K/π production ratios from 450 GeV/c protons on beryllium

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Abstract

This paper reports on the charged K/π production ratios and on the shape of the p_T distributions of π fluxes measured by the SPY/NA56 experiment for 450 GeV/c proton interactions on beryllium targets. The present data cover a secondary momentum range from 7 GeV/c to 135 GeV/c in the forward direction and with p_T values up to 600 MeV/c. An

experimental accuracy of about 3% has been achieved. These results will reduce the uncertainty on the estimation of the ν_e component of neutrino beams. © 1998 Published by Elsevier Science B.V.

1. Introduction

The SPY/NA56 (Secondary Particle Yields) experiment [1] has been devoted to the measurement of the production rates of charged pions and kaons and their ratios below 60 GeV/c from 450 GeV/c protons hitting beryllium targets of different thicknesses and shapes. These data are of great importance for the accurate estimation of the neutrino flux at the current West Area Neutrino Facility [2] used by the neutrino oscillation experiments CHORUS [3] and NOMAD [4] and for the planning and simulation of future neutrino beams. Recent proposals include short and long baseline options at CERN [5], Fermilab [6] and Japan [7].

A previous experiment (Atherton et al.) [8] measured the production of $\pi^\pm$, $K^\pm$, p and $\bar{p}$ from 400 GeV/c protons incident on beryllium in the range 60 GeV/c $\leq p \leq$ 300 GeV/c at transverse momenta up to 500 MeV/c. At lower momenta (below 60 GeV/c) there has been no direct measurement of these particle production yields, and so extrapolations of the existing data [9] or Monte Carlo calculations had to be used to make flux predictions for existing and for future neutrino experiments.

This paper reports on the K/π production ratios and on the shape of the p_T distributions of π fluxes measured by the SPY/NA56 experiment. A major interest in the measurement of the K/π ratios is that the ν_e contamination of ν_μ neutrino beams, which is about 1%, is dominated by the decay of kaons to electrons (K_{e3}). The present uncertainty in the K/π production ratio is one of the dominant sources of systematic error in $\nu_\mu \rightarrow \nu_e$ oscillation searches. Below 60 GeV/c this ratio has not been measured and the predictions from the available models of particle production in proton–Be interactions do not agree to better than 15%. This experiment reduces the uncertainty in this ratio to less than 3%. The present data cover a momentum range from 7 GeV/c to 135 GeV/c and the entire range of transverse momenta

(up to 600 MeV/c) relevant to present and future neutrino beams. Comparisons will be made to the previous ratios deduced from the Atherton et al. data in the area of overlap. A forthcoming paper will report on the absolute production yields.

The analysis reported in this paper is limited to data collected with a Be plate 160 mm wide (horizontal plane), 2 mm high (vertical plane) and 100 mm thick. These include a momentum scan in the forward direction at $p = \pm 7$, ± 10, ± 15, $+20$, $+30$, ± 40, ± 67.5 and $+135$ GeV/c [4] and scans in production angle up to 600 MeV/c of transverse momentum at $p = \pm 15$ GeV/c and ± 40 GeV/c. No corrections for differential π/K reabsorption or decays of short lived particles within the target length, nor for the contribution from secondary interactions will be applied. These effects, which might be of interest for deriving 'elementary' partcile ratios as they would be produced in an infinitesimally thin target, will be addressed in a future paper, where a comparative analysis of yields from targets of different thickness will be presented. The reader may also refer to [10] for the extrapolation to targets of different thickness and shape.

2. Experimental apparatus

The SPY/NA56 experiment was performed using the NA52 spectrometer [11] in the H6 beam in the North area of the SPS at CERN. The beam is derived from a target station served by a primary proton beam of 450 GeV/c with typical intensities of 10^{12} protons per burst. The H6 beamline is basically a four-stage focusing spectrometer, of total length 524 m. The first and third stages encompass the principal, equal and opposite, vertical deflections, which provide momentum analysis and recombination. It

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[4] Throughout this paper the sign of the momentum indicates the charge of the particles.
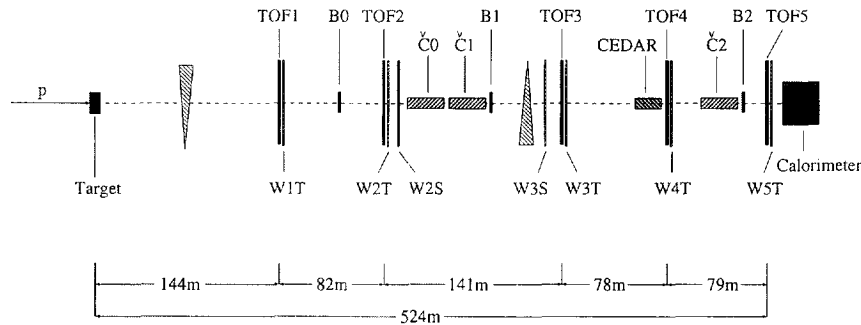
NA52 spectrometer (H6 beamline)

Fig. 1. The SPY/NA56 experimental set-up.

can transport secondary particles in the momentum range $5 \le p \le 200$ GeV/c, within a maximum acceptance of $\Delta p/p \times \Delta\Omega = \pm 1.5\% \times 2.1\,\mu sr$. A set of collimators served to define the acceptance and to ensure an acceptable trigger rate. Angles up to 15 mrad with a precision of 0.1 mrad were selected in the normal operating mode, while larger production angles (up to 30 mrad) were obtained by changing the angle of incidence (wobbling) of the primary beam on the target.

The NA52 equipment used for this experiment (Fig. 1) provided redundant particle identification over a wide momentum range through a set of time of flight (TOF) hodoscopes, threshold (Č0–Č2) and differential (CEDAR) Cherenkov counters and a hadron calorimeter. Proportional wire chambers (WnT, WnS) allowed particle tracking along the spectrometer. The TOF system ensured a clean π/K (K/p) separation up to 10 (20) GeV/c; the Cherenkov counters, filled with N$_2$ (Č0, Č1) or He gas (Č2), allowed for a good π, K separation up to high momenta and for an effective K/p separation above 15 GeV/c; the CEDAR counter [12] was capable of flagging pions over the entire momentum range of particles transported by the spectrometer. A segmented uranium/scintillator calorimeter, located at the end of the spectrometer, allowed for an effective separation of electrons and muons from hadrons.

The trigger logic was based on two independent trigger signals formed 268 m (trigger A = TOF2 · B1) and 505 m (trigger B = TOF4 · B2) downstream of the target. In addition, the threshold

Cherenkov counters were used in anti-coincidence to veto or prescale with a special logic particles above threshold. In order to enrich the relative K content of the collected sample, approximately one half of the collected statistics was not biased by the trigger, reflecting the natural beam composition, while the remaining half contained only kaons and protons. Protons, which were abundant in both the samples, could be used to normalize the K flux to the π flux and extract the K/π production ratios.

3. Data analysis

At 7 and 10 GeV/c, trigger A alone was required in order to increase the detection efficiency for short lived particles. Data taking was accomplished in two separate steps by setting the pressure in the Č0-Č1 counters to veto particles lighter than pions in one case and lighter than kaons in the other case. The latter setting was adopted to increase the kaon statistics in the collected sample and to reinforce the π/K separation provided by the TOF system. In the analysis of 10 GeV/c data, particles were tagged at TOF3, where the mass resolution of the TOF system allowed for a clean particle identification. At 7 GeV/c particles were only required to reach B1, since longer distances would have degraded the kaon content of the beam. The systematic error due to particle misidentification was estimated to be less than 1%, except in the case of negative particles at 7 GeV/c (about 7%), where data were not taken with

the Č0-Č1 veto for particles lighter than kaons and the π/K separation had to rely only on the TOF system.

At higher momenta, we required a coincidence of both triggers (A · B). At 15 and 20 GeV/c, the Č0-Č1 counters were used to prescale pions, while the Č2 counter was included in the trigger to veto electrons and muons. During the data analysis, particles were tagged at the calorimeter by requiring an energy deposition and a shower development consistent with the expectation for hadrons. This rejected the muon background coming from meson decays downstream of Č2. The proton identification was performed with the TOF system, while π/K separation was based on the light yield in the Č0-Č1 counters and in the CEDAR. As an example, the quality of particle identification at 15 GeV/c is demonstrated in Fig. 2, which shows the mass reconstruction with the TOF system, combined with the π/K separation provided by the Cherenkov counters. Particle misidentification was negligible (below 10^{-3}) both at 15 and 20 GeV/c, by exploiting the redundancy of the Č0-Č1 counters, the CEDAR counter and the TOF system.

Above 20 GeV/c, the particle identification was based solely on the Č counters. Č2 was devoted to π/K separation, while p/K separation was performed with Č0 and Č1. Hadrons were identified at
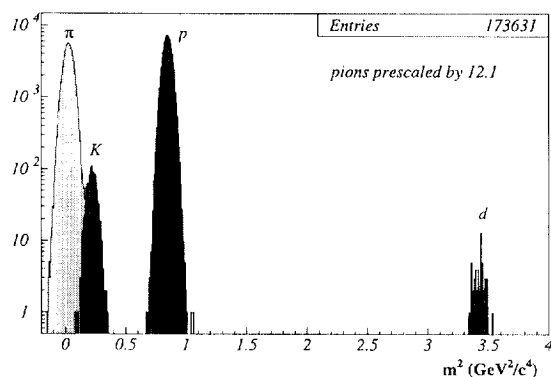

Fig. 2. Mass reconstruction with TOFs at 15 GeV/c. The π/K separation was performed with Č0 and Č1, muons were rejected in the calorimeter and electrons were vetoed by Č2 at the trigger level.

the calorimeter, while redundant information on the π/K separation was provided by the CEDAR. The selection efficiencies and misidentification probabilities between the different particles could be precisely determined by combining the information from the different detectors. This was particularly important at 135 GeV/c, where the detection efficiency of the Cherenkov counters was not optimal. The resulting systematic uncertainty on the K/π ratios was evaluated to be around 1% at 135 GeV/c and less than 1% elsewhere.

To extract the K/π production ratios, data were corrected for particle decays in flight, particle dependent losses along the beamline and contributions to secondary particle fluxes due to interactions of the primary beam with the material around the target area.

Since secondary particles were tagged after several decay lengths from the target, a precise determination of the K/π production ratios depended on the knowledge of the absolute beam momentum and of the meson lifetimes. The beam momentum was derived in each run with high accuracy using the TOF system to measure the speeds of particles of different mass. The uncertainty in the correction for particle decays was always less than 1%. At low momenta it was limited by the 0.2% precision in the knowledge of the kaon lifetime [13], while at high momenta by the precision of the momentum estimate.

Particle losses along the beamline were calculated by means of an updated version of the TURTLE Monte Carlo simulation of beam transport [14], with the inclusion of multiple scattering and nuclear collisions in the detector and beam material (about 20% of a nuclear collision length in total). These effects introduce a correction of about 3% on the K/π ratios due to the different nuclear cross-sections of pions and kaons, with a systematic error on the ratio of $\leq 1\%$ due to the 3% error on the published nuclear cross-sections [15] and a 10% uncertainty in the amount of material along the beamline.

Empty target runs were taken at each momentum and some angles, to evaluate the background from the material around the target area. From this data, a correction to the K/π production ratios was evaluated at each momentum and angle. This correction

Table 1

K/π production ratios with the 100 mm Be target in the forward direction as a function of secondary particle momentum. The first error is statistical; the second includes all the systematic uncertainties added in quadrature (see text for details). Values in parentheses are not corrected for the pion flux coming from strange particle decays.

p (GeV/c)	K^+/π^+	K^-/π^-
7	0.0693 ± 0.0029 ± 0.0012	0.0630 ± 0.0046 ± 0.0052
	(0.0660 ± 0.0028 ± 0.0008)	(0.0575 ± 0.0042 ± 0.0046)
10	0.0747 ± 0.0020 ± 0.0013	0.0688 ± 0.0033 ± 0.0018
	(0.0715 ± 0.0019 ± 0.0009)	(0.0632 ± 0.0030 ± 0.0008)
15	0.0831 ± 0.0024 ± 0.0014	0.0737 ± 0.0020 ± 0.0017
	(0.0802 ± 0.0023 ± 0.0011)	(0.0689 ± 0.0019 ± 0.0009)
20	0.0970 ± 0.0018 ± 0.0014	
	(0.0938 ± 0.0017 ± 0.0011)	
30	0.1052 ± 0.0016 ± 0.0011	
	(0.1028 ± 0.0016 ± 0.0009)	
40	0.1095 ± 0.0010 ± 0.0013	0.0857 ± 0.0016 ± 0.0011
	(0.1074 ± 0.0010 ± 0.0011)	(0.0835 ± 0.0016 ± 0.0009)
67.5	0.1053 ± 0.0012 ± 0.0013	0.0842 ± 0.0017 ± 0.0010
	(0.1040 ± 0.0012 ± 0.0012)	(0.0830 ± 0.0017 ± 0.0009)
135	0.0811 ± 0.0010 ± 0.0010	
	(0.0801 ± 0.0010 ± 0.0010)	

was typically of the order of a few tenths of a percent. The resulting systematic error was negligible.

The ratios of the kaon to the pion yield from the 100 mm target, as derived from the outlined analysis, were corrected for contributions to the pion flux from strange particle decays (K_s^0, Λ, Σ, ...) outside the target. These can be of importance, especially at low momenta, due to the 1.35 m distance between the target station and the first bending magnet in the H6 beamline. A full simulation of the beam target area was implemented using the GEANT package [16], to compare the yields of pions produced inside the target with those coming from K_s^0 or Λ^0 decays outside the target. Results were cross-checked with a fast generator, in which pions from K_s^0 decay were generated within our experimental acceptance, transported along the beamline and weighted according to the parent K_s^0 production cross-section [17]. The two calculations were found to agree within 20%. An additional systematic uncertainty of around 10% was attributed to the contributions of $\Sigma^\pm$ and $\overline{\Lambda}$ decays, neglected in both models. The estimated contamination ranges from 4.8% (8.6%) at 7 GeV/c to 1.2% at 135 GeV/c for positive (negative) pions in the forward direction and decreases as a function of the production angle. An

overall uncertainty of 25% on the knowledge of this contamination was assumed.

4. Results

Results on the K/π production ratios in the forward direction as a function of the nominal momentum of secondary beam [5] are given in Table 1. Both the K/π ratios corrected for strange particle decays and the raw K/π ratios (in parentheses) are reported with their statistical and systematic errors. The statistical accuracy of the measurements was always better than 3%, with the exception of the 7 GeV/c data. The systematic uncertainties were never larger than the statistical accuracy. As discussed in the previous sections, the systematic errors include the uncertainties on the particle identification efficiencies and backgrounds, on the correction for particle decays and transmission along the beamline and on the subtraction of the empty target fluxes and of strange particle decays.

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[5] The true beam momentum, derived from the TOF measurement of the speeds of particle of different mass, was always within 1.5% of the nominal momentum.
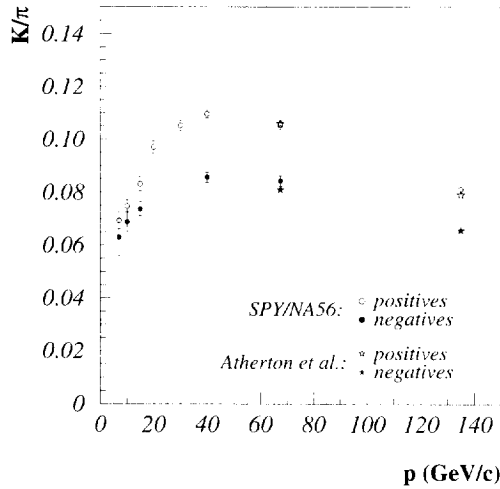
Fig. 3. K/π production ratios in the forward direction as a function of secondary particle momentum. Open (full) dots refer to positive (negative) particles. The SPY/NA56 data are corrected for the contribution of strange particle decays. The measurements of Atherton et al. have been rescaled to account for the lower primary beam momentum in their experiment (see text).

The corrected ratios in the forward direction are plotted in Fig. 3, together with the results from Atherton et al. [8]. Since the primary beam in our experiment (450 GeV/c) had a higher momentum than in Atherton et al. (400 GeV/c), their measurements at 60 and 120 GeV/c, corresponding to the same x_F as our measurements at 67.5 and 135

GeV/c are shown in the figures at $p = 67.5$ and 135 GeV/c. It should be stressed that the Atherton et al. data are not corrected for strange particle decays. Owing to the similarity of the spectrometers, this correction can be estimated to be of the same order as in our experiment. If this is taken into account, the results are in good agreement.

Angular scans were performed at 15 and 40 GeV/c, to cover the entire range of angular acceptance relevant to present and future neutrino beams. Some of the measurements were repeated at symmetric angles, to check the precision of the production angle selection. Since compatible results were always obtained, these were combined. The results are presented in Tables 2 and 3 as a function of the transverse momentum. The first table gives the K/π production ratios and the second the pion p_T distribution.

Note that most of the sources of systematic errors on the K/π production ratios are common to all the points of the angular scans at a fixed momentum, except for the correction for strange particle decays, which was found to decrease with the transverse momentum. The common systematic errors are not listed in Table 2 and amount to 1.3% at 15 GeV/c and 1.1% at 40 GeV/c.

The pion fluxes as a function of the transverse momentum are normalized to the flux at $p_T = 0$ (Table 3). The statistical accuracy in the measure-

Table 2

K/π production ratios with the 100 mm Be target as a function of the transverse momentum given by the production angle. Values in parentheses are not corrected for the pion flux coming from strange particle decays. The first error is statistical, the second gives the systematic uncertainty due to the correction for strange particle decays. Common systematic errors are not included and amount to 1.3% at 15 GeV/c and to 1.1% at 40 GeV/c (see text).

p_T (MeV/c)	p = +15 GeV/c	p = −15 GeV/c	p = +40 GeV/c	p = −40 GeV/c
0.0	0.0831 ± 0.0024 ± 0.0009	0.0737 ± 0.0020 ± 0.0014	0.1095 ± 0.0010 ± 0.0007	0.0857 ± 0.0016 ± 0.0006
	(0.0802 ± 0.0023)	(0.0689 ± 0.0019)	(0.1074 ± 0.0010)	(0.0835 ± 0.0016)
75.0	0.0804 ± 0.0023 ± 0.0009	0.0687 ± 0.0019 ± 0.0013	0.1035 ± 0.0014 ± 0.0005	0.0838 ± 0.0011 ± 0.0004
	(0.0775 ± 0.0022)	(0.0641 ± 0.0018)	(0.1019 ± 0.0014)	(0.0822 ± 0.0011)
150.0	0.0809 ± 0.0017 ± 0.0008	–	0.0916 ± 0.0012 ± 0.0004	0.0786 ± 0.0010 ± 0.0004
	(0.0784 ± 0.0016)	–	(0.0904 ± 0.0012)	(0.0773 ± 0.0010)
225.0	0.0875 ± 0.0014 ± 0.0009	0.0771 ± 0.0021 ± 0.0012	0.0923 ± 0.0008 ± 0.0004	0.0786 ± 0.0014 ± 0.0004
	(0.0848 ± 0.0014)	(0.0726 ± 0.0020)	(0.0911 ± 0.0008)	(0.0773 ± 0.0014)
337.5	0.1175 ± 0.0035 ± 0.0011	–	–	–
	(0.1138 ± 0.0034)	–	–	–
450.0	0.1359 ± 0.0044 ± 0.0012	–	0.1323 ± 0.0009 ± 0.0005	0.1051 ± 0.0016 ± 0.0005
	(0.1317 ± 0.0043)	–	(0.1302 ± 0.0009)	(0.1035 ± 0.0016)
600.0	–	–	0.1691 ± 0.0020 ± 0.0006	0.1269 ± 0.0018 ± 0.0005
	–	–	(0.1669 ± 0.0020)	(0.1248 ± 0.0018)

Table 3

Pion fluxes normalized to the forward direction ($p_T = 0$) as a function of the transverse momentum. The errors include statistical and systematic contributions (see text for details). Values in parentheses are not corrected for the pion flux coming from strange particle decays.

p_T (MeV/c)	p = +15 GeV/c	p = −15 GeV/c	p = +40 GeV/c	p = −40 GeV/c
75.0	1.054 ± 0.018	1.011 ± 0.022	1.039 ± 0.016	1.014 ± 0.016
	(1.055 ± 0.016)	(1.013 ± 0.015)	(1.033 ± 0.016)	(1.009 ± 0.015)
150.0	0.952 ± 0.015	–	1.099 ± 0.017	0.988 ± 0.015
	(0.948 ± 0.014)	–	(1.092 ± 0.017)	(0.980 ± 0.015)
225.0	0.696 ± 0.011	0.693 ± 0.014	0.948 ± 0.015	0.837 ± 0.013
	(0.694 ± 0.010)	(0.688 ± 0.011)	(0.943 ± 0.014)	(0.831 ± 0.013)
337.5	0.373 ± 0.006		–	–
	(0.371 ± 0.006)	–	–	–
450.0	0.201 ± 0.004	–	0.350 ± 0.006	0.327 ± 0.005
	(0.200 ± 0.004)		(0.349 ± 0.006)	(0.324 ± 0.005)
600.0	–	–	0.140 ± 0.002	0.152 ± 0.003
	–	–	(0.139 ± 0.002)	(0.150 ± 0.002)

ment of the pion fluxes was at the 0.3% level. Moreover, since in the angular scans at each momentum the magnet strengths and the collimator settings were kept fixed, the uncertainties related to the acceptance definition cancel and the measurement of the p_T distribution was only limited by the long term
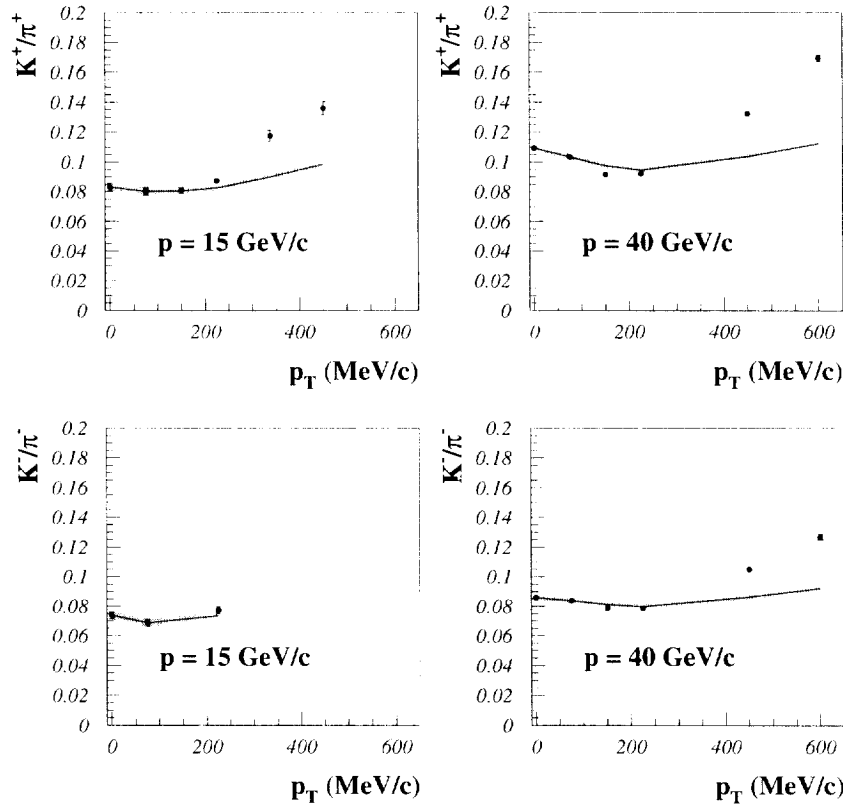

Fig. 4. K^+/π^+ (top) and K^-/π^- (bottom) production ratios as a function of the transverse momentum (full points). The continuous line gives the ratio of the K to the π fluxes integrated from 0 to p_T. The shaded area gives the error on the integrated K/π ratio, including the common systematic errors. Data are corrected for strange particle decays.

stability of primary beam intensity and steering on the target (about 1.5%).

The p_T dependence of the K^+/π^+ and K^-/π^- production ratios is shown in Fig. 4. The figure also gives the ratio of the K flux to the π flux integrated from 0 to p_T, as derived from the differential distributions reported in the tables. This quantity, which is of more direct use in the calculation of the ν_e contamination of ν_μ neutrino beams, is determined from SPY/NA56 data with a precision that improves as a function of the transverse momentum from 3.3% to 1.8% at 15 GeV/c and from 1.8% to 1.3% at 40 GeV/c, including the common systematic error on the K/π production ratios.

5. Conclusions

The present paper has reported on the first results from the SPY/NA56 experiment. The redundancy in the particle identification has demonstrated the capabilities of the experiment to identify protons, pions and kaons, with negligible contamination, for secondary particle momenta from 7 GeV/c up to 135 GeV/c. Measurements of the K/π ratio in the forward direction and with p_T values up to 600 MeV/c for both positively and negatively charged particles have been performed in the same momentum range, achieving an accuracy of about 3%. In addition, the shape of the p_T distribution normalized to the forward direction has been measured from 0 to 600 MeV/c.

Acknowledgements

References

[1] G. Ambrosini et al., CERN-SPSLC/96-01, SPSLC/P294, (1996).

[2] G. Acquistapace et al., CERN-ECP/95-14

[3] M. de Jong et al., CHORUS Collaboration, CERN-PPE/93-131 (1993).

[4] P. Astier et al., NOMAD Collaboration, CERN-SPSLC/91-21 (1990); CERN-SPSLC/91-48 (1991); CERN-SPSLC/91-53 (1991).

[5] M. Bonesini et al., CERN-SPSLC/95-37, SPSLC/1205 (1995); J.J. Gomez Cadenas, J.A. Hernando, A. Bueno, Nucl. Instr. Meth. A378 (1996) 196; J.J. Gomez Cadenas, J.A. Hernando, Nucl. Instr. Meth. A381 (1996) 223; A.S. Ayan et al., CERN-SPSC/97-5, SPSC/1213 (1997); A. Rubbia et al., CERN-SPSLC 96-58/P304, (1996); M. Ambrosio et al., NOE Collaboration, Nucl. Instr. Meth. A363 (1995) 604; T. Ypsilantis, Nucl. Instr. Meth. A371 (1996) 330.

[6] COSMOS Collaboration, 1995 Update Report on Fermilab E803/COSMOS, MINOS Collaboration, Fermilab Report No. NuMI-L-63 (1995); MINOS Collaboration, Fermilab Report No. NuMI-L-79 (1995).

[7] K. Nishikawa et al., University of Tokyo Report, 1992 (unpublished); Y. Suzuki, Proc. XVII International Conference on Neutrino Physics and Astrophysics, Helsinki, Finland, June 13-19 (1996).

[8] H.W. Atherton et al., CERN 80-07, August 1980.

[9] A.J. Malensek, Fermilab Report FN-341 (1981).

[10] M. Bonesini, S. Ragazzi, T. Tabarelli de Fatis, Nucl. Instr. Meth. A378 (1996) 349.

[11] K. Pretzl et al., Conference Proceedings of the International Symposium on Strangeness and Quark Matter, Sept. 1-5 1994, Krete (Greece), ed G. Vassiliadis, A. D Panagiotou, S Kumar, J. Madsen, World Scientific, 1995.

[12] C. Bovet et al., CERN 82-13 (1982).

[13] R.M. Barnett et al., Particle Data Group, Phys. Rev. D 54 (1996) 398.

[14] K.L. Brown, C. Iselin, Decay Turtle, CERN 74-2 (1974).

[15] A.S. Carrol et al., Phys. Lett. B 80 (1979) 319.

[16] GEANT: Detector Description and Simulation Tool, CERN Programming Library Long Writeup W5013.

[17] The K_S^0 production cross-section was evaluated from our measurements of the K^+ and K^- fluxes, according to $N_{K_S^0} = \frac{1}{4}(N_{K^+} + 3 \cdot N_{K^-})$ as suggested by N. Doble et al., NA31 Internal note 83 (1990).