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PHYSICAL REVIEW D VOLUME 4, NUMBER 7 1 OCTOBER 1971

# Pion Production in Proton-Beryllium Collisions at 12.4 GeV/$c$*

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The absolute cross sections for $\pi^+$- and $\pi^-$-meson production in proton-beryllium collisions at 12.4 GeV/$c$ are reported. Measurements were made for laboratory production angles between 0 and 12° and pion momenta between 2 and 6 GeV/$c$. All recent data for pion production in $p$-Be collisions are fitted with an empirical relation first suggested by Sanford and Wang.

## I. INTRODUCTION

The yields of secondary particles produced in the collisions of high-energy protons with complex nuclei have been measured at many of the accelerator laboratories.[1-7] Such beam surveys are useful in planning the arrangement of secondary beams and in predicting the fluxes of particles to be expected in them. More recently such measurements have become of more crucial importance in estimating the absolute flux incident on the detector for neutrino experiments.

An extensive study was carried out at the Zero Gradient Synchrotron (ZGS) several years ago,[3] but several more recent measurements[4-6] found production cross sections about twice as high as originally reported. Since an accurate knowledge of the neutrino flux is of great importance for neutrino experiments using the recently completed 12-ft bubble chamber, we have made a second extensive survey.

Measurements were made for production angles in the laboratory between 0 and 12° and $\pi^+$ and $\pi^-$ momenta between 2 and 6 GeV/$c$ for 12.4-GeV/$c$ protons incident on Be targets.

## II. EXPERIMENTAL METHOD

The measurements were carried out in the second extracted proton beam of the ZGS at Argonne using equipment of Day *et al.*[8] shown in Fig. 1. About $5 \times 10^{10}$ protons were extracted during a spill of 0.5 sec every 3.8 sec. The angular spread in the beam was about ±3 mrad, and it was focused to a spot about 1 cm in diam on the Be target. Two targets were used, consisting of disks 3.7 cm in diam and length 2 cm or 5 cm in the direction of the beam. The targets were held in a thin plastic ring supported from a metal frame by four wires. Measurements, at small pion-production angles, were also made using Be targets 15, 30, and 40 cm long.

The number of protons hitting the target was monitored by two telescopes $M$ and $N$, each consisting of three small scintillation counters. The absolute calibration of the counter telescopes was done using gold foils placed in the proton beam several feet upstream of the target. An ionization chamber placed just upstream of the target was also used to monitor the proton beam intensity. The ion-chamber readings were used in normalizing the background data taken with no target in place and also for the data taken with the long targets. The ion-chamber calibration as measured using the gold foils remained constant throughout the entire experiment to better than 1%. Eight such calibration runs were made spaced throughout the 100 h of data taking. The number of protons passing through the gold foil was determined by the $\alpha$ particles given off by $Tb^{149}$ produced in the proton-gold collisions, assuming a cross section for the $Au^{197}(p, 15p\ 34n)\ Tb^{149}$ of $1.05 \pm 0.08$ mb.[9] The ratio of the number of protons traversing the target to the $M$ and $N$ monitor telescopes was measured to a relative accuracy of ±1.2% for the two short targets. In addition to this error, there is a scale uncertainty of 8% resulting from the uncertainty of the $Tb^{149}$ production cross section.

The produced pions were detected in the single-arm spectrometer (shown in Fig. 1) consisting of a magnet $B_2$, which defined the momentum of the particles, and two magnets $C$ and $B_1$, which defined the production angle. The $C$ and $B_1$ magnets were set so that particles of the required momentum and production angle emerged from $B_1$ always along the same line. The particles were recorded by the three sets of counters $S_1S_2S_3$, $C_1C_2C_3$, and $S_4S_5$. The threshold Čerenkov counter $C_2$ was filled with nitrogen gas and tagged the particles as pions. The contamination to the $\pi^+$ spectrum due to protons counting in the Čerenkov counter via knock-on electrons was estimated to be less than 0.4% for the worst case. The operating pressures of this counter were determined by measuring the counting rate as a function of the gas pressure. The phase-

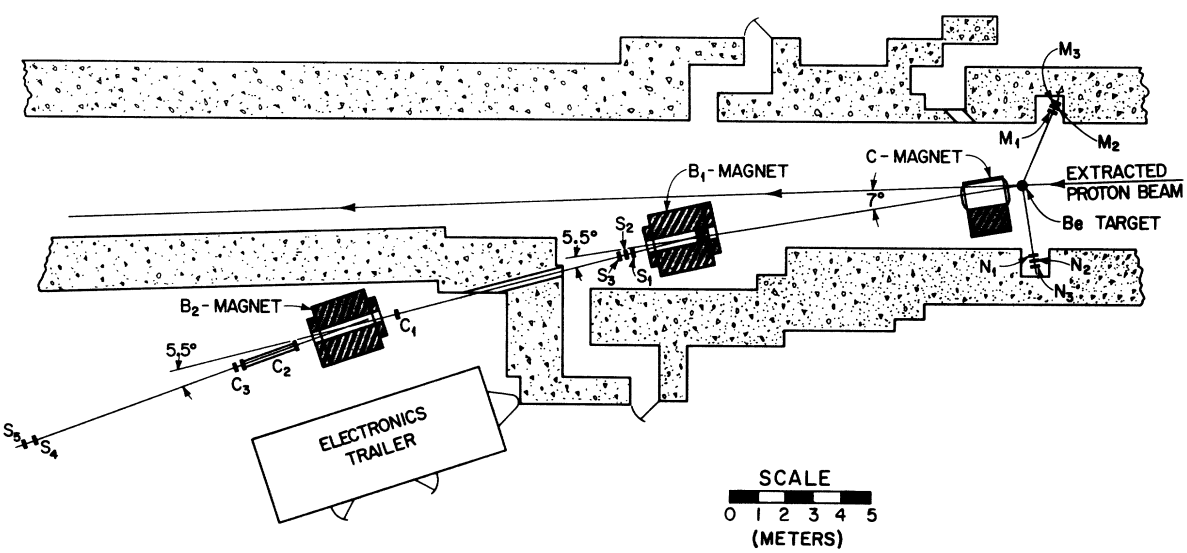


FIG. 1. Layout of spectrometer.

space acceptance of the spectrometer was defined by the counters $S_1$ and $S_5$ and all other counters were overmatched. An event was defined by the eightfold coincidence $S_1S_2S_3S_4S_5C_1C_2C_3$, called SC. The accidental rate was measured by taking the time-of-flight spectrum between $S_1$ and $S_5$ and was always found to be less than 0.3%.

For nearly all angle-momentum combinations, measurements were made for both 2-cm and 5-cm targets and in most cases data were also taken with the target removed. The normalization of the background data was done using the ionization chamber. Since the $M$ and $N$ telescopes counted very little with no target in place, the matrix of background measurements were fitted with smooth curves in $p$ and $\theta$ and these smoothed values, expressed as normalized SC coincidences were subtracted from the appropriate counts from the targets. The background fraction varied from 7 to 20% for the data taken with the 2-cm target and from 2 to 8% for the 5-cm target.

Several corrections had to be applied to the data in order to calculate the production cross sections. The multiple scattering in the target and the counters was taken into account by using a Monte Carlo calculation. The same program was used to include the effects of decay of the pions during the flight path to the last counter. This included a calculation of the acceptance of the spectrometer for forward decays in which the muon recorded in the downstream counters.

The nuclear interactions in the counters leading to loss of particles from the spectrometer were calculated using a pion-carbon total cross section of 287 mb. The total thickness of scintillator in the spectrometer was 3 in. The total cross section was used here since almost all pions diffractively scattered by the scintillator nuclei were lost from the spectrometer.

Since all measurements were made using both 2- and 5-cm Be targets, the combined correction for the attenuation of the proton beam and the interactions of the produced pions in the target itself could be measured. If the pion production cross section is $\Sigma$ and the pion and proton absorption mean free paths are equal to $\lambda$, then the number of pions emerging from the end of the target ($n$) is related to the number of incident protons ($N$) by

$$n = NN_T\Sigma L e^{-L/\lambda}, \qquad (1)$$

where $L$ is the length of the target, and $N_T$ is the number of target particles per unit volume. Since only two target lengths were used, the assumption of equality of the pion and proton absorption lengths is required to determine $\Sigma$.

Yield measurements made for 3, 4, 5, and 6 GeV/$c$ at small angles for the 15-, 30-, and 40-cm targets were also used to measure $\lambda$ since with these lengths, the reabsorption is a major effect. The interaction length resulting from this analysis was $50 \pm 3$ cm, corresponding to an absorption cross section of $163 \pm 10$ mb in agreement with previous measurements of 170 mb for high-energy protons[10] and 156 mb for 3.5-GeV/$c$ $\pi^{\pm}$ mesons.[11]

For the 30-cm-long target, a measurement was made of the electron contamination in the beam at 2, 4, and 6 GeV/$c$ by taking pressure curves with the Čerenkov counter. The results of 25% at 2 GeV, < 2% at 4 GeV/$c$, and negligible at 6 GeV/$c$ were in qualitative agreement with the low-momentum observations of Marmer *et al.*[5] No corrections were made for possible electron contamination from the 2- and 5-cm targets. This would only affect the lower momenta, and the 2-GeV/$c$ cross sections measured using the 2- and 5-cm target lengths agreed to within 1.5%.

All the spectrometer corrections are shown as a function of momentum in Fig. 2, together with the over-all correction which is the product of the individual contributions. The spectrometer was designed for use at the higher momenta and is clearly becoming poor at 2 GeV/$c$, where the correction is about a factor of 2.

## III. RESULTS

The differential cross section was calculated from the equation

$$\frac{d^2\sigma}{d\Omega\, dp} = \frac{n(\text{correction factor})}{N(N_0/A)\rho\, L\Delta\Omega\, \Delta p}, \qquad (2)$$

where $n$, $N$, and $L$ have the same meaning as in Eq. (1), and $N_0$ is Avogadro's number, $A$ is the atomic mass number of Be, $\rho$ is the density of Be measured to be 1.844 cm$^{-3}$, and $\Delta\Omega\Delta p$ is the accep-

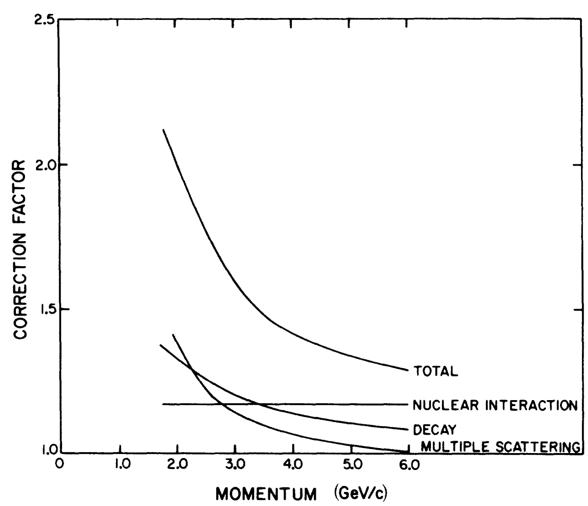


FIG. 2. Spectrometer correction factors.

TABLE I. Pion production cross sections from $p$-Be collisions at 12.4 GeV/$c$.

| Momentum (GeV/$c$) | Angle (deg) | $\pi^+$ $d^2\sigma/d\Omega dp$ [mb sr$^{-1}$(GeV/$c$)$^{-1}$] | $\pi^+$ Error | $\pi^-$ $d^2\sigma/d\Omega dp$ [mb sr$^{-1}$(GeV/$c$)$^{-1}$] | $\pi^-$ Error |
|---|---|---|---|---|---|
| 2.05 | 0.13 | 340.4 | 17.0 | 240.8 | 12.0 |
| 2.06 | 1.14 | 312.6 | 15.6 | | |
| 2.07 | 2.15 | 312.7 | 15.6 | 205.8 | 11.0 |
| 2.08 | 3.13 | 308.2 | 15.4 | | |
| 2.08 | 4.12 | 304.4 | 15.0 | 185.7 | 9.5 |
| 2.08 | 5.08 | 282.5 | 14.1 | | |
| 2.09 | 6.04 | 264.9 | 13.2 | 156.7 | 7.6 |
| 2.09 | 7.96 | 193.1 | 9.6 | 120.0 | 6.0 |
| 2.09 | 9.87 | 134.7 | 6.8 | 90.1 | 4.5 |
| 2.09 | 11.78 | 95.4 | 4.8 | 66.5 | 3.5 |
| 2.58 | 1.14 | 310.1 | 18.6 | | |
| 2.59 | 2.15 | 319.0 | 19.2 | | |
| 2.59 | 3.13 | 310.5 | 18.6 | | |
| 2.60 | 5.08 | 232.4 | 13.8 | | |
| 3.08 | 0.13 | 393.2 | 20.0 | 185.7 | 9.5 |
| 3.09 | 1.14 | 343.3 | 17.1 | | |
| 3.10 | 2.15 | 324.4 | 19.7 | 143.2 | 7.0 |
| 3.11 | 3.13 | 284.5 | 14.3 | | |
| 3.12 | 4.12 | 222.2 | 11.1 | 110.1 | 5.5 |
| 3.12 | 5.08 | 174.3 | 8.7 | | |
| 3.13 | 6.04 | 139.6 | 7.0 | 77.5 | 4.0 |
| 3.13 | 7.96 | 86.4 | 4.3 | 53.4 | 2.3 |
| 3.13 | 9.87 | 55.0 | 2.8 | 35.5 | 1.5 |
| 3.14 | 11.78 | 34.2 | 21.7 | 22.4 | 1.1 |
| 3.61 | 1.14 | 353.1 | 21.0 | | |
| 3.62 | 2.15 | 306.7 | 18.1 | | |
| 3.63 | 3.13 | 233.8 | 13.8 | | |
| 3.64 | 5.08 | 130.0 | 7.8 | | |
| 4.11 | 0.13 | 446.7 | 22.3 | 148.0 | 7.5 |
| 4.12 | 1.14 | 330.1 | 16.5 | | |
| 4.14 | 2.15 | 249.7 | 12.5 | 96.4 | 5.0 |
| 4.15 | 3.18 | 177.2 | 8.9 | | |
| 4.16 | 4.12 | 127.8 | 6.4 | 61.3 | 3.1 |
| 4.17 | 5.08 | 95.8 | 4.8 | | |
| 4.17 | 6.04 | 70.0 | 3.5 | 37.6 | 1.9 |
| 4.17 | 7.96 | 40.7 | 2.14 | 22.7 | 1.1 |
| 4.18 | 9.87 | 21.8 | 1.1 | 12.3 | 0.61 |
| 4.18 | 11.78 | 10.4 | 0.51 | 6.47 | 0.33 |
| 5.15 | 1.14 | 173.9 | 8.5 | | |
| 5.17 | 2.15 | 137.6 | 6.9 | 57.6 | 2.7 |
| 5.19 | 3.13 | 104.3 | 5.2 | | |
| 5.20 | 4.12 | 70.7 | 3.6 | 32.5 | 1.5 |
| 5.20 | 5.08 | 49.1 | 2.5 | | |
| 5.21 | 6.04 | 34.4 | 1.7 | 17.1 | 0.90 |
| 5.21 | 7.96 | 16.8 | 0.8 | 8.58 | 0.43 |
| 5.22 | 9.88 | 6.90 | 0.35 | 3.64 | 0.18 |
| 5.22 | 11.78 | 2.46 | 0.12 | 1.44 | 0.07 |
| 6.20 | 2.14 | 91.5 | 4.6 | 36.0 | 1.5 |
| 6.22 | 3.13 | 61.4 | 3.1 | | |
| 6.24 | 4.11 | 38.7 | 1.9 | 18.1 | 0.90 |
| 6.24 | 6.04 | 16.6 | 0.8 | 6.94 | 0.32 |
| 6.25 | 7.96 | 5.82 | 0.29 | 2.58 | 0.13 |
| 6.26 | 9.88 | 1.70 | 0.09 | 0.863 | 0.045 |
| 6.27 | 11.79 | 0.446 | 0.022 | 0.233 | 0.012 |

tance of the spectrometer which varied from $0.4627\times10^{-6}$ sr GeV/$c$ at 4°, 2 GeV/$c$ to 1.418 $\times10^{-6}$ sr GeV/$c$ at 12°, 6 GeV/$c$. The $\Delta p/p$ acceptance was 2.6%. Table I summarizes the results. In all cases the average cross section from the measurements using the two targets is given. The differences between the measurements using the two target lengths were typically 1–2%.

All measurements were made for nominal integral angle and secondary momentum values but because of an error in the calibration of the $B_2$ magnet, the actual values are those shown in Table I.

The errors quoted are compounded from (1) the statistical error on the SC counts, 1–3%; (2) count-

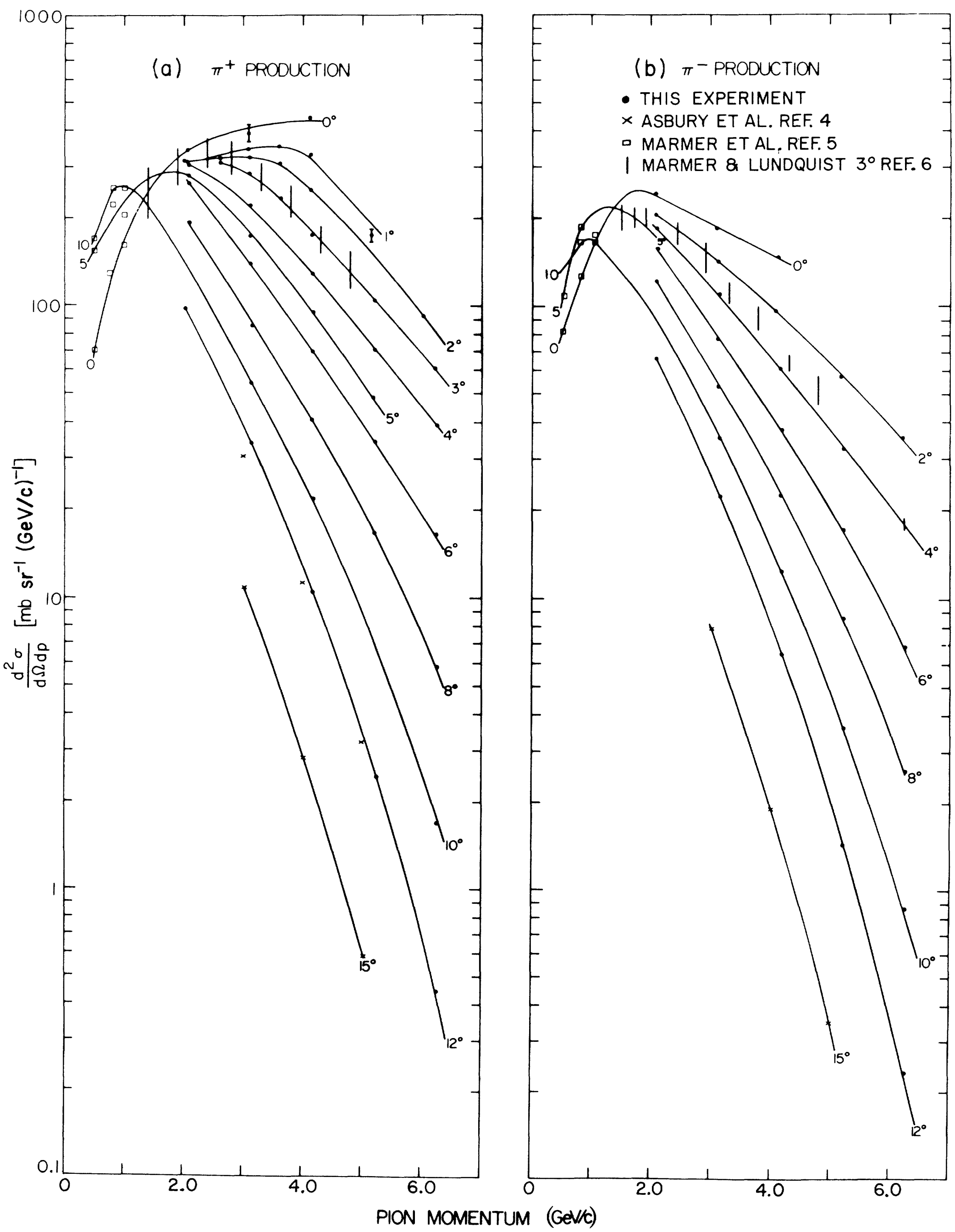


FIG. 3. Pion production cross sections: (a) $\pi^+$, (b) $\pi^-$.

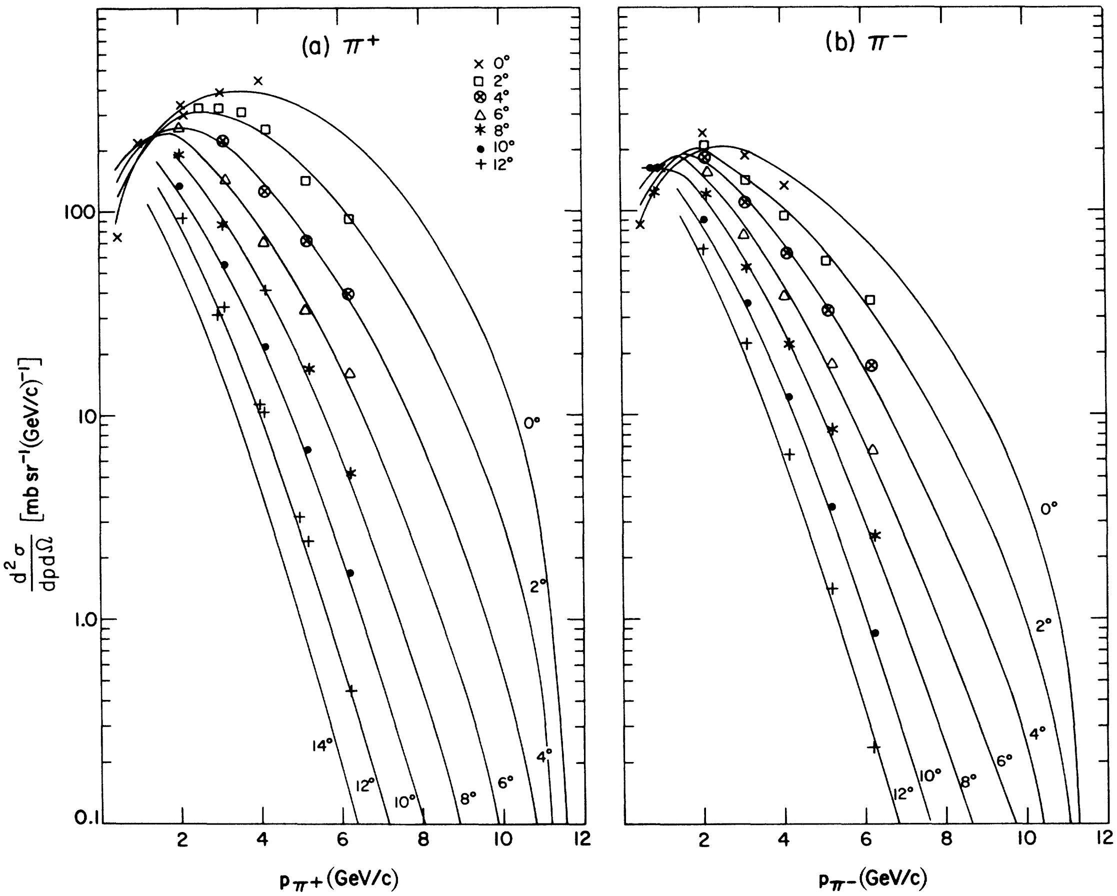


FIG. 4. Sanford and Wang fits: The data points are from Refs. 4–6 and this experiment. The solid lines are generated from the coefficients shown in Table II.

TABLE II. Fit (*A*) includes the data from Refs. 4–7 and this experiment. Fit (*B*) is the results of the original fits by Sanford and Wang.

| | $\pi^+$ | | $\pi^-$ | |
|---|---|---|---|---|
| Coeff. | Fit (*A*) | Fit (*B*) | Fit (*A*) | Fit (*B*) |
| $C_1^A$ | 196 | 227 [a] | 161 | 186 [a] |
| $C_1^B$ | 212 | | 253 | |
| $C_2$ | 1.08 | 0.65 | 0.900 | 0.53 |
| $C_3$ | 2.15 | 4.05 | 1.55 | 3.98 |
| $C_4$ | 2.31 | 1.63 | 1.68 | 1.73 |
| $C_5$ | 1.98 | 1.66 | 1.19 | 1.62 |
| $C_6$ | 5.73 | 5.03 | 5.09 | 4.74 |
| $C_7$ | 0.137 | 0.172 | 0.149 | 0.198 |
| $C_8$ | 24.1 | 82.7 | 29.2 | 88.75 |
| $\chi^2$/(No. of degrees of freedom) | 148/110 | | 114/77 | |

[a]The $C_1$ parameters for the original fits were 1.09 and 0.821 for the $\pi^+$ and $\pi^-$, respectively. Here we rewrote the $C_1$ as the product of the $\sigma_T$ and the original $C_1$.

ing loss, 0.3%; (3) decay correction error, 1%; (4) multiple-scattering uncertainty, 2%; (5) nuclear interactions in target and counters, 1%; (6) target-empty subtraction, 1%; (7) proton beam normalization, 2.4%. Compounding all these factors gives a total typical error from point to point of 5%. There is, in addition, the absolute-scale uncertainty of 8% mentioned previously. The results are plotted in Fig. 3 for both $\pi^-$ and $\pi^+$. Also shown on these figures are the data of Refs. 4, 5, and 6. The lines are drawn on the figures to connect the points and guide the eye. The agreement with the previous measurements is remarkable; the only obvious discrepancy is the cross section for $\pi^+$ production at 3 GeV/$c$ and 12°, where the two measurements differ by 15% after correcting for the small differences in momentum and angle. This is an effect of just over 2 standard deviations. For the other two direct comparisons (4 and 5 GeV/$c$ for 12°) the agreement between the two measurements is within the 7% expected from the quoted errors. All the data shown in Fig. 3 disagree with those of Ref. 3 in absolute normalization.

## IV. COMPARISON OF DATA WITH MODEL OF SANFORD AND WANG

Sanford and Wang[12] have constructed an empirical formula which gives a quantitative description of the secondary particle production in proton-Be collisions based on the characteristics of experimental data from Refs. 1, 2, and 3. The Sanford and Wang formula is

$$\frac{d^2n}{d\Omega\, dp} = C_1 p^{C_2}\left(1 - \frac{p}{p_B - 1}\right)\exp\left(-\frac{C_3 p^{C_4}}{p_B{}^{C_5}} - C_6\theta(p - C_7 p_B \cos^{C_8}\theta)\right),$$

where $d^2n/d\Omega\, dp$ is the differential particle yield per interacting proton, the $C_i$'s are the constants to be found by fitting, $\theta$ is the laboratory production angle, and $p$ and $p_B$ are the momenta of the secondary and incident particles, respectively. The factor $1 - p/(p_B - 1)$ is used to ensure that the cross section falls to zero at the kinematic limit. For pion production in a free nucleon-nucleon collision the maximum pion momentum is $(p_B - 1)$ GeV/$c$. In the original fitting, the data from Lundy *et al.*[3] are the main base for the angular dependence, and the experiment by Dekkers *et al.*[2] was the base for the normalization.

Since this experiment replaces that of Lundy *et al.*, and the measurements by Allaby *et al.*[7] supersede those of Dekkers *et al.*, we have tried to refit the data to the Sanford and Wang model. The yield is related to the differential cross section by

$$\frac{d^2\sigma}{d\Omega\, dp} = \sigma_T \frac{d^2n}{d\Omega\, dp},$$

where $\sigma_T$ is the total absorption cross section. If we fit the cross section instead of the yield, the parameter $C_1$ is proportional to the total absorption cross section. In addition, the $C_1$ is determined by the absolute normalization, which is the most difficult parameter to measure. In fitting the cross-section data, we allowed two normalizations, one for all measurements done at the ZGS, $C_1^A$, and the other for the measurements by Allaby *et al.*, $C_1^B$. Although each individual experiment has small relative errors, the absolute normalizations are ~10% uncertain.

The $C_1$ values obtained are given in Table II together with the other constants. The $C_1^A$ and $C_1^B$ values obtained for $\pi^+$ measurements are consistent within the errors, whereas the $\pi^-$ measurements at 12.4 and 19.2 GeV/$c$ are not consistent. The difference corresponds to 3 standard deviations. It is not clear if this discrepancy represents a breakdown of the parametrization or comes from the neglect of some systematic error in the data.

In Table II we show the results of fits using the data from Refs. 4-7 and this experiment. The $\chi^2$/(number of degrees of freedom) of the fits were 148/110 and 114/77 for the $\pi^+$ and $\pi^-$, respectively. Figure 4 shows the fitted curves for the data from Refs. 4-6 and this experiment. We also tried to include the data from Dekkers *et al.*; however, fits were poor, and there seems to be an inconsistency between the measurements of Dekkers *et al.* and those of Allaby *et al.* The $\chi^2$/(number of degrees of freedom) of the latter fits were 340/138 and 222/105 for the $\pi^+$ and $\pi^-$, respectively.

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PHYSICAL REVIEW D VOLUME 4, NUMBER 7 1 OCTOBER 1971

# $K^*(890)$ Production in the Charge-Exchange Reaction $K^+n \to K^+\pi^-p$ at 9 GeV/$c$*

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The energy dependence of the cross section for reactions $K^+n \to K^*(890)p$ and $K^-p \to K^*(890)n$ is compared over a wide range of incident momenta and found to be identical. This excludes odd $C$-parity exchanges in addition to the dominant $\pi$ exchange. The conventional absorption model does not reproduce the rapid decrease of $\rho_{00}$ as a function of the four-momentum transfer. The Reggeized $\pi$-$A_2$ model of Dass and Froggatt reproduces the $t$ dependence of $\rho_{00}$ and Re$\rho_{10}$, but there is serious disagreement for $\rho_{1-1}$ which may indicate the need to include $A_1$ exchange. The asymmetry in the decay angular distribution is interpreted as $S$-$P$ wave interference.

## I. INTRODUCTION

In this paper we present results from our analysis of the charge-exchange reaction

$$K^+n \to K^+\pi^-p \qquad (1)$$

at 9 GeV/$c$. We obtained 4030 events of this type from approximately 280 000 pictures, taken in the Brookhaven 80-in. deuterium-filled bubble chamber exposed to an rf separated beam. This corresponds to a microbarn equivalent of 8 events/$\mu$b. For the subsequent analysis we use 3882 events since on part of the film, we measured only events with a recoil momentum less than 1 Gev/$c$.

The most dominantly produced meson resonances are the $K^*(890)$ and $K^*(1420)$, as can be seen in

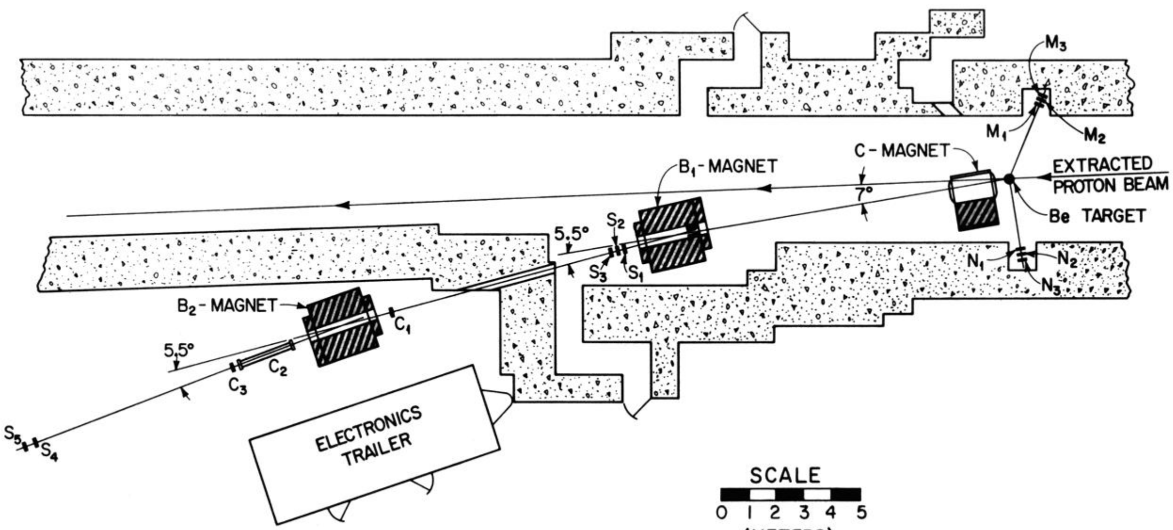


FIG. 1. Layout of spectrometer.