Total and Differential Cross Sections for $\pi^+ + d \rightarrow p + p$ below 21 MeV

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Absolute total and differential cross sections for the reaction $\pi^+ + d \rightarrow p + p$ have been measured for pion energies from 3.7 to 20.5 MeV. Evidence for p-wave strength was observed for all energies. Using detailed balance and corrections for Coulomb effects, the measured differential and total cross sections were found to be consistent with recent measurements for the reaction $n + p \rightarrow d + \pi^0$, offering no evidence for charge-independence breaking. The measured total cross sections for energies below 30 MeV are in disagreement with predictions by Blankleider and by Vogelzang, Bakker, and Boersma.

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The reaction $\pi NN \rightarrow NN$ is of fundamental significance in nuclear physics inasmuch as the long-range component of the nucleon-nucleon interaction is mediated by the production and absorption of virtual pions. While high-quality data exist for the total and differential cross sections for energies above 19 MeV, the only published data for the $\pi^+ + d \rightarrow p + p$ reaction below 19 MeV are the total cross sections measured by Rose[1] using a bubble chamber. So few events were observed that the errors on the total cross sections were large, the smallest being approximately 8%. No differential cross sections have been published. The lack of data is mainly due to the difficulty in developing pion beams with sufficient purity and intensity at these low energies.

Recently, data taken at TRIUMF by Hutcheon *et al.* were published[2] for the reaction $n + p \rightarrow d + \pi^0$, which can be related to $\pi^+ + d \rightarrow p + p$ by detailed balance and charge independence. Their measurements of the total and differential cross sections, normalized by phase-shift predictions for the $np \rightarrow pn$ cross sections measured simultaneously, correspond to measurements with incident pion energies from less than 1 to 7 MeV. Their results generally indicated that Rose's measurements appeared to be high, but no conclusions concerning charge-independence breaking were made due to the large uncertainties in Rose's data. The Ritchie *et al.* $\pi^+ + d \rightarrow p + p$ measurements[3] above 19 MeV have much smaller uncertainties than the Rose measurements, but the 12-MeV gap between the TRIUMF work and those cross sections occurs where the cross section should reach a minimum, so determining the consistency of the two data sets is difficult. The new TRIUMF differential cross sections also indicated that the angular distributions remained anisotropic even at the lowest energy.

We report here the results of measurements of the total and differential cross sections for $\pi^+ + d \rightarrow p + p$ for energies from 3.7 to 20.5 MeV based on absolute measurements of the beam flux, removing the necessity of normalizing to some other reaction, as was the case in Ref. 2. The salient aspects of the experimental procedure are reviewed here; a more detailed discussion appears elsewhere.[4] The experiment was performed at the low-energy pion channel[5] at the Clinton P. Anderson Meson Physics Facility using pion beams with energies at the center of the target of 3.7, 5.0, 9.6, 15.2, and 20.5 MeV. The purity of the pion beam was enhanced by the use of a crossed electric- and magnetic-field velocity filter 1.5 m in length, which separated pions from the muons and electrons. The energies of 3.7 and 5.0 MeV were obtained with the 9.6-MeV beam by inserting graphite and aluminum degraders directly in front of the target.

A deuterated scintillator 0.119 ± 0.001 cm thick wrapped in 0.0254-cm-thick aluminum foil was used both as the target and to count the beam particles. Assayed by infrared and nuclear-magnetic-resonance techniques, the deuteron areal density was $(5.57 \pm 0.12) \times 10^{21}$ deuterons/cm^2. Pulse-height sampling was used to *continuously* monitor the beam composition during data collection and to determine the pion fraction of the beam, which ranged from 0.49 at the lowest energy to 0.69 at 20.5 MeV. The uncertainties in the determined pion fractions, generally less than 4%, are entirely due to uncertainties in the shape of the pulse-height distributions associated with the electrons, muons, and pions.

The incident beam flux was adjusted to limit the instantaneous rates in the target scintillator to under 10^6/s to minimize pileup. Dead-time corrections were made by means of four separate scalers fed with discriminator logic signals with widths of 15, 40, 60, and 100 ns. Extrapolation of the scaler values to 0 ns effective width yielded the value of the beam flux with uncertainties much smaller than the uncertainty in the pion fraction. At 3.7 MeV the extrapolation included an exponential term to account for double counting of pions that

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TABLE I. Parametrization of differential cross sections measured in this experiment as described in the text. T_π is the mean pion beam energy; the standard deviation for the beam energy distribution is given in parentheses. Statistical uncertainties for α_0, α_2, and Γ are given in parentheses. Uncertainties for the total cross sections σ are given in parentheses and include normalization and systematic uncertainties.

T_π (MeV)	α_0 (mb/sr)	α_2 (mb/sr)	$\Gamma=\alpha_2/\alpha_0$	$\sigma_{\rm tot}$ (mb)
3.7(11)	0.62(7)	0.19(12)	0.31(22)	3.9(5)
5.0(8)	0.68(3)	0.24(7)	0.35(12)	4.3(2)
9.6(4)	0.62(3)	0.22(5)	0.36(9)	3.9(2)
15.2(3)	0.67(2)	0.51(4)	0.77(7)	4.19(15)
20.5(5)	0.79(4)	0.52(8)	0.66(12)	4.9(3)

stopped in the target, with the decay muon producing a second count. This fraction was determined to be $(11.4 \pm 0.2)\%$; a correction was made for the shorter path length in the target based on computer simulations which resulted in a 1% effect in the cross-section results.

The two reaction-product protons were detected in coincidence with three pairs of the plastic-scintillator E-ΔE telescopes described in Ref. 3. The solid angles, determined entirely by the ΔE counter on one member of each pair, were 9.95 ± 0.03, 9.20 ± 0.03, and 9.17 ± 0.03 msr. The energy resolution of the telescopes was more than adequate to separate the deuterium events from the carbon-absorption events; the background from the latter was determined to be negligible near the deuteron peak. Corrections measured previously[6] for nuclear interactions of the protons in the detector material were applied; these varied from 4% to 23% with absolute uncertainties of less than 1%. At most energies, several configurations of the detectors were used to provide checks on systematic errors or to increase angular coverage.

The measured center-of-mass differential cross sections, presented elsewhere,[4] were fitted using the form $d\sigma/d\Omega = \alpha_0 P_0(\cos(\theta_{\rm c.m.})) + \alpha_2 P_2(\cos(\theta_{\rm c.m.}))$. The parameters obtained are presented in Table I. Even at 3.7 MeV, the cross sections remain anisotropic, consistent with the findings of Ref. 2, though the uncertainty in α_2 measured here is large. Using this form to fit the angular distributions, the total cross section is equal to $2\pi\alpha_0$; these are also given in Table I. The total cross sections are compared to the data of Rose and of Ritchie *et al.* in Fig. 1. Although Rose's large uncertainties overlap our measurements, the total cross sections determined here have much smaller uncertainties. The results at 20.5 MeV for both the total and differential cross sections are also slightly higher than the measurements of Ref. 3, but are nearly within uncertainties.

With appropriate Coulomb corrections and the application of the principle of detailed balance, the total and differential cross sections obtained here can be compared to the TRIUMF results for $n+p \rightarrow d+\pi^0$. The Coulomb corrections, calculated by Reitan,[7] range from 4.1% at 20.5 MeV to 9.7% at 3.7 MeV, and represent a source of uncertainty in assessing the level of charge-independence breaking for these reactions. Our Coulomb-corrected cross sections agree within errors with the $n+p \rightarrow d+\pi^0$ measurements, as seen in Fig. 2. The two sets provide a precise determination of the energy dependence for energies from threshold to 20 MeV.

The data shown in Fig. 2, which includes the results of Refs. 2 and 3, were fitted by the Gell-Mann and Wat-

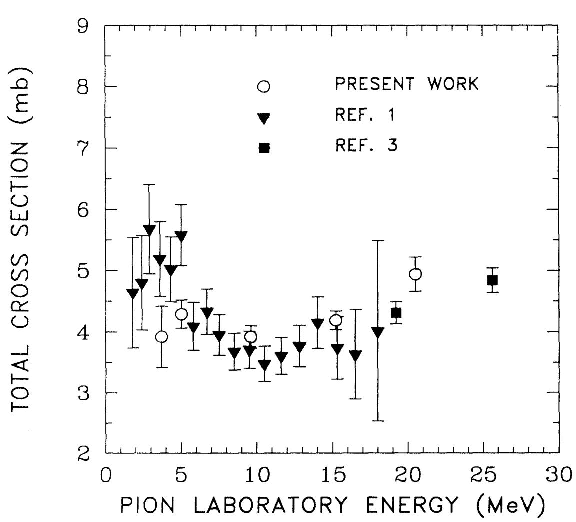

FIG. 1. Total cross sections for $\pi^+ + d \rightarrow p+p$ measured in this work and from Refs. 1 and 3.

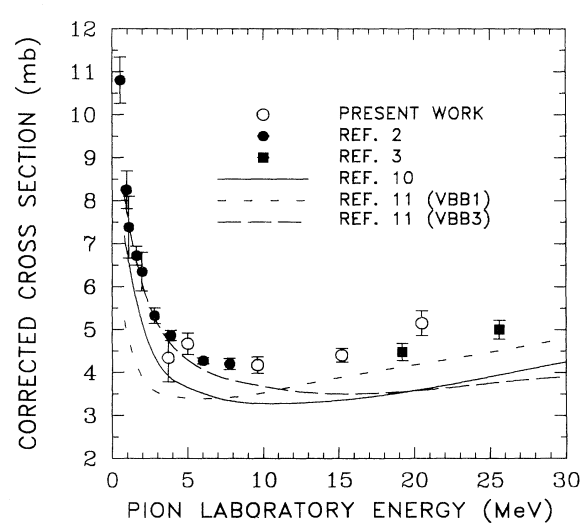

FIG. 2. Total cross sections for $\pi^+ + d \rightarrow p+p$ measured in this work and in Ref. 3, and those for $n+p \rightarrow d+\pi^0$ reported in Ref. 2. The cross sections for $\pi^+ + d \rightarrow p+p$ have been corrected for Coulomb effects using the calculations of Ref. 7. Also shown are predictions from Refs. 10 and 11, as discussed in the text.

son[8] threshold formula, $\sigma_{pp\to\pi d}=\alpha\eta+\beta\eta^3$. The values $\alpha=174\pm3$ and $\beta=982\pm38$ μb were obtained with a reduced χ^2 per degree of freedom of 1.2. The value for β is in excellent agreement with the predictions of the coupled-channels Faddeev-type treatment of Blankleider,[9] who found β to be approximately constant with energy at approximately 1000 μb. The value obtained for α in those calculations was energy dependent, decreasing rapidly with energy from 140 μb near threshold. The α and β values obtained in this analysis disagree outside quoted uncertainties with those obtained from the TRIUMF data alone, $\alpha=184\pm5$ and $\beta=781\pm79$ μb. The disagreement in α is probably not significant because of the large uncertainty in the Coulomb corrections at lower energies. The disagreement in β is probably due to the larger energy range covered in our fit, as well as to the shortcomings of extrapolating the threshold formula to higher energies.

Estimating the degree of charge-independence breaking requires a detailed model for predicting the cross sections for the two reactions. A simple estimate can be made, however, by fitting the Gell-Mann and Watson formula separately to the Coulomb-corrected cross sections obtained here and those obtained in Ref. 2. The α values agree within the 9.3% uncertainty in the fit to the data; we thus infer that there is no charge-independence breaking demonstrated above the 10% level.

Also shown in Fig. 2 are predictions for the total cross sections by Blankleider and Afnan[10] and Vogelzang, Bakker, and Boersma,[11] an example of approaches based on perturbation theory; their "standard 1" (VBB1) and "standard 3" (VBB3) calculations are used for comparison here. No Coulomb corrections have been applied to the calculations, which did not explicitly include Coulomb effects.[12,13] It is seen in Fig. 2 that neither of these calculations provides a successful quantitative description of the energy dependence of the total cross section. While VBB3 describes well the cross sections observed in Ref. 2, as noted there, as well as our data below 10 MeV, it consistently underestimates our data above 10 MeV, as well as the data of Ref. 3. VBB1, which was very successful at energies above 20 MeV, also falls well below our data.

As noted in Ref. 2, at low energies the ratio $\Gamma=\alpha_2/\alpha_0$, given in Table I, is also equal to $R/(1+R)$, where R is the ratio of the p-wave to s-wave strength. The values of Γ obtained from our data without Coulomb correction should be directly comparable to the results of the TRIUMF data since the Reitan calculations indicate that the s- and p-wave corrections are nearly identical. While the absolute normalization uncertainties cancel in Γ, the statistical errors in α_0 and α_2 result in considerable uncertainty in the ratios, as seen in Fig. 3. Our results agree within uncertainties with the new TRIUMF measurements as well as with Ref. 3. Though the ratio is known far too poorly in the energy range of this study to make conclusive comparisons with the predictions of Refs. 9 and 11, the entire data set shown in Fig. 3 indicates that VBB3 is more successful in describing the ratio.

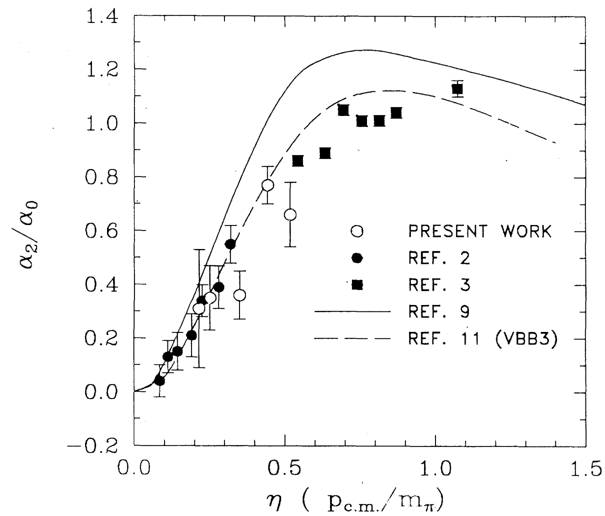

FIG. 3. α_2/α_0 ratios for the data reported here and in Refs. 2 and 3. The curves shown are from calculations by Blankleider in Ref. 9 (solid) and by Vogelzang, Bakker, and Boersma (VBB3) in Ref. 11 (dashed).

In conclusion, absolute measurements of the total and differential cross sections for the reaction $\pi^+ + d \to p+p$ at energies below 21 MeV have been made to typical accuracies of about 5%. Some p-wave strength appears to exist even at 3.7 MeV, consistent with similar observations by Hutcheon *et al.* The Coulomb corrections of Reitan bring the two sets into excellent agreement, so that within the measurement uncertainties there is no evidence of charge-independence breaking in the $\pi NN \to NN$ reaction at very low energies. Both the Faddeev and perturbation-theory predictions typified by Refs. 9–11 fare poorly when compared with the measurements reported here and in Refs. 2 and 3. Our data and those of Hutcheon *et al.* together provide an accurate determination of the energy dependence of the total and differential cross sections from threshold up to about 20 MeV, where earlier sets of high-accuracy data begin.

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