Differential Cross Sections for $pp \to pn\pi^+$ near Threshold

W. W. Daehnick, S. A. Dytman, J. G. Hardie,* W. K. Brooks,† and R. W. Flammang
Nuclear Physics Laboratory, University of Pittsburgh, Pittsburgh, Pennsylvania 15260

L. Bland, W. W. Jacobs, and T. Rinckel
Indiana University Cyclotron Facility, Bloomington, Indiana 47408

P. V. Pancella
Physics Department, Western Michigan University, Kalamazoo, Michigan 49007

J. D. Brown‡ and E. Jacobson
Physics Department, Princeton University, Princeton, New Jersey 08540
(Received 22 December 1994)

Differential cross sections from kinematically complete measurements of $pp \to pn\pi^+$ production are presented for proton beam energies of 294.2, 299.5, and 319.5 MeV. Total cross sections are given for 294.2, 299.5, 306.5, 314.3, and 319.5 MeV. The two angular distributions close to threshold are dominated by s wave contributions. Total cross sections within the first 30 MeV of threshold show qualitative agreement with an early theoretical prediction based on PCAC.

PACS numbers: 25.10.+s, 11.40.Ha, 13.75.Cs

The PCAC (partial conservation of axial vector current) hypothesis suggests that all low energy interactions that are mediated by axial currents are dominated by pionic processes, which can be calculated from the pion decay amplitude [1]. Interest in this subject has been rekindled in recent years with the discovery of chiral perturbation theory solutions to QCD [2] that provide a rigorous low energy realization of the PCAC hypothesis in terms of hadronic degrees of freedom. Experimental advances now allow much more quantitative testing of these unifying principles and the "soft pion theorems." The E_{0^+} amplitude for pion photoproduction has been predicted from these ideas, and this prediction has been confirmed by recent experiments at threshold [3].

Meyer *et al.* [4] and Korkmaz *et al.* [5] measured the $pp \to pp\pi^0$ and $p\vec{p} \to d\pi^+$ reactions, respectively, near threshold with values for η (the maximum pion momentum in the center-of-mass frame divided by the pion mass) as low as 0.186 and 0.14. Of the two, $pp \to pp\pi^0$ seems most favorable for the extraction of the s-wave strength because the Δ resonance is suppressed. Nevertheless, a comparison with standard calculations [6] showed that the observed strength was a factor of 5 larger than expected. Recently it has been shown that use of the full PCAC amplitude *plus* isoscalar meson exchange [7,8] can make up the difference.

Apart from the general relationships for pion production in $pp \to pn\pi^+$, $pp \to pp\pi^0$, and $pp \to d\pi^+$, there exist two theoretical predictions for $pp \to pn\pi^+$. Schillaci, Silbar, and Young (SSY) [9(a)] used the PCAC amplitude for pion production and the Adler-Dothan theorem [1] to reduce the complexity of the calculation. Their result is that the inelastic cross section close to threshold comes from a single diagram that is closely related to the $NN \to NN$ off-shell scattering amplitude; however, this diagram is calculated to all orders. This includes all partial waves for the NN amplitudes, but necessarily accounts for only s-wave pion-nucleon states. Their prediction for $pp \to pp\pi^0$ is qualitatively correct, and their prediction for $pp \to pn\pi^+$ is used here. However, the prediction for $pp \to d\pi^+$ is off by a large factor, presumably because of their inability to correctly account for the deuteron final state [9(b)]. It would also fail if contributions from the delta resonance are significant.

The second total cross section prediction was made by Lee and Matsuyama [10] with a coupled channels formalism that aimed to explain the NN inelasticity in the Δ kinematic region. In their calculations the Δ processes are handled rigorously while the nonresonant pion production process is introduced as a perturbation. Without $pp \to pn\pi^+$ data near threshold (292.3 MeV) the applicability of such calculations and of low energy theorems for low energy $NN \to NN\pi$ pion production has remained uncertain.

Kinematically complete cross section measurements for $pp \to pn\pi^+$ were performed in the T section of the IUCF Cooler. Measurements over the full angular range of the outgoing nucleons were made at 290, 294.2, 299.5, 306.5, 314.3, and 319.5 MeV. The run at 290 MeV served to verify that below threshold no accidental coincidences survived our selection procedure. Statistics at 294.2, 299.5, and 319.5 MeV were sufficient to also deduce angular distributions. The apparatus shown in Fig. 1 uses the fact that near threshold all reaction products of $pp \to pn\pi^+$ are confined to a narrow cone about the circulating beam. At 294.2 MeV the nucleons in the final state are constrained to polar angles of less than 4.6°. For 319.5 MeV, the highest bombarding energy used, the

0031-9007/95/74(15)/2913(4)$06.00

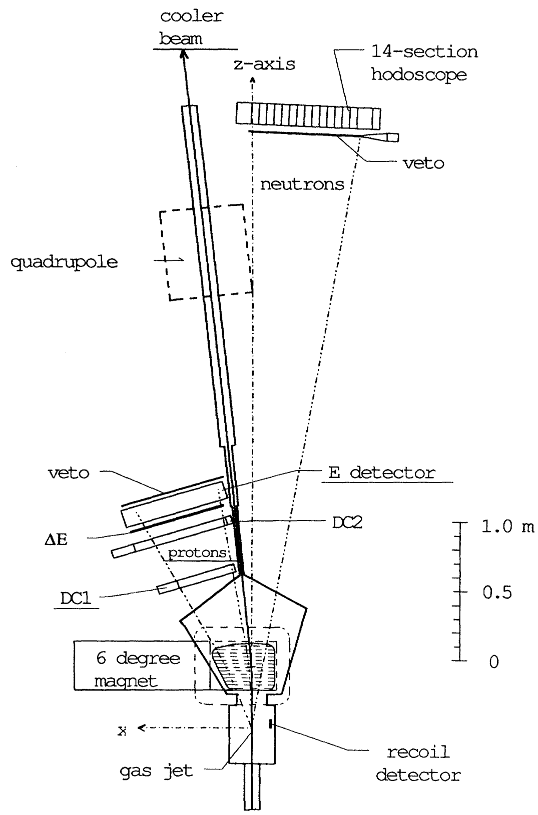

FIG. 1. Scale drawing of the two-arm detector at the IUCF T site.

cone opens to 16.9°. Pions have a wider angular range, but the direct detection of soft pions in this situation is difficult. Most would decay before they reach a large aperture detector.

The experimental methods and hardware used in this work have been described earlier [11]. Low energy nucleons were separated from the beam magnetically. The Cooler Ring contains a 6° bend that was utilized to insert a large aperture analyzing magnet. We designed and installed a new (6°) ring magnet that accepts reaction products from a nearby windowless gas jet target up to ±20° in the horizontal and up to ±6.5° in the vertical direction, thereby covering the angular range of interest. On average, the $pp \rightarrow pn\pi^+$ reaction protons have 50% of the beam rigidity and their typical bending angle is 12°, twice that of the beam. Consequently even protons emerging at small "negative" angles can be bent into the proton detector. The 6° bend in the Cooler Ring also permits easy detection of neutrons at angles of 0° and larger.

A kinematically complete measurement of the reaction requires knowledge of 5 of the 9 degrees of freedom of the three-body final state. We measured 6. The energy of the charged reaction particles was measured by a stack of five plastic E scintillators, each 60 cm wide, 7.6 cm high, and 12.7 cm deep, i.e., just deep enough to stop the most energetic reaction protons. Proton energy resolution was 2.5% FWHM at 70 MeV. Elastic protons lose only about 20% of their energy in these scintillators and are rejected by the veto detectors. The directions of the proton momenta were determined by the two position sensitive drift chambers DC1 and DC2 and by ray tracing through the magnetic field. Each horizontal drift chamber had two x and two y wire planes of conventional construction. The proton angular resolution was about 0.25°. It was limited primarily by multiple scattering in the Kevlar vacuum exit foil of 13 mg/cm^2, by several thin Al foils near the jet, and by the air. The resolution of the drift chambers was 0.3 mm FWHM, and made a negligible contribution to the angular resolution. Our neutron hodoscope [11(a)], of active area 0.7 m × 1.2 m, covers reaction neutron angles as low as 0° when placed near the beam line as shown.

The magnet, the two-arm detector, and the precise beam definition of the Cooler helped avoid or discriminate against background from the dominant elastic scattering at small angles. Monte Carlo simulations showed that the n-p coincidence acceptance ranged from 40% at 294 MeV to 20% at 320 MeV with high acceptance when both nucleons are emitted at 0°. The luminosity for the experiment was determined by concurrently measuring the known pp elastic scattering [12], using the proton arm of the apparatus in coincidence with a position sensitive silicon detector positioned at 78°. The neutron energy was measured by time of flight. Its resolution was limited by the 15 cm depth of the hodoscope bars and the 4.5 m neutron flight path to 6.6% FWHM. The average neutron angular definition of θ and ϕ was about 0.47°.

The computed neutron detection efficiency for the 15 cm deep bars at 10 MeV threshold was 0.137. Similar efficiency calculations in the literature [13] assume an absolute model error of ±5%. The experimental threshold calibration error leads to ±0.005, or 3.7%, added uncertainty in the efficiency, and we assign a 6.2% scale error for the neutron detector efficiency. Adding this error in quadrature to the 11% uncertainty in the luminosity measurements and to several smaller, uncorrelated systematic uncertainties we obtain a ±15% error for the absolute experimental scale.

Hardware coincidence and veto requirements eliminated over 99% of the background for this low-cross-section experiment; however, software cuts were required to fully eliminate all background. Ray tracing to the target through the 6° magnet proved to be our most powerful analysis tool. For the 294.2 MeV run the FWHM of the pion missing mass peak was below 1 MeV. It broadened slightly for the higher energies. Ultimately, loose cuts around the target coordinate $x = y = z = 0$, around the E-ΔE proton locus, and the correct missing mass were used. This resulted in the total elimination of background with small, correctable losses for the true pion events.

An n-p final state interaction (FSI) [14] must be used for the computed n-p coincidence acceptance to avoid inconsistencies in the differential cross sections deduced from measurements with different hodoscope positions.

The smoothest match of overlapping angular distributions was found for a statistical mix of n-p triplet and singlet strengths. We note that the FSI effect on the *pion* angular distributions is weak, smaller than current statistics, but systematic errors of ≥ 1 MeV for the extracted nucleon energies were found to have a significant effect on the deduced pion angular distributions. Energy calibration errors are most troublesome closest to threshold; they generally were below 0.5 MeV.

Figure 2 compares the $pp \to pn\pi^+$ data of this experiment and the $pp \to pp\pi^0$ data of Meyer *et al.* with previous higher energy data for these reactions [15]. The lowest five points for π^+ production (squares) are cross sections from this work. The new data join well to higher energy cross sections, but an extrapolation of the Ver West and Arndt fit [16] is high by about a factor of 2. By contrast, the equivalent Ver West and Arndt fit for $pp \to pp\pi^0$ lies considerably below the Meyer data (open circles).

In Fig. 3 cross sections for the three related pion production reactions are compared for $\eta < 0.6$. Close to threshold, the $\pi^+ d$ final state dominates by about an order of magnitude. In turn the $pp \to pn\pi^+$ cross section is roughly a factor of 6 larger than that of $pp \to pp\pi^0$ and rises faster than either. Two sets of theoretical predictions (for $pp \to pn\pi^+$ only) are shown in Fig. 3. Schillacci, Silbar, and Young [9] (solid lines) as well as Lee and Matsuyama [10] (dashed lines) each provided two predictions indicating the cross-section range for realistic input parameters. Our cross sections do not agree in detail with these calculations. While there is a 15% uncertainty in the absolute scale for the new data, the random and relative errors total only about 4%. Rescaling would not lead to good agreement with any of the four theoretical curves, although there would be rough agreement with the higher SSY curve. The predicted *range* of the SSY curves [9] for $pp \to pp\pi^0$ (not shown) does include the Meyer *et al.* data [4], but the SSY approximation used for the "upper" curve for $pp \to pn\pi^+$ greatly *overpredicts* the $pp \to pp\pi^0$ data.

The two Lee and Matsuyama curves correspond to two different πNN range parameters, $\beta_\pi = 600$ and 1200 MeV/c. They do obtain the strong observed rise in the cross section above 314.3 MeV ($\eta = 0.379$), but below 310 MeV the curves are far above the data and have the wrong energy dependence. Their model significantly overestimates the nonresonant pion production.

It is important to find a model-independent determination of the s-wave strength because the soft pion theorems predict only the s-wave strength for pion production. Total cross sections have been used to extract partial wave amplitudes through the η dependence for $pp \to pp\pi^0$, but this analysis is difficult for $pp \to pn\pi^+$ because here η^4 and η^6 dependences must be separated. Therefore, we also measured angular distributions. Figure 4 shows the pion angular distribution in the three-body center-of-mass frame, which is the appropriate frame for comparison with $pp \to d\pi^+$ data. The experimental uncertainties shown

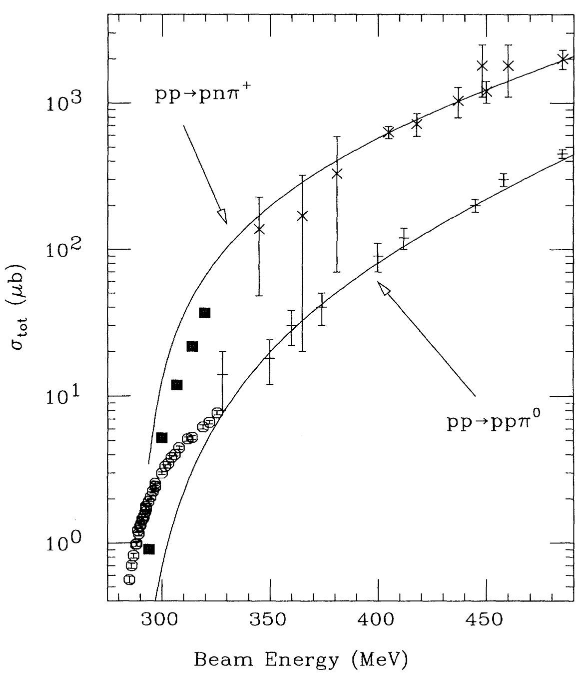

FIG. 2. Comparison of the new $pp \to pn\pi^+$ data and the $pp \to pp\pi^0$ data of Meyer *et al.* [4] with higher energy data in the literature [15] and with theoretical calculations. The new data have random errors as shown. They also have an estimated scale uncertainty of $\pm 15\%$, which is not shown. The solid lines present earlier empirical fits of Ver West and Arndt [16].

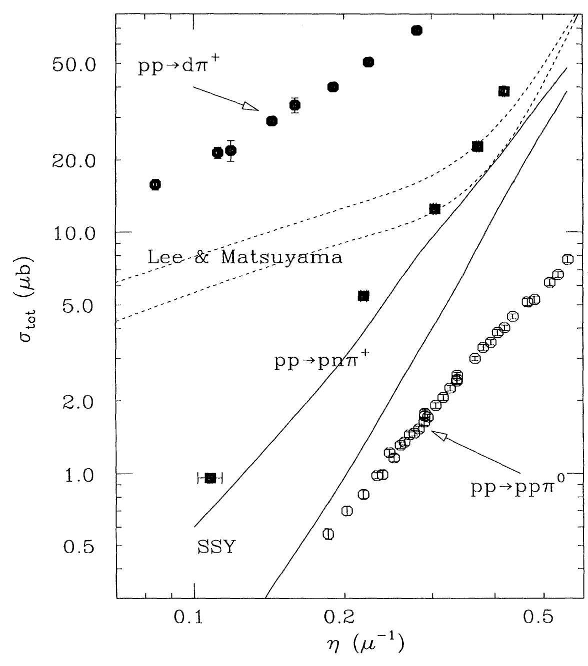

FIG. 3. Comparison of measured total $pp \to pn\pi^+$ cross sections with related reactions [4,5] and with calculations [9,10] as described in the text.

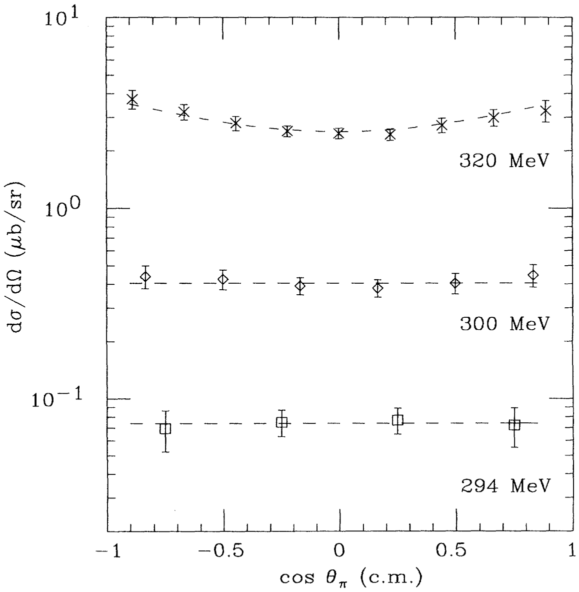

FIG. 4. Pion angular distributions for $pp \rightarrow pn\pi^+$ in the three-body center-of-mass frame. The errors shown include all but the absolute scale uncertainties. They are dominated by errors in energy and angle calibrations. The absolute scale errors are 15%. They do not affect the angular distributions and are not shown. The dashed line fits for 300 and 294 MeV represent isotropic distributions whereas, for 320 MeV, a $\cos^2\theta$ component is included.

are a combination of random errors and systematic energy calibration errors. The latter dominate, especially at 294 MeV.

The $pp \rightarrow pn\pi^+$ and the $pp \rightarrow d\pi^+$ reactions produce qualitatively different angular distributions. The former are fairly isotropic, while the $pp \rightarrow d\pi^+$ angular distributions have a strong $\cos^2\theta$ dependence, possibly indicating mechanisms involving the Δ resonance [5]. This is understood in part because of the differences between the 3- and 2-particle phase space close to threshold. Within errors the $pp \rightarrow pn\pi^+$ distributions are symmetric about 90°, as expected from isospin symmetry considerations. In the absence of higher partial waves we expect isotropy, as illustrated by the horizontal lines for 294 and 300 MeV, but if the pion is produced in the most prominent delta excitation channel, the angular distribution would be proportional to $(1/3 + \cos^2\theta)$ [17].

The 294 and 300 MeV angular distributions are compatible with isotropy, although the calibration uncertainties might mask a $\cos^2\theta$ contribution as large as 20%. However, at 320 MeV there is a significant deviation from isotropy. We conclude that *at and below* 300 MeV the $pp \rightarrow pn\pi^+$ experiment seems to primarily measure the s-wave strength of interest as the corresponding angular distributions do not give any significant evidence for anisotropic contributions. However, at 319.5 MeV fits to the energy averaged pion data suggest a 30% to 40% component of $(1/3 + \cos^2\theta)$. To test our current conclusions we are now measuring the $p\vec{p} \rightarrow pn\pi^+$ analyzing powers, which greatly enhance our sensitivity for p- and higher partial waves and may permit more quantitative statements.

The experiment benefited greatly from the good beam quality and the assistance of the staff of the IUCF Cooler Ring. This work and the IUCF accelerator operation have been supported by the National Science Foundation.

Note added.—We have learned that T. S. H. Lee has succeeded in reproducing all pion production cross sections shown in Fig. 3 by extending his model for π^0 production, as proposed in Ref. [7], to π^+ production (to be published).

*Present address: IUCF, Indiana University, IN 47408.
†Present address: CEBAF, Newport News, VA 23606.
‡Present address: Physics Department, Yale University, New Haven, CT 06511.

[1] S. Weinberg, Phys. Rev. Lett. **16**, 879 (1966); S. L. Adler and Y. Lothan, Phys. Rev. **151**, 1267 (1966).
[2] J. Gasser and H. Leutwyler, Nucl. Phys. **B307**, 709 (1988).
[3] D. Drechsel and L. Tiator, J. Phys. G **18**, 449 (1992).
[4] H. O. Meyer *et al.,* Phys. Rev. Lett. **65**, 2846 (1990); Nucl. Phys. **A539**, 633 (1992).
[5] E. Korkmaz *et al.,* Nucl. Phys. **A535**, 636 (1991); D. A. Hutcheon *et al.,* Nucl. Phys. **A535**, 618 (1991).
[6] D. S. Koltun and A. Reitan, Nucl. Phys. **B4**, 629 (1968); G. A. Miller and P. U. Sauer, Phys. Rev. C **44**, R1725 (1991).
[7] T. S. H. Lee and D. O. Riska, Phys. Rev. Lett. **70**, 2237 (1993).
[8] C. J. Horowitz, H.O. Meyer, and D. K. Griegel, Phys. Rev. C **49**, 1337 (1994).
[9] (a) M. E. Schillaci, R. R. Silbar, and J. E. Young, Phys. Rev. Lett. **21**, 711 (1968); Phys. Rev. **179**, 1539 (1979). (b) M. E. Schillaci and R. R. Silbar, Phys. Rev. **185**, 1830 (1969).
[10] T. S. H. Lee and A. Matsuyama, Phys. Rev. C **36**, 1459 (1987); (private communications).
[11] (a) W. W. Daehnick, W. K. Brooks, Swapan K. Saha, and D. O. Kreithen, Nucl. Instrum. Methods Phys. Res., sect. A **320**, 290 (1992); (b) J. G. Hardie, Ph.D. Thesis, University of Pittsburgh, 1993; W. W. Daehnick, in *Proceedings of the 5th International Symposium on Meson-Nucleon Physics and the Structure of the Nucleon, Boulder, CO, 1993* edited by W. Kluge, G. Hoehler, and B. M. K. Nefkens, piN Newsletter (UCLA, Los Angeles, 1994) Vol. I, p. 104.
[12] R. A. Arndt, Scattering Interactive Dial-In (SAID) program; see R. A. Arndt *et al.,* Phys. Rev. D **28**, 97 (1983).
[13] R. A. Cecil, B. D. Anderson, and R. Madey, Nucl. Instrum. Methods **161**, 439 (1979).
[14] K. M. Watson, Phys. Rev. **88**, 1163 (1952).
[15] Data taken from Physics Data, N-N Scattering Data, Nr. 11-2 (1981), edited by J. Bystricky and F. Lehar.
[16] B. J. Ver West and R. A. Arndt, Phys. Rev. C **25**, 1979 (1982).
[17] A. H. Rosenfeld, Phys. Rev. **96**, 139 (1954).