Measurement of $np \rightarrow d\pi^0$ Cross Sections Very Near Threshold

D. A. Hutcheon,[1] E. Korkmaz,[2] G. A. Moss,[2,a] R. Abegg,[1] N. E. Davison,[3] G. W. R. Edwards,[2] L. G. Greeniaus,[1,2] D. Mack,[2] C. A. Miller,[1] W. C. Olsen,[2] I. J. van Heerden,[4] and Ye Yanlin[2,b]

[1]*TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia, Canada V6T 2A3*
[2]*Nuclear Research Center, University of Alberta, Edmonton, Alberta, Canada T6G 2N5*
[3]*Department of Physics, University of Manitoba, Winnipeg, Manitoba, Canada R3T 2N2*
[4]*Department of Physics, University of Western Cape, Bellville 7535, South Africa*

(Received 5 July 1989)

We have measured $np \rightarrow d\pi^0$ cross sections at eleven beam energies within 16 MeV of threshold. Total cross sections are only 0.67 ± 0.10 of the value which has been generally accepted for s-wave pion production strength near threshold. The differential cross sections are anisotropic at only 1 MeV (c.m.) above threshold. Our results are compared to $\pi^+ d \rightarrow pp$ data and to predictions of two models.

PACS numbers: 13.75.Cs, 25.10.+s, 25.40.Gr

A precision measurement of the $NN \rightarrow d\pi$ cross section at energies near threshold is important for at least two reasons. First, the total cross section is an important property of the interaction of s-wave pions with a pair of nucleons, providing through the optical theorem the imaginary part of the pion-deuteron scattering length. Second, models for the $NN \rightarrow d\pi$ reaction may be tested in a regime where the usually dominant $NN \rightarrow \Delta N \rightarrow \pi^+ d$ mechanism is suppressed.

Early studies of the $NN \rightarrow d\pi$ reaction near threshold focused on determining the relative amounts of s-wave and p-wave pion production. The total reaction cross section was expressed[1] as $\sigma_{\text{tot}}(pp \rightarrow d\pi^+) = \alpha\eta + \beta\eta^3$, where η is the pion c.m. momentum in units of $m_\pi c$ and the two terms give the s-wave and p-wave production, respectively. The imaginary part of the π-d scattering length is proportional to α in the limit $\eta \rightarrow 0$. A fit to $pp \rightarrow d\pi^+$ cross sections[2] between $\eta = 0.38$ and 0.58 gave $\alpha = 138 \pm 15$ μb. However, the $\pi^+ d \rightarrow pp$ data measured by Rose[3] for $0.15 < \eta < 0.48$, after correction for Coulomb-barrier effects, yielded $\alpha = 240 \pm 20$ μb. The validity of the Watson-Brueckner model[1] was put in some doubt by calculations of Afnan and Thomas[4] and of Blankleider,[5] which predicted α to be energy dependent. When Spuller and Measday[6] reanalyzed these and other data, they found values for α_0 between 180 and 300 μb, depending upon whether or not they allowed α to vary with energy. A further complication in the analysis of the low-energy $\pi^+ d \rightarrow pp$ data is the need to correct for the Coulomb barrier between the deuteron and charged pion; Spuller and Measday used the Coulomb correction of Reitan[7] which treats the deuteron as a point charge, while Rose used a method giving significantly larger corrections. Despite these uncertainties, the result $\alpha_0 = 275 \pm 40$ μb of Spuller and Measday often has been quoted in the literature as the Coulomb-corrected strength for s-wave pion production at threshold (see, for example, Ref. 8, p. 123). There is a clear need for a precision measurement of total cross sections very near threshold and free of uncertainty in Coulomb corrections.

A qualitative and quantitative understanding of the $NN \rightarrow d\pi$ reaction has been the goal of a large number of theoretical calculations. Out of the many models, we wish to single out two which present results at the low energies of interest to us: the three-body (Faddeev) calculation of Blankleider[5] and the perturbative calculation of Vogelzang, Bakker, and Boersma[9] (VBB). The Faddeev calculation attempts a unitary treatment of the two- and three-body channels using π-N and N-N interactions. The perturbative model considers the direct emission of a pion by one of the nucleons and also emission of a pion by one nucleon and its rescattering by the other; the "emitted" pion may move either forward or backward in time. Both models agree that the dominant contribution near threshold is from pion rescattering, with the π-N intermediate state being primarily P_{33} (Δ) for p-wave production and S_{31} for s-wave production. Thus a calculation of cross sections near threshold will be more sensitive to π-N S-wave rescattering than is the case at higher energies, where the Δ resonance dominates.

This situation prompted us to undertake a precision measurement of $NN \rightarrow d\pi$ cross sections very close to threshold energy. Our method was to detect deuterons from the $np \rightarrow d\pi^0$ reaction using the CHARGEX neutron-beam facility at TRIUMF. This technique has several advantages over $\pi^+ d \rightarrow pp$: (1) The beam does not lose energy in the target and so the spread in reaction energies depends only upon the spread in energies in the neutron beam (< 1 MeV); (2) the mean reaction energy can be determined from the momentum-versus-angle distribution of the deuterons making the experiment "self-calibrating;" (3) the $np \rightarrow d\pi^0$ yields can be normalized to $np \rightarrow pn$ yields which are measured simultaneously; and (4) decay in flight by particles of the beam is negligible. Most important for the interpretation of the measurement, there is no Coulomb-barrier

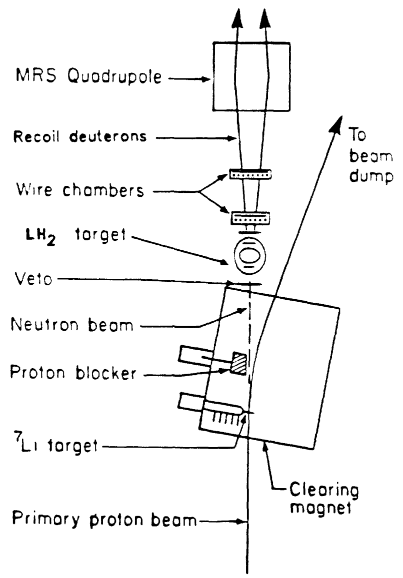

FIG. 1. Schematic view of the CHARGEX neutron-beam facility, liquid-hydrogen (LH_2) target, and front detectors of the spectrometer.

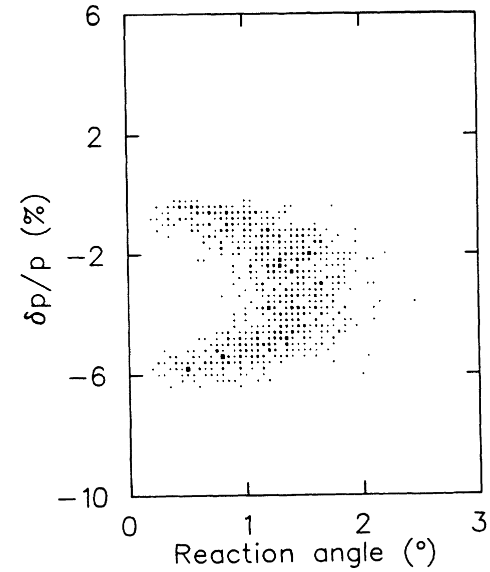

FIG. 2. Correlation of laboratory reaction angle vs momentum of deuterons detected at nominal neutron-beam energy of 278 MeV. Momentum is shown as a fractional difference from the central momentum $p = 735$ MeV/c.

correction to be performed.

The CHARGEX facility[10] and the liquid-hydrogen target[11] are shown schematically in Fig. 1. The neutrons were produced by a momentum-dispersed beam of protons incident on a ^{7}Li strip target of thickness 220 or 110 mg/cm^2. The energy spread of the neutron beam depended upon the proton-beam energy spread (400 keV), energy loss by the protons in the ^{7}Li target (725 or 360 keV), and the separation of the ground and first excited state of the residual ^{7}Be nucleus (430 keV). Data were collected with LH_2 target cells either 1.5 or 6 cm thick. The deuterons from $np \to d\pi^0$ and the protons from $np \to pn$ were detected in the medium-resolution spectrometer (MRS), which consisted of two pairs of x-y multiwire drift chambers to define tracks of particles emerging from the target, a quadrupole and dipole magnet, and drift chambers plus plastic scintillators at the focal plane. Energy loss in the scintillators combined with time of flight through the spectrometer provided unambiguous identification of protons and deuterons.

Near threshold the deuterons from $np \to d\pi^0$ are confined to a small cone of angles in the forward direction. Figure 2 illustrates the correlation between laboratory angle and momentum of the deuterons for a 278-MeV neutron beam, with a complete distribution in c.m. reaction angle collected in a single spectrometer setting (which is possible for beam energies below 284 MeV). Background from (n,d) reactions in windows and counters was small, as is evident in Fig. 2.

The cross-section normalization was provided by protons from the $np \to pn$ reaction, which were accumulated at the same time as the deuterons. Their momenta were several percent higher than for any of the deuterons, and one of the chief concerns of the experiment was to map the MRS acceptance as a function of momentum in order to relate the ratio of counts (deuterons/protons) to the ratio of cross sections $[(np \to d\pi^0)/(np \to pn)]$. The mapping was done by varying the fields of the MRS magnets so as to put the proton peak at various positions on the focal plane. At each field setting we found the region of full acceptance and analyzed only events from the four-dimensional acceptance volume which was common to the momentum range of interest (13%). There was a $\pm 2\%$ statistical uncertainty in measuring acceptance, which has been included in the statistical uncertainties quoted for the cross sections.

The deuterons underwent multiple scattering and differential energy loss in the LH_2 target, causing the locus of $np \to d\pi^0$ events to be broadened and shifted compared to the ideal case of a "thin" target. This mixes contributions from different c.m. angles and neutron-beam energies, determining our resolution in both of these variables. We modeled reaction kinematics, energy loss, and multiple scattering and fitted quantities of interest to the yields binned as shown in Fig. 2. The c.m. differential cross section was expressed in terms of Legendre polynomials as $d\sigma/d\Omega = a_0 P_0(\theta) + a_2 P_2(\theta)$. The quantities fitted were as follows: mean energy and energy spread of the neutron beam; total $np \to d\pi^0$ cross section ($=4\pi a_0$) and its variation with beam energy; the ratio a_2/a_0. Proton and deuteron data were fitted simultaneously. For the $np \to pn$ cross sections we used the predictions of Arndt's SP88 phase shifts,[12] parametrized as

$$d\sigma/d\Omega_{\mathrm{c.m.}}(\mathrm{mb}) = [11.55 + (295 - T_n)/40] \times [1 - T_n \theta_p^2/118\,000]\,,$$

with T_n the beam energy in MeV and θ_p the c.m. proton angle in degrees.

Good fits were obtained, with values of χ^2 per degree of freedom typically in the range 0.75 to 1.4. At and above 278 MeV the single-energy fits gave a "local" energy variation of cross section which was consistent with cross sections at neighboring beam energies; below 278 MeV the system resolution did not permit reliable fitting of this parameter and it was fixed according to the energy dependence found by fitting the data from all beam energies. Similarly, a_2/a_0 could not be extracted at the lowest energies, especially for the 6-cm target, and was fixed according to the trend from higher energies. The beam energy calibration rests upon a fit to the deuteron local at 278 MeV, where the maximum in laboratory reaction angle depends sensitively on beam energy. The statistical uncertainty from this fit was ± 30 keV. The mean beam energy for other runs was related to that of the 278-MeV run via shifts in the mean energy of the protons. The statistical uncertainty in centroids of the proton peaks was always small compared to ± 30 keV, so the uncertainty in the 278-MeV fit to deuterons was the dominant factor.

Total cross sections are presented in Fig. 3 and Table I. We have also plotted the $\pi^+ d \to pp$ data of Rose[3] and a $pp \to d\pi^+$ cross section of Crawford and Stevenson.[2] In converting these results we have divided them by an isospin coupling factor of 2 and also by a Coulomb-barrier factor as calculated by Reitan.[7] Finally, for the pion-absorption data we applied detailed balance. Our total cross sections follow very nearly the relationship

$$\sigma_{\mathrm{tot}}(np \to d\pi^0) = \tfrac{1}{2}[\alpha\eta + \beta\eta^3],$$

with $\alpha = 184 \pm 5$ μb and $\beta = 781 \pm 79$ μb (dotted line of Fig. 3), where the quoted errors include the statistical uncertainties of the cross sections and the effect of a ± 30-keV uncertainty in energy of the neutron beam. This is to be compared to Rose's fit to his data, $\alpha = 240$

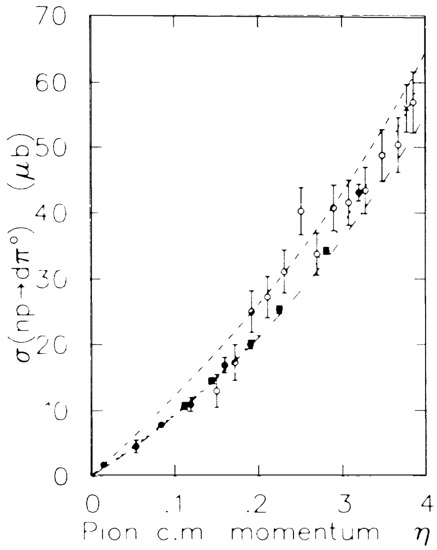

FIG. 3. Total $np \to d\pi^0$ cross sections as a function of pion c.m. momentum in units of $m_\pi c$. The solid circles are our results, the open circles the data of Ref. 3, and the cross from Ref. 2. The dashed and dotted lines are fits to the data, as described in the text. The dash-dotted curve is the Standard-3 calculation of Ref. 9.

± 20 μb and $\beta = 520 \pm 200$ μb (dashed line). Note, however, that his values were obtained using different Coulomb factors from Reitan's. The dash-dotted curve is the "Standard-3" prediction of VBB.[9]

The coefficient α which Rose[3] obtained by fitting his $\pi^+ d \to pp$ data is $(28 \pm 11)\%$ larger than the value we find from our $np \to d\pi^0$ measurement. It would be premature to claim that this is evidence of charge-independence breaking, however, because of the problem of Coulomb corrections. It is possible that even the Reitan factors, which assume point charges, overestimate the Coulomb suppression and more sophisticated calculations of Coulomb effects are very much needed. Our

TABLE I. Our measured values of $np \to d\pi^0$ total cross sections and ratio of Legendre coefficients as a function of mean beam energy.

Neutron beam energy (MeV)	η	LH_2 target thickness (cm)	σ_{tot} $np \to d\pi^0$ (μb)	a_2/a_0
275.09	0.015	1.5	1.77 ± 0.26	...
275.50	0.054	6.0	4.61 ± 0.99	...
276.14	0.084	1.5	7.89 ± 0.39	0.04 ± 0.06
276.98	0.112	1.5	10.71 ± 0.57	0.13 ± 0.06
277.25	0.119	6.0	10.93 ± 1.07	...
278.25	0.144	1.5	14.48 ± 0.47	0.15 ± 0.07
278.99	0.160	6.0	16.84 ± 1.20	...
280.64	0.191	6.0	19.98 ± 0.67	0.21 ± 0.08
282.82	0.225	1.5	25.29 ± 0.60	0.34 ± 0.06
287.11	0.281	1.5	34.23 ± 0.56	0.39 ± 0.08
290.61	0.320	6.0	43.08 ± 1.30	0.55 ± 0.07

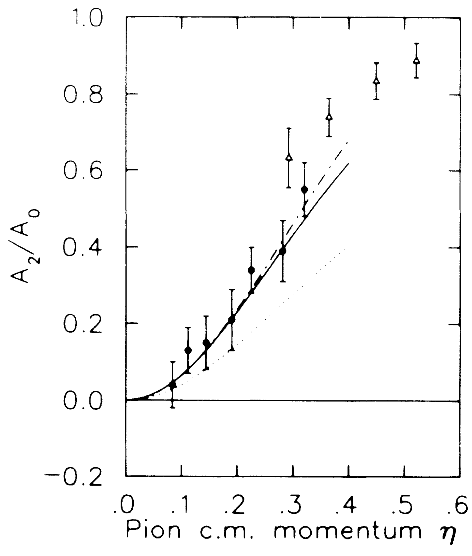

FIG. 4. Ratio of Legendre-polynomial coefficients, a_2/a_0, as a function of pion c.m. momentum. The solid circles are our data and the triangles are data of the Freiburg group, reported in Ref. 13. The dotted line is the prediction of the Watson-Brueckner model (Ref. 1), the solid line that of Blankleider (Ref. 5), and the dash-dotted line the Standard-3 prediction of VBB (Ref. 9).

data, which do not require a Coulomb-barrier correction and get much closer to threshold, should give a much more dependable a_0 than previous $\pi^+ d \rightarrow pp$ data. We find a substantial downward revision in a_0, obtaining 0.68 ± 0.10 of the value for solution F of Spuller and Measday.[6]

We obtained also from our experiment a_2/a_0, the anisotropy in the differential cross section. In Fig. 4 we plot these results along with those obtained in a previous $np \rightarrow d\pi^0$ experiment by the Freiburg group.[13] We can use our data for a_2/a_0 to estimate r, the ratio of p-wave to s-wave strength: Assuming that the p-wave strength is predominantly in the $J=2$ partial wave, we have $a_2/a_0 = r/(1+r)$. Two of the curves are based on the ratios r obtained in Blankleider's calculation (solid line) and the Watson-Brueckner[1] picture (dotted line). The Standard-3 calculation of VBB predicts a_2/a_0 as shown by the dash-dotted curve. Our data clearly rule out the simple Watson-Brueckner model, but are consistent with both of the other calculations. The success of these models should be viewed with caution, however. The analysis of VBB indicates that truncation of the multiple-scattering series by VBB and the neglect of the "backward-moving" pion terms by Blankleider each could cause the cross sections to be underestimated by almost a factor of 2.

In summary, we have made precision measurements of $np \rightarrow d\pi^0$ cross sections within 8-MeV c.m. of threshold. Total cross sections are measured to be substantially lower than expected from extrapolation of charged-pion data. They show a simple power-law dependence upon pion momentum, with no evidence of a resonance near threshold. There is p-wave production strength at c.m. momenta as low as 0.1 fm^{-1}. Our results, because of their precision and absence of Coulomb interaction, should provide a good test of models for the $NN \rightarrow d\pi$ reaction at low energy.

We are pleased to acknowledge the work of Walter Kellner in making and running the liquid-hydrogen targets. The experiment was supported in part by a grant from the Natural Sciences and Engineering Research Council of Canada.

[a]Present address: Science World, 1455 Quebec Street, Vancouver, British Columbia, Canada V6B 5E7.

[b]Present address: Nuclear Physics Division, Department of Technical Physics, Peking University, Beijing, People's Republic of China.

[1]K. Watson and K. Brueckner, Phys. Rev. **83**, 1 (1951).

[2]F. S. Crawford and M. S. Stevenson, Phys. Rev. **97**, 1305 (1955).

[3]C. M. Rose, Phys. Rev. **154**, 1305 (1967).

[4]I. R. Afnan and A. W. Thomas, Phys. Rev. C **10**, 109 (1974).

[5]B. Blankleider, Ph.D. thesis, Flinders University, 1980 (unpublished).

[6]J. Spuller and D. F. Measday, Phys. Rev. D **12**, 3550 (1975).

[7]A. Reitan, Nucl. Phys. **B11**, 170 (1969).

[8]T. Ericson and W. Weise, *Pions and Nuclei* (Clarendon, Oxford, 1988).

[9]J. Vogelzang, B. L. G. Bakker, and H. J. Boersma, Nucl. Phys. **A452**, 644 (1986).

[10]R. Helmer, Can. J. Phys. **65**, 588 (1987).

[11]G. W. R. Edwards, Ph.D. thesis, University of Alberta, 1989 (unpublished).

[12]R. Arndt, Scattering Analysis Interactive Dial-in (SAID) program; R. A. Arndt *et al.*, Phys. Rev. D **28**, 97 (1983).

[13]G. Jones, in *Pion Production and Absorption in Nuclei —1981*, edited by R. Bent, AIP Conference Proceedings No. 79 (American Institute of Physics, New York, 1981), p. 15.