well reconstructed charged tracks whose total charged energy is greater than 25% of the center-of-mass energy are defined to be hadronic-event candidates. The sphericity axis defined by the charged tracks is also required to have $|\cos\theta|<0.65$ with respect to the beam axis. A well reconstructed track is defined as one with

$|z| < 10$ cm, $r < 2$ cm [at the point of closest approach to the average beam interaction point (IP)], momentum perpendicular to the beam axis $p_\perp > 100$ MeV/c, and $|\cos\theta| < 0.85$. For tracks with momenta less than 1 GeV/c the cut on r is loosened to $rp < 2$ cm GeV/c to avoid losses due to multiple scattering. After these cuts the hadronic-event samples are 33 846 events for the $K^\pm$ and 27 231 for the K^0 with contamination from beam-gas, two-photon processes, and $e^+e^- \to \tau^+\tau^-$ of less than 4%.[9]

K_S are reconstructed from the decay $K_S \to \pi^+\pi^-$. Candidate pions from K_S decay are required to have $|\cos\theta| < 0.80$ and an impact parameter greater than 1 mm relative to the IP in the x-y plane. We calculate the intersection points for pairs of oppositely charged pions and choose as the assumed decay vertex the intersection point which yields the smallest decay length. The momentum vector of each candidate $\pi^+\pi^-$ pair, extrapolated through the decay vertex, is required to pass within 5 mm of the IP and the proper decay length $c\tau$ is required to be greater than 5 mm. The pion momenta are corrected for energy loss in the material traversed and the tracks are constrained to pass through a single point in space. The resulting $\pi^+\pi^-$ mass spectrum is shown in Fig. 1. K_S candidates with masses within 30 MeV/c^2 of the nominal mass are defined to lie in the signal region while those with masses between 410 and 440 or 560 and 590 MeV/c^2 are used to define a sideband sample. There are 5683 K_S candidates in the signal region and 1483 in the sidebands, yielding a background-subtracted signal of 4200 ± 85 $K_S \to \pi^+\pi^-$ decays.

We estimate the K_S reconstruction efficiency by performing an identical analysis on a simulated data set produced by Monte Carlo[10] methods. The efficiency for reconstructing the decay $K_S \to \pi^+\pi^-$ in a detected hadronic event is found to range between 20 and 50% with minima at very low and high momenta and maximal efficiency between 1 and 4 GeV/c. The Monte Carlo simulation is also used to derive corrections for initial-state radiation[11] and the hadronic-event detection efficiency. After correction for branching fractions, radiation, and reconstruction efficiency, the number of $K^0 + \bar{K}^0$ in the momentum range 0.2–10.0 GeV/c normalized by the number of hadronic events in the sample is 1.24 ± 0.03 per event. The systematic error on this measurement is estimated to be 12% and is dominated by a 10% uncertainty in the reconstruction efficiency and a

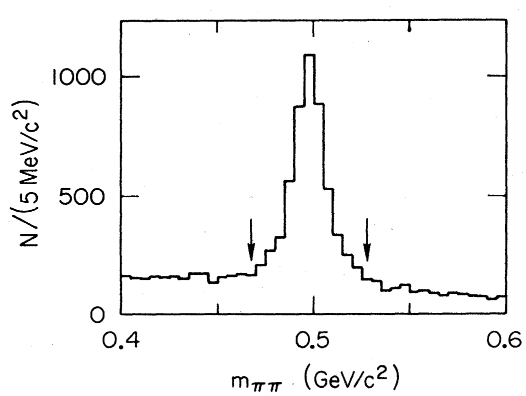

FIG. 1. The $\pi^+\pi^-$ mass spectrum after all cuts. The arrows indicate the signal region.

TABLE I. $K^0,\bar{K}^0$ per event as a function of p. Statistical errors only.

p (GeV/c)	$\bar{x}$	No. per event	$\frac{1}{\beta\sigma_H}\frac{d\sigma}{dx}$
0.200– 0.300	0.038	0.020 ±0.007	14.2 ±3.8
0.300– 0.400	0.042	0.044 ±0.008	19.4 ±3.5
0.400– 0.500	0.046	0.049 ±0.008	15.7 ±2.5
0.500– 0.600	0.051	0.050 ±0.007	12.6 ±1.9
0.600– 0.700	0.056	0.055 ±0.007	11.3 ±1.5
0.700– 0.800	0.062	0.036 ±0.006	8.3 ±1.4
0.800– 0.900	0.068	0.041 ±0.005	8.8 ±1.3
0.900– 1.000	0.074	0.044 ±0.005	8.7 ±1.1
1.000– 1.250	0.085	0.110 ±0.007	7.5 ±0.6
1.250– 1.500	0.100	0.099 ±0.006	6.5 ±0.5
1.500– 1.750	0.117	0.083 ±0.006	5.1 ±0.4
1.750– 2.000	0.133	0.071 ±0.005	4.5 ±0.4
2.000– 2.500	0.159	0.122 ±0.007	3.7 ±0.3
2.500– 3.000	0.192	0.106 ±0.006	3.2 ±0.3
3.000– 3.500	0.226	0.069 ±0.005	2.2 ±0.2
3.500– 4.250	0.269	0.087 ±0.006	1.7 ±0.2
4.250– 5.000	0.320	0.057 ±0.005	1.1 ±0.1
5.000– 6.000	0.380	0.045 ±0.005	0.69 ±0.09
6.000– 7.000	0.449	0.027 ±0.004	0.39 ±0.07
7.000– 8.500	0.535	0.017 ±0.003	0.17 ±0.04
8.500–10.000	0.638	0.014 ±0.003	0.13 ±0.04

5% uncertainty in the hadronic-event detection efficiency and radiative corrections. Monte Carlo studies indicate that an additional 0.03 K^0 per event lie outside the momentum range 0.2–10.0 GeV/c. The total $K^0 + \bar{K}^0$ rate is thus $1.27 \pm 0.03 \pm 0.15$ per event. This rate is consistent with published rates from the TASSO,[3,4] PLUTO,[12] JADE,[13] and TPC[6] collaborations at similar energies. Table I and Fig. 2

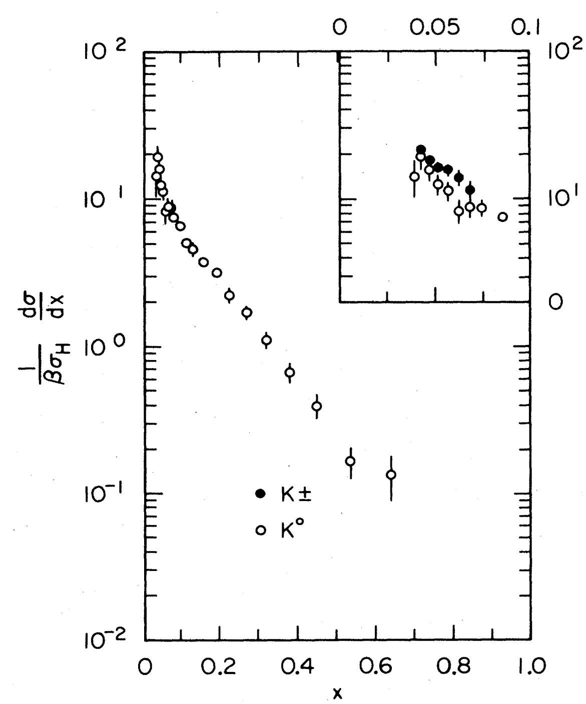

Fig. 2. The $K^0 + \bar{K}^0$ differential rate from the present experiment. The inset displays the $K^\pm$ and $K^0 + \bar{K}^0$ rates for $x < 0.1$. Statistical errors only.

summarize the $x \equiv E_K / E_{\rm beam}$ dependence of the K^0 rate.

We determine the $K^\pm$ rate over the momentum range 300–900 MeV/c using time-of-flight information for particle identification. We require that charged tracks considered as $K^\pm$ candidates be well reconstructed as defined above, and have $|\cos\theta| < 0.5$. In addition, the track is required to hit a scintillator, to be the only charged track which traces into that counter, and to produce a time measurement at both ends which is consistent with a single hit in the counter.

Monte Carlo studies indicate that 25–50% of $K^\pm$ produced at momenta from 300–900 MeV/c decay before reaching the time-of-flight system. Kaons which decay usually cannot be properly fitted with a single helical curve and are not reconstructed at all or are reconstructed improperly. Poorly reconstructed tracks have bad r or z information and usually do not have hits beyond the decay point. The reconstruction cuts thus remove many decays in flight. In addition at least one hit is required in the outer four layers of the drift chamber and the z determined by the time-of-flight system is required to agree within 25 cm with that predicted by the drift chamber. These cuts lower the fraction of $K^\pm$ accepted which decayed in flight to 5–9% with most of the residual decays occurring within 50 cm of the scintillators, where they have little effect on the measured velocity.

The number of $K^\pm$ is extracted from the measured times of flight by a fit of the distribution of the difference between the measured time and the expected time for a $K^\pm$ in each of twelve 50-MeV/c momentum slices between 300 and 900 GeV/c. The expected time is a simple function of the measured track path length, the momentum, and the $K^\pm$ mass. Figure 3 shows the distribution of $t_{\rm meas} - t_K$ for all tracks in two typical momentum bins. The $K^\pm$ contribution should be centered around zero and reflects the resolution of the time-of-flight measurement, while contributions from $e^\pm$, $\pi^\pm$, and $p/\bar{p}$ are, in addition, widened by the spread in path lengths and momenta within each momentum bin. The measured distributions of path lengths and

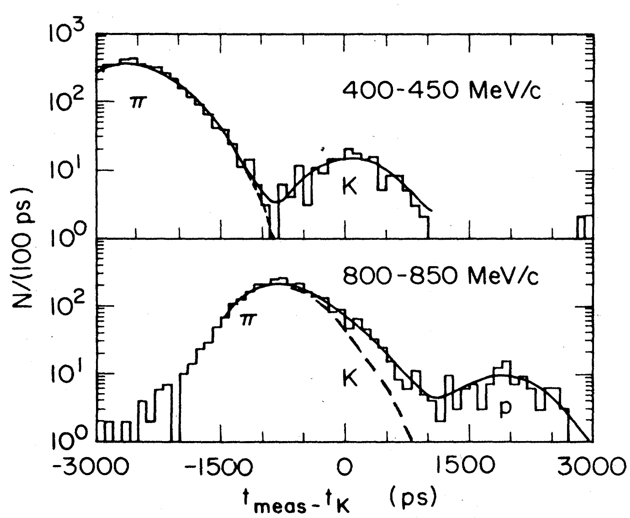

FIG. 3. Distribution of measured times of flight for momentum slices $0.400 < p < 0.450$ GeV/c and $0.800 < p < 0.850$ GeV/c. The dashed curves are the π contribution in the $K^\pm$ region. The χ^2 for the fits are 40.1 for 43 degrees of freedom and 50.0 for 54 degrees of freedom, respectively.

momenta in the data are used to construct the distributions of expected $e^\pm$, $\pi^\pm$, or $p/\bar{p}$ time of flight minus expected $K^\pm$ time. These distributions are then convoluted with a resolution function to produce fit functions which reproduce the expected contribution for each particle hypothesis. The resolution function for the time-of-flight system is determined from tracks with momenta greater than 3 GeV/c and thus includes any non-Gaussian tails. The relative normalizations of the fit functions are varied to fit the observed distribution of time of flight minus $K^\pm$ time. Protons contribute only for $p > 700$ MeV/c.

Figure 3 shows such fits to two typical momentum slices. The pion contributions in the region of the kaon are shown by the dashed lines in the figure. The same procedure has been performed on simulated data and reproduces the true number of $K^\pm$ to within 4%. As a check on the effects of any systematic momentum errors the measured momenta for drift-chamber tracks have been varied by 10 MeV/c, producing large changes in fit χ^2 but only 6% shifts in the measured numbers of $K^\pm$.

The momenta used to determine the slices are those measured at the drift chambers. The true momenta are somewhat higher due to energy loss in the material traversed by charged tracks. The correction ranges between 3 and 10 MeV/c and is included in the determination of x.

The numbers of $K^\pm$ found by this method are corrected for efficiency and initial-state radiation to yield the numbers of $K^\pm$ per event. The efficiency for a $K^\pm$ which passes all of the cuts is determined by Monte Carlo methods for each momentum slice. Studies of all charged tracks which yield good time-of-flight (TOF) information—such tracks are over 90% pions in this energy range—indicate that the requirement of a single hit in a counter and good $z_{\rm TOF}$ information is only (86 ± 2)% efficient for well-reconstructed tracks in the data as compared with the Monte Carlo simulation. This is believed to be due to the absence of neutral-particle interactions in the Monte Carlo simulation, which lowers the simulated occupancy of the counters. The efficiencies are corrected for this factor and for measured variations in the charged-track efficiency with time. These efficiencies are used to determine the number of $K^\pm$ in the event sample. The corrected number of $K^\pm$ is then normalized to the number of hadronic events.

The systematic uncertainty in the $K^\pm$ rate is dominated by the Monte Carlo simulation of individual track efficiencies and by the fit procedure and momentum errors. The drift-chamber-efficiency correction and model dependence have been studied[9] and yield an estimated systematic error of 8% for all charged tracks including radiative corrections, hadronic-event efficiencies, and variations in data-sample quality. This 8% uncertainty is appropriate for those $K^\pm$ which do not decay in flight. As decays in flight contribute only 5–9% of the total detected $K^\pm$, a very conservative estimate of 50% uncertainty in the efficiency for tracks which decay in flight contributes only an additional 4% to the uncertainty in the total efficiency. The uncertainty in the correction for differing time-of-flight efficiencies in the data and Monte Carlo simulation was 2%. Combining these errors with the previously discussed 4% error due to the fit procedure and 6% uncertainty introduced by momentum measurement errors, we estimate a systematic error of 12%.

Table II summarizes the $K^\pm$ rate as a function of p and Fig. 4 compares the x dependence of the invariant rate with results from the TASSO[2] and TPC[5] collaborations. A mea-

TABLE II. Summary of $K^{\pm}$ cross section. The momentum bins reflect energy-loss corrections appropriate to charged kaons. Statistical errors only.

p (GeV/c)	$\bar{x}$	No. per event	$\frac{1}{\beta\sigma_H}\frac{d\sigma}{dx}$
0.310–0.406	0.0422	0.048 ±0.003	21.1 ±1.3
0.406–0.504	0.0464	0.056 ±0.004	18.0 ±1.3
0.504–0.604	0.0513	0.062 ±0.005	16.5 ±1.2
0.604–0.703	0.0565	0.069 ±0.005	15.8 ±1.2
0.703–0.803	0.0621	0.067 ±0.007	14.0 ±1.5
0.803–0.902	0.0680	0.059 ±0.008	11.5 ±1.5

surement from TASSO at $\sqrt{s}=22$ GeV is also shown. As both TASSO measurements are higher than the TPC and Mark II values, the difference between the 29 and 34 GeV results cannot easily be interpreted as a beam-energy-dependent effect. Our results are somewhat higher than, but compatible with, the TPC values.

The inset in Fig. 2 compares the measured rates for $K^{\pm}$ and $K^0+\bar{K}^0$ from this experiment. Over the momentum range 300–900 MeV/c the $K^0+\bar{K}^0$ rate is 0.28 ±0.02 ±0.04 per event and the $K^{\pm}$ rate is 0.36 ±0.02 ±0.04 per event. Standard fragmentation models do not predict a significant difference in kaon rates at low momenta.

In conclusion, we have measured the inclusive $K^0+\bar{K}^0$ production rate in e^+e^- annihilation at $\sqrt{s}=29$ GeV over the full momentum range and the $K^{\pm}$ rate over a narrow region of low momentum. The $K^0+\bar{K}^0$ results agree well with other measurements. The $K^{\pm}$ rate is slightly larger than, but consistent with, a previous measurement by the TPC collaboration at the same energy and substantially lower than the TASSO measurements at $\sqrt{s}=22$ and 34 GeV.

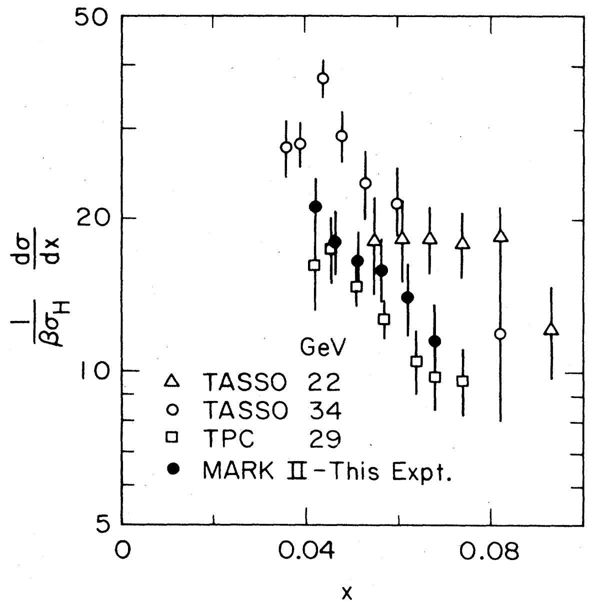

FIG. 4. The $K^{\pm}$ differential rate from the present experiment compared with the TASSO and TPC results. Systematic errors are included in the error bars.

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[1]The notation $K^0+\bar{K}^0$ for inclusive rates denotes the sum of the two individual rates.

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