TRI-PP--89-55

TRI-PP-89-55
Jun 1989

Measurement of $np \rightarrow d\pi^0$ Cross Sections very near Threshold

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Abstract

We have measured $np \rightarrow d\pi^0$ cross sections at ten beam energies within 16 MeV of threshold. Total cross sections followed closely the relationship $\sigma_{\text{tot}}(np \rightarrow d\pi^0) = (1/2)[(184 \pm 5)\eta + (781 \pm 79)\eta^3]\mu\text{b}$, where η is the c.m. pion momentum in units of $m_\pi c$. The differential cross sections are anisotropic at only 1 MeV (c.m.) above threshold. These results are predicted by Faddeev model calculations and by a perturbative model. Our cross sections are in fair agreement with previous $\pi^+ d \rightarrow pp$ data.

(submitted to Physical Review Letters)

A precision measurement of the $NN \rightarrow d\pi$ cross section at energies near threshold can test our understanding of the pion production process in two important ways. First, 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. Second, through a chain of relationships involving detailed balance, charge independence, and extrapolation to zero (pion) energy, the $NN \rightarrow d\pi$ cross section may be compared to those for the reactions $\gamma p \rightarrow \pi^+ n$ and $\pi N \rightarrow \pi N$. Key links in this chain are the validity of charge independence and a calculated ratio of transition rates for stopped-pion reactions $\pi^- d \rightarrow nn\gamma$ and $\pi^- p \rightarrow n\gamma$.

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 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 very early models of this reaction[1] assumed α and β were constants, the energy dependence due to phase space and centrifugal barrier factors simply described by η and η^3. Since then, more realistic calculations have been done, and more complicated energy dependences found for α and β. 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[2] and the perturbative calculation of Vogelzang, Bakker, and Boersma[3] (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.

A key step in relating $NN \rightarrow d\pi$ to the pion photoproduction and elastic scattering processes is EZE — extrapolation to zero energy above threshold. For $NN \rightarrow d\pi$ EZE has been done by means of the model of Watson and Brueckner[1] with constant α and β. A fit to $pp \rightarrow d\pi^+$ cross sections[4] between $\eta = 0.38$ and 0.58 gave $\alpha = 138 \pm 15$ μb, nearly a factor of 2 smaller than expected from comparison with the $\gamma p \rightarrow \pi^+ n$ cross sections.[5] However, the $\pi^+ d \rightarrow pp$ total cross sections measured by Rose[5] 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 was put in some doubt by the Faddeev model calculations of Afnan and Thomas[6] and of Blankleider,[2] which predicted α to be energy dependent. When Spuller and Measday[7] reanalyzed the data, they found values from 180 to 300 μb in the EZE limit depending upon whether they did not or did allow α to vary with energy. Clearly, more precise cross-section data closer to threshold were needed for EZE but until now there has been no improvement on the 1967 results of Rose.[5]

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-vs-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, (4) the lab energies of neutron beam and detected deuterons vary only a few per cent where the equivalent pion beam energies would vary an order of magnitude, and (5) decay in flight by particles of the beam is negligible. In addition there is the advantage that the long-range Coulomb potential need not be included in a model calculation.

The CHARGEX facility[8] and the liquid hydrogen target[9] 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 mg/cm^2 or 110 mg/cm^2. The energy spread of the neutron beam depends 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). The deuterons from $np \rightarrow d\pi^0$ and the protons from $np \rightarrow pn$ were detected in the medium resolution spectrometer (MRS), which consisted of two pairs of x-y multi-wire 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 scintillators combined with time of flight through the spectrometer provided unambiguous identification of protons and deuterons.

Near threshold the deuterons from $np \rightarrow d\pi^0$ 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, where a complete distribution in c.m. reaction angle may be collected in a single spectrometer setting.

Background from (n, d) reactions in windows and counters was small, as is evident in Fig. 2. Data were collected with LH_2 target cells either 1.5 cm or 6 cm thick, to be contrasted with <0.04 cm of other materials which could contribute to background.

The cross section normalization was provided by protons from the $np \rightarrow pn$ reaction, which were accumulated at the same time as the deuterons. Their momenta were several per cent 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 ($np \rightarrow d\pi^0/np \rightarrow pn$). 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, i.e. to vary the ratio of proton momentum to momentum of the central trajectory. At each field setting we found the region of full acceptance and analyzed only events from the 4-dimensional acceptance volume which was common to the momentum range of interest (13%). This volume was 660 mm·mrad in the horizontal by 1500 mm·mrad in the vertical. Reaction angle and momentum defined a pixel for binning counts. We wrote a computer program to reduce the 4-dimensional acceptance volume to an acceptance for each bin in reaction angle; it was necessary to calculate this acceptance for those runs where the MRS was not set at 0°, because the $np \rightarrow pn$ acceptance scan was done only for the MRS set at 0°.

The deuterons underwent multiple scattering and differential energy loss in the LH_2 target, causing the locus of $np \rightarrow d\pi^0$ 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 these variables. We modelled reaction kinematics, energy loss, and multiple scattering and used a χ^2 minimization program (MINUIT) to extract quantities of interest from yields binned as shown in Fig. 2. The c.m. differential cross section was expressed in terms of Legendre polynomials as $d\sigma/d\Omega = a_0P_0(\theta) + a_2P_2(\theta)$. The quantities fitted were: mean energy and energy spread of the neutron beam; total $np \rightarrow d\pi^0$ 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 $np \rightarrow pn$ cross sections we used the predictions of Arndt's SP88 phase shifts,[10] parametrized as

$$d\sigma/d\Omega_{\mathrm{c.m.}}(\mathrm{mb}) = [11.55 + (295 - T_n)/40][1 - T_n\theta_p^2/118000] ,$$

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

Total cross sections are presented in Fig. 3 and Table I. We have plotted also the $\pi^+d \rightarrow pp$ data of Rose[5] and a $pp \rightarrow d\pi^+$ cross section of Crawford and Stevenson.[4] 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.[11] Finally, for the pion absorption data we applied detailed balance. Our total cross sections follow very nearly the relationship

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

with $\alpha = 184 \pm 5$ μb and $\beta = 781 \pm 79$ μb (dotted line of Fig. 3). This is to be compared to Rose's fit to his data, $\alpha = 240 \pm 20$ μb and $\beta = 520 \pm 200$ μb (dashed line). Note, however, that these values were obtained using different Coulomb factors from Reitan's (see discussion below). The dash-dot curve is the "Standard-3" prediction of VBB.

Since our total cross sections are so well described by the two-term polynomial in η, it is tempting to assume that all and only s-wave strength is in the $\alpha\eta$ term and the p-wave strength in the $\beta\eta^3$ term. However, Blankleider[2] has calculated s-wave production strength to be energy dependent, below $\eta = 0.4$ having a form $\alpha_0[1-0.154\eta-1.714\eta^2]\eta$ with $\alpha_0 = 148\ \mu\text{b}$, and p-wave strength very nearly $\beta_0\eta^3$ with $\beta_0 = 1000\ \mu\text{b}$. This is quite close to what we measure, and if α_0 and β_0 are fitted to our data the agreement is as good as for the two-term polynomial fit (χ^2/d.o.f. $= 0.45$ in both cases), yielding $\alpha_0 = 186\pm5$ and $\beta_0 = 1170\pm70$. Thus Blankleider predicts higher ratios of p-wave to s-wave strengths than does the Watson-Brueckner model. We can use our data for differential cross section anisotropy 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 $a_2/a_0 = r/(1+r)$. In Fig. 4 we plot our data, along with the results obtained in a previous $np \to d\pi^0$ experiment by the Freiburg group.[12] Two of the curves are based on the ratios r obtained in Blankleider's calculation (solid line) or the Watson-Brueckner picture (dotted line). The Standard-3 calculation of VBB predicts a_2/a_0 as shown by the dash-dot curve. Our data clearly rule out the simple Watson-Brueckner model, but are consistent with both of the other calculations.

The success of the calculations shown 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 about a factor two.

The coefficient α which Rose[5] obtained by fitting his $\pi^+d \to pp$ data is (28 ± 11)% larger than the value we find from our $np \to d\pi^0$ measurement. It would be premature to claim that there is clear evidence of charge independence breaking, however, because of the problem of Coulomb corrections. The Coulomb barrier factors calculated by Reitan[11] are substantially larger than those of Rose, and if applied to the Rose data they result in a best-fit value of $\alpha = 214 \pm 16$ μb rather than the $\alpha = 240 \pm 20$ μb found using Rose's correction. It is quite possible that even the Reitan factor, which assumes point charges, overestimates the Coulomb suppression and more sophisticated calculations of Coulomb effects are very much needed.

A chain of experimental and theoretical relationships connects the present reaction to $\gamma p \rightarrow \pi^+ n$ and $\pi N \rightarrow \pi N$ cross sections (see Refs. 5 and 7). From the other reactions one predicts that the $NN \rightarrow d\pi$ cross sections should have $\alpha > 250$ μb; our near-threshold results call in question the assumptions and measurements forming that chain.

In summary, we have made precision measurements of $np \rightarrow d\pi^0$ cross sections within 8 MeV c.m. of threshold. The total cross sections 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 $\mathrm{fm.}^{-1}$ 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.

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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

Figure Captions

1. Schematic view of the CHARGEX neutron beam facility, liquid hydrogen target, and front detectors of the spectrometer.

2. Correlation of lab reaction angle *vs* momentum of deuterons detected at nominal neutron beam energy of 278 MeV.

3. Total $np \rightarrow d\pi^0$ 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. 5, and the cross from Ref. 4. The dashed and dotted lines are fits to the data, as described in the text. The dash-dot curve is the Standard-3 calculation of Ref. 3.

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. 12. The dotted line is the prediction of the Watson-Brueckner model (Ref. 1), the solid line that of Blankleider (Ref. 2), and the dash-dot line the Standard-3 prediction of VBB (Ref. 3).

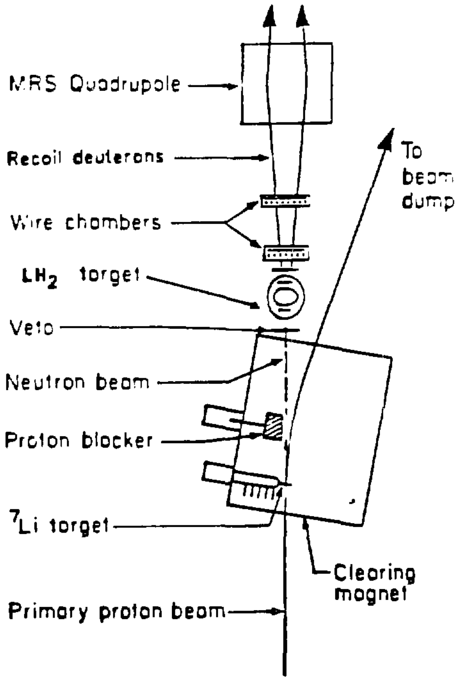

Fig. 1

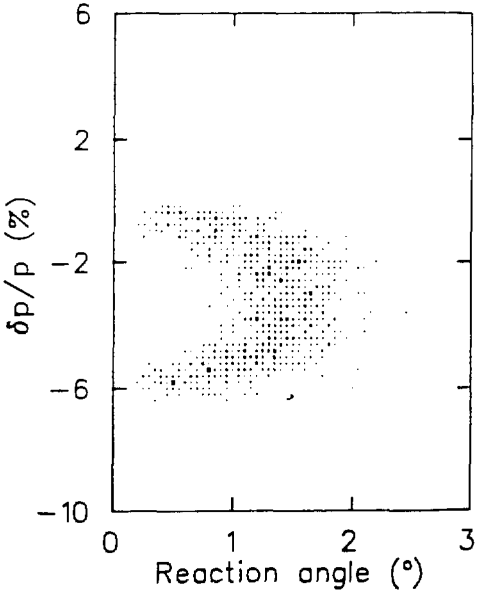

Fig. 2

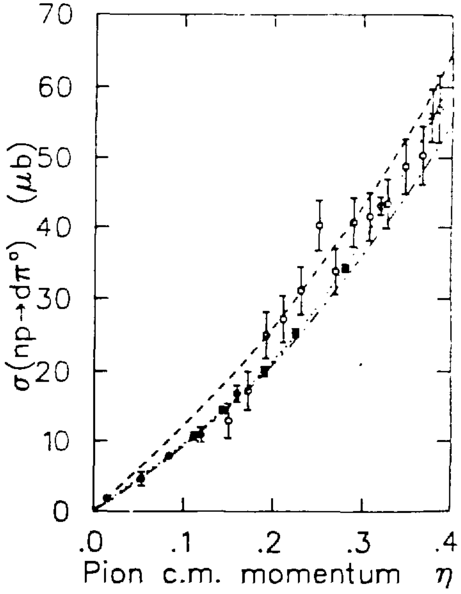

Fig. 3

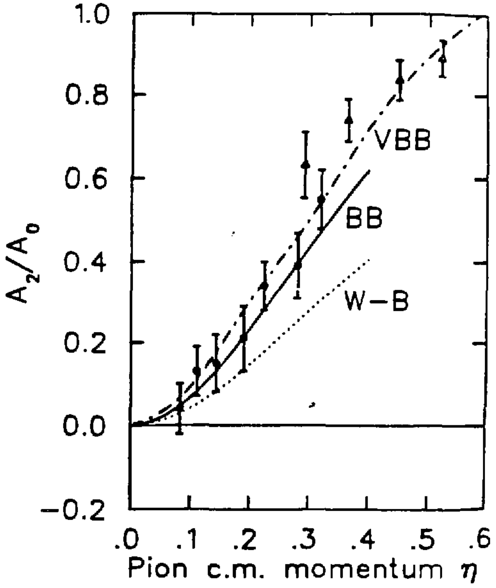

Fig. 4