Test of charge symmetry in the $np \rightarrow d\pi^0$ reaction at 795 MeV

C. L. Hollas, C. R. Newsom,* and P. J. Riley
University of Texas, Austin, Texas 78712

B. E. Bonner
Los Alamos National Laboratory, University of California, Los Alamos, New Mexico 87545

G. Glass
Texas A & M University, College Station, Texas 77843

(Received 09 March 1981)

The angular distribution for the $np \rightarrow d\pi^0$ reaction has been measured at 795 MeV from 2° to 178° center of mass to search for direct evidence for charge symmetry breaking forces. No evidence for an asymmetry about 90° is found to the order of $\pm 0.50\%$ for the integrated asymmetry parameter A_{fb}. Good agreement is obtained for the shape of the angular distribution with those for the $pp \rightarrow d\pi^+$ reaction near 800 MeV. Definite evidence is found for the f-wave pion-deuteron final state.

[NUCLEAR REACTIONS $np \rightarrow d\pi^0$, $E = 795$ MeV; measured $\sigma(\theta)$ deduced Legendre polynomial coefficient ratios: test of charge symmetry breaking forces of strong interaction.]

I. INTRODUCTION

A restricted definition of the charge independence of nuclear forces states that pp, np, and nn forces are equal to each other in the same space-spin states. If charge independence (CI) is valid, the Hamiltonian of the system must commute with the total isospin operator T^2;$[H,T^2]=0$. Charge symmetry (CS) requires the same behavior for a charge-reflected system as for the original one, and a charge symmetry operator P_{CS}, can be defined such that $[P_{CS},H]=0$ if CS is a valid symmetry. Charge symmetry implies the equality of nn and pp forces, but this is not a sufficient condition for CS, since the statement $[P_{CS},H]=0$ also has implications for the np system.

Henley and Miller[1] have characterized the charge dependence of nuclear forces according to their isospin dependence as follows:

Class (I): forces which are isospin invariant or charge independent; in this case any isospin dependence is proportional to $\vec{\tau}(1)\cdot\vec{\tau}(2)$, where $\tau(i)$ is the Pauli isospin operator for particle i.

Class (II): forces which maintain charge symmetry but break charge independence.

Class (III): forces which break both charge independence and charge symmetry of the form $V_{III}=d[\tau_3(1)+\tau_3(2)]$; a class (III) force differentiates between nn and pp systems, but does not give rise to transitions between states of different isospin in the two-body system.

Class (IV): forces which break both charge symmetry and charge independence; these cause transitions between states of different isospin. These forces are proportional to

$$V_{IV}=e[\tau_3(1)-\tau_3(2)]+f[\vec{\tau}(1)\times\vec{\tau}(2)]_3,$$

with $[V_{IV},T^2]\neq 0$. Both class (III) and class (IV) forces contribute to charge symmetry breaking (CSB) effects.

Although it is known that charge independence is not strictly valid, primarily due to the mass difference of neutral and charged mesons exchanged between nucleons, no clearcut violation of charge symmetry of nuclear forces has yet been detected.[2,3] As pointed out by Henley and Miller,[1] low energy $^1S_0$ N-N scattering lengths and effective ranges show a clear but small violation of charge independence, but within the experimental and theoretical uncertainties show no evidence for violation of charge symmetry.

Possibly the best indirect evidence for CSB forces comes from the comparison of binding energies of mirror nuclei, particularly ^{3}He-^{3}H. Brandenburg, Coon, and Sauer,[4] after examination of the binding energy difference for the ^{3}He, ^{3}H systems, concluded that 81 ± 29 keV of the experimental binding energy difference of 764 keV must be attributed to nuclear CSB forces; the rest is due to Coulomb forces. Friar and Gibson[5] deduced very nearly the same result. Another experimental manifestation of CSB forces would be the inequality of the nuclear part of the π^+ and π^--deuteron scattering cross sections. Pedroni *et al.*[6] measured the total cross sections for $\pi^+ d$ and $\pi^- d$ scattering in the energy range 70–370 MeV. After correcting their results for Coulomb effects of the order of 3%, they report energy dependent differences, also of a few percent, between the $\pi^+ d$ and $\pi^- d$ total cross sections at energies corresponding to formation of the pion-nucleon Δ resonance, indicating a violation of charge symmetry. In all of the above cases, it should be noted that large Coulomb effects must be calculated before the extraction of any CSB portions of the strong interaction. Differences between the *nn* and *pp* interactions, and the energy splitting of the mirror nuclei pair ^{3}He-^{3}H, can be attributed to class (III) type forces, since although class (IV) forces contribute in general to energy splittings of mirror nuclei, they vanish for $l = 0$ states, and, therefore, vanish for the ^{3}He-^{3}H pair. Myhrer and Pilkuhn[7] have discussed how the mass differences of the Δ^{++}, Δ^+, Δ^0, and Δ^- can lead to cross section differences for $\pi^+ d$ and $\pi^- d$ scattering at the energies reported by Pedroni *et al.*[6] Henley and Miller[1] discuss the effects of CSB in two pion exchange processes which lead to long range forces due to these mass differences.

Theoretical calculations have been carried out for two experiments which are sensitive to class (IV) CSB forces. The presence of CSB forces can be tested in *n-p* scattering by comparing the polarizations of the neutron elastically scattering at a c.m. angle θ with that of the proton at $(\pi - \theta)$ or in an experiment which compares the analyzing power for *np* scattering with that for *pn* scattering. Calculations indicate that polarization differences between the polarization of the neutron and the proton are due mainly to electromagnetic interactions (one-photon exchange), and are of the order of several tenths of a percent.[2] Cheung, Henley, and Miller[8] have also carried out theoretical calculations for the second experiment; the measurement of the angular asymmetry about 90° of deuterons produced in the $np \to d\pi^0$ experiment. They calculate a cross-section difference at the extremes of the angular distribution

$$\frac{\Delta\sigma}{\sigma} = \frac{\sigma(0) - \sigma(180)}{0.5[\sigma(0) + \sigma(180)]} \tag{1}$$

of 0.8% for neutrons incident at 577 MeV. The asymmetry arises mainly from the $\pi^0 - \eta^0$ mixing occurring through electromagnetic forces. Cheung[9] has carried out a similar calculation at 800 MeV for $\pi^0 - \eta^0$ mixing.

As first suggested by Yang,[10] if the strong interaction is charge independent (isospin conserving), the cross sections for the two reactions

$$pp \to d\pi^+ \ , \tag{2}$$

$$np \to d\pi^0 \tag{3}$$

must differ exactly by a factor of 2. That is, differential cross sections measured at the same center of mass energy for the two reactions must have the same angular dependence and differ only in magnitude. A comparison of the shapes of the two reactions requires accurate measurements for both reactions, as well as corrections for Coulomb effects and for (n,p) and (π^+,π^0) mass differences. Considering only the $np \to d\pi^0$ reaction, if CSB forces are not present, the $np \to d\pi^0$ angular distribution must be symmetric about 90°, since for reaction (2) identical particles are in the entrance channel. Cheung, Henley, and Miller[8] show that the presence of either class (III) or class (IV) CSB forces leads to an asymmetry about 90 degrees. This test of the asymmetry about 90°, which we report on here in a measurement of the full angular distribution from 2 to 178 degrees at 795 MeV, does not rely on any other measurement, or upon Coulomb corrections, and so provides a direct test for charge symmetry breaking forces.

In 1952 Hildebrand[11] reported the first measurement of the $np \to d\pi^0$ angular distribution, and found no asymmetry about 90°. The most accurate recent $np \to d\pi^0$ measurements are those of Bartlett *et al.*[12] and of Wilson *et al.*[13] However, Bartlett *et al.* were not able to detect the need for a $\cos^4\theta$ term to fit their $np \to d\pi^0$ data. Wilson *et al.* were able to place an upper limit of about 1% on the real part of the ratio of isospin violating to isospin conserving amplitudes.

Both of the measurements of Refs. 12 and 13 used a continuum neutron beam. Due to the reaction kinematics, deuterons corresponding to center-of-mass angles both greater and less than 90° are emitted into a forward cone in the laboratory system. In some regions ambiguities exist in determining the correct c.m. angle associated with an event. These ambiguities can be avoided if a monokinetic neutron beam is used. The development at the Clinton P. Anderson Meson Physics Facility (LAMPF) of an intense, nearly monokinetic neutron beam[14] has enabled the $np \to d\pi^0$ angular distribution to be measured with greater precision than had been previously obtained.

II. EXPERIMENTAL METHOD

The $np \to d\pi^0$ angular distribution measurement was carried out using the neutron beam produced at zero degrees from an 800 MeV proton beam from LAMPF, incident on a liquid deuterium target. The experimental apparatus, shown in Fig. 1, is located in the nucleon-physics laboratory at LAMPF, and has been described in detail previously.[15] The neutron beam was collimated by a steel circular collimator to approximately 2.5 cm in diameter. The relative intensity of the neutron beam was continuously monitored with a pair of range telescopes, each composed of two scintillators, with 4.6 cm of copper absorber between them. These telescopes viewed from equal angles to the left and right of the beam a 0.64 cm thick sheet of CH_2 which totally encompassed the beam. A thin 0.16 cm scintillator placed upstream of the CH_2 vetoed counts registered in the telescopes due to charged particles in the neutron beam. After the neutron monitor assembly, a dipole magnet $M1$ swept the neutron beam clear of charged particles. The momentum spectrum of the neutron beam is shown in Fig. 2.

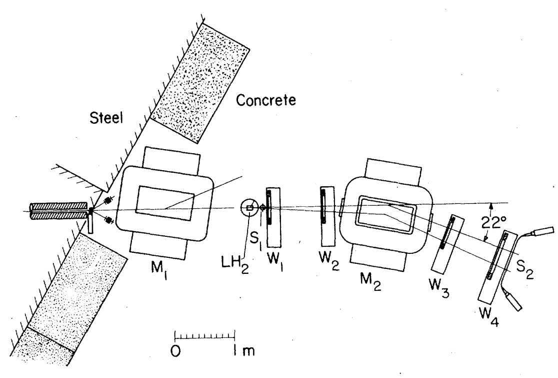

FIG. 1. The experimental apparatus used in the $np \to d\pi^0$ angular distribution measurement. M_1 clears the neutron beam of charged particles; LH_2 is the liquid hydrogen scattering target; $S1$ and $S2$ are thin scintillators; $W1$, $W2$, $W3$, and $W4$ are the multiwire proportional chambers. $M2$ is the spectrometer magnet.

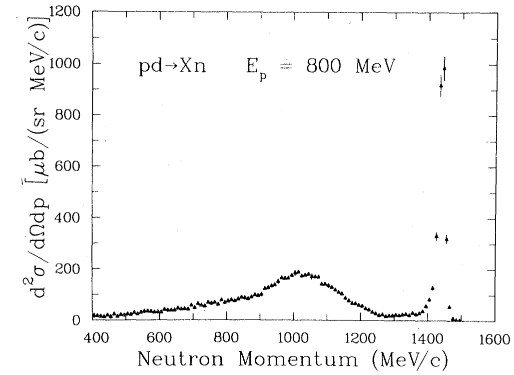

FIG. 2. The neutron momentum spectrum from 800 MeV protons incident on a liquid deuterium target at zero degrees. Only neutrons from the sharp "charge-exchange" peak near 1450 MeV/c were used in the measurement.

Neutron time-of-flight measurements allowed the selection of events initiated only by neutrons within the sharp high momentum peak of the neutron spectrum. For each neutron initiating an event the relative flight time from the liquid deuterium target to the liquid hydrogen target was determined by measuring the time difference between events in scintillator $S1$ and a signal obtained from the accelerator RF. A small correction for the charged particle flight time from the liquid hydrogen target to the scintillator $S1$ was subsequently made using the velocity of the charged particle determined with the spectrometer. The proton beam was prepared in a chopped mode, providing approximately 40 nsec between proton beam pulses instead of the usual 5 nsec.

After passing through $M1$, the neutron beam struck a liquid hydrogen target of 0.04 g/cm^2 areal density and the emitted charged particles were momentum analyzed in the spectrometer. The pressure of the liquid hydrogen target was continuously monitored and regulated to 690 Pa. Mass identification of the charged particles was provided by simultaneous measurement of the momentum and the flight time between scintillators $S1$ and $S2$. Figure 3 illustrates the mass spectrum obtained. Unambiguous mass determination was possible for greater than 99.9% of the events.

The experiment consisted of the measurement of deuteron momentum and angle in the $np \to d\pi^0$ reaction. A deuteron momentum spectrum binned over the laboratory angles from 0 to 4 degrees is shown in Fig. 4. The peaks near 1600 MeV/c and 850 MeV/c momenta result from deuterons from the $np \rightarrow d\pi^0$ reaction, emitted near 0° and 180°, respectively, in the center of mass. The difference in size of the two peaks results from the difference in the Jacobians which translate the laboratory cross sections to the center of mass. The momentum region between the peaks contains deuterons associated with double pion production.[16] All the $np \rightarrow d\pi^0$deuterons are emitted in the forward direction into a cone of a half angle of approximately 15°, and since the spectrometer has an angle acceptance of approximately 4°, it was possible to measure the full deuteron angular range with four positions of the spectrometer.

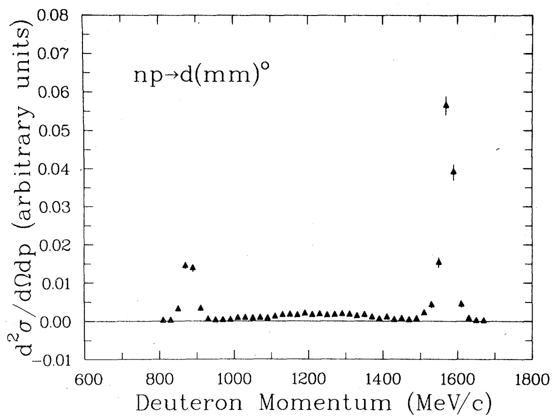

FIG. 4. A deuteron momentum spectrum obtained near 4 degrees. The two peaks near 850 and 1550 MeV/c result from the $np \rightarrow d\pi^0$ reaction for deuterons emitted near 180 and 0 degrees, respectively, in the center of mass. The deuterons between the two peaks result from double pion production.

III. RESULTS AND DISCUSSION

A. Corrections to the data

The beam chopper at the ion source allowed some contamination from beam bursts 1 micropulse ($\simeq$ 5 nsec) on either side of the main beam pulse; that is, a small satellite burst was present on either side of the main burst. The neutron flight path length from the liquid deuterium to the liquid hydrogen target was such that any 490 MeV neutrons produced by protons in the early beam satellite would arrive at the liquid hydrogen target at the same time as 795 MeV neutrons from the main beam burst; these 490 MeV neutrons would produce $np \rightarrow d\pi^0$ deuterons at a laboratory angle near 11° with a momentum of 950 MeV/c, kinematically indistinguishable from deuterons near 11° produced by 795 MeV neutrons as shown in Fig. 5. To minimize events caused by 490 MeV neutrons, the beam chopper was adjusted to minimize the size of the early beam satellite. The relative sizes of the beam satellites were monitored in the off-line analysis by means of the $np \rightarrow pn$ elastic scattering reaction which was measured simultaneously with the $np \rightarrow d\pi^0$ reaction. A two parameter plot of neutron flight time versus proton momentum showed the satellite peaks clearly resolved from the main burst for the high momentum charge exchange protons. An on line monitor of the satellites enabled the size of the early satellite to be kept at less than

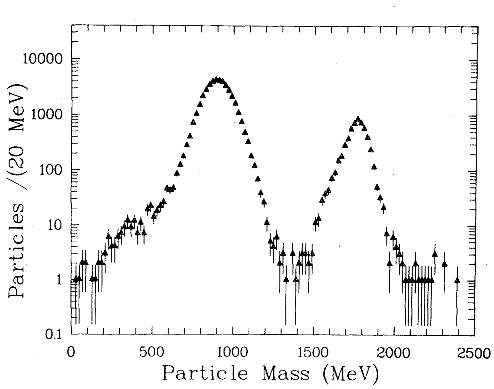

FIG. 3. The mass spectrum obtained with the spectrometer for charged particles resulting from all incident neutron momenta. Protons and deuterons are unambiguously separated.

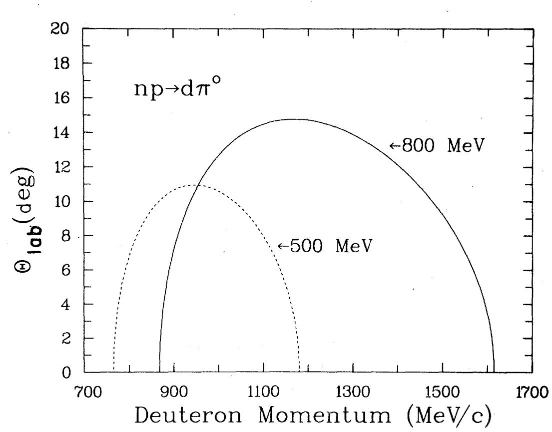

FIG. 5. The two-body reaction kinematics showing deuteron laboratory momentum versus angle for the $np \rightarrow d\pi^0$ reaction at 800 and 500 MeV. Note that near 11 degrees, deuterons from both incident energies appear with the same momentum.

0.7% that of the main peak. In order to correct for deuterons produced by contamination resulting from the early satellite, cross sections from the measurements of Aebischer *et al.*[17] were used; the resulting correction for the $np \rightarrow d\pi^0$ deuteron yield for 795 MeV for a laboratory angle near 11° was 3%. A further correction was applied to the neutron monitor yields, since the monitors were not able to distinguish neutrons in the main burst from those from satellite bursts. This correction, namely the percentage of neutrons resulting from the satellite proton bursts, ranged from 0.7% to 1.8%.

Target empty runs were made at all angles to provide data for background subtraction. This background resulted primarily from deuteron producing reactions in the Mylar entrance and exit walls of the liquid hydrogen flask, and varied from $< 3\%$ at the larger angular positions to $\simeq 13\%$ at 0 degrees. Dead time effects in the data acquisition were accounted for and ranged from 4% to 11%.

Some deuterons were lost primarily due to breakup in traversing the liquid hydrogen target and spectrometer. The fraction lost is momentum dependent and this leads directly to an angle dependent error which is manifest as an asymmetry in the center-of-mass cross section. Two prescriptions have been used in the past to calculate the magnitude of the effect. In one case[13] the deuteron-nucleus total cross section is built up from the neutron- and proton-nucleus cross sections, multiplied by a screening factor: $\sigma_{dA} = (\sigma_{nA} + \sigma_{pA}) \times 0.97$. The nucleon-nucleus cross sections are given by $\sigma_{NA} = [(A - Z)\sigma_{Nn} + Z\sigma_{Np}] \times [1 - 0.155A^{0.26}]$. The data for the nucleon-nucleon total cross sections are taken from the compilation in Ref. 18. An alternative method[19] approximated the cross section for the various materials as $\sigma_{dA} = \sigma_{dN}A^{2/3}$. Using the parametrization of the total nucleon-deuteron cross section given by Seagrave,[20] the two prescriptions agreed for our particular application to within $\pm 0.3\%$ over the range of deuteron momenta covered. The correction ranged from 1.3% to 4.2%.

The angular and momentum resolutions of the spectrometer were not adequate to resolve the $np \rightarrow d\pi^0$ deuterons from contamination due to the $np \rightarrow d\gamma$ reaction, except near the kinematic angular limit. Corrections were made for this contamination by subtracting $np \rightarrow d\gamma$ cross sections from the data. The $np \rightarrow d\gamma$ cross sections were obtained by using detailed balance to transform the 405 MeV $\gamma d \rightarrow np$ cross sections of Keck and Tollestrup[21] to the equivalent ~ 800 MeV $np \rightarrow d\gamma$ cross sections. For these corrections the neutron flux and target thickness factors were estimated from the absolute $np \rightarrow d\pi^0$ cross sections, which were assumed to be one half the $pp \rightarrow d\pi^+$ cross sections of Ref. 22. The $np \rightarrow d\gamma$ corrections varied from $< 0.1\%$ near 170° c.m. to $\simeq 0.5\%$ near 70° c.m. The other deuteron producing reaction, $np \rightarrow d(\pi\pi)^0$, was easily separated kinematically from the single pion production reaction over the whole angular range.

B. $np \rightarrow d\pi^0$ angular distribution data

For each event, the deuteron center-of-mass angle was calculated from a combination of the measured neutron flight time, and deuteron laboratory angle and momentum. The neutron momentum was determined from the flight time to ~ 25 MeV/c, the deuteron momenta to $\sim 1\%$, and the deuteron angle to ~ 6 mrad. The events were then binned directly in the center of mass in angular bins of three degrees. The relative differential cross sections are listed in Table I. The measured angular distribution is shown in Fig. 6, with $\theta_{\text{c.m.}}$ being that of the deuteron. The symbol ∇ (Δ) indicates data for angles less than (greater than) 90° c.m. The errors shown are statistical only. The solid curve is a sixth order Legendre polynomial fit to the data, using even orders only. The coefficients are listed in Table II. The inclusion of the sixth order term improves the quality of the fit significantly.

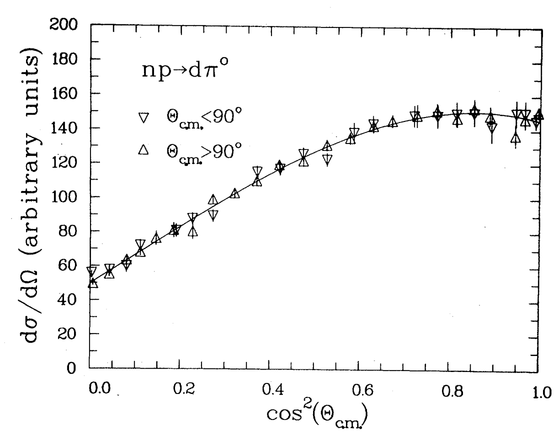

FIG. 6. The angular distribution for the $np \rightarrow d\pi^0$ reaction measured in the present experiment, plotted versus $\cos^2(\theta_{\text{c.m.}})$ with $\theta_{\text{c.m.}}$ that of the deuteron. the symbol ∇ (Δ) is for center of mass angles less than (greater than) 90 degrees. The solid line represents the 6th order Legendre polynomial fit which best describes the data.

TABLE I. Relative differential cross sections for the $np \to d\pi^0$ reaction at 795 MeV, normalized to provide a maximum value of 1.0. $\theta_{c.m.}$ is that for the deuteron. The errors are statistical only.

$\theta_{c.m.}$ (deg)	$\cos^2(\theta_{c.m.})$	$d\sigma/d\Omega \pm \Delta d\sigma/d\Omega$ (relative units)	
2.01	0.999	0.985	0.071
4.64	0.993	0.948	0.041
7.62	0.982	0.870	0.042
10.54	0.967	0.949	0.046
13.35	0.947	0.950	0.049
19.14	0.893	0.899	0.056
22.52	0.853	0.949	0.046
25.55	0.814	0.947	0.045
28.53	0.772	0.939	0.044
31.51	0.727	0.943	0.045
33.40	0.697	0.929	0.081
37.53	0.629	0.908	0.032
40.05	0.586	0.876	0.038
43.49	0.526	0.776	0.025
46.52	0.473	0.796	0.024
49.50	0.422	0.740	0.024
52.48	0.371	0.729	0.024
58.50	0.273	0.567	0.023
61.54	0.227	0.556	0.021
64.11	0.191	0.512	0.025
70.53	0.111	0.456	0.023
73.51	0.081	0.379	0.023
76.49	0.055	0.373	0.022
79.53	0.033	0.357	0.021
82.51	0.017	0.356	0.021
85.43	0.006	0.341	0.021
88.52	0.001	0.356	0.012
91.50	0.001	0.314	0.011
94.48	0.006	0.321	0.012
97.52	0.017	0.308	0.011
100.50	0.033	0.328	0.012
103.48	0.054	0.371	0.012
106.51	0.081	0.402	0.014
109.49	0.111	0.431	0.014
112.47	0.146	0.482	0.026
115.51	0.185	0.513	0.028
118.49	0.227	0.508	0.029
121.47	0.272	0.628	0.015
124.50	0.321	0.651	0.015
127.48	0.370	0.695	0.016
129.55	0.405	0.844	0.063
130.46	0.421	0.747	0.020
133.50	0.474	0.771	0.020
136.48	0.526	0.829	0.020
139.46	0.577	0.856	0.022
142.50	0.629	0.900	0.022
145.02	0.671	0.920	0.023
148.45	0.726	0.941	0.041
150.69	0.760	0.883	0.066

TABLE I. *(Continued).*

$\theta_{c.m.}$ (deg)	$\cos^2(\theta_{c.m.})$	$d\sigma/d\Omega \pm \Delta d\sigma/d\Omega$ (relative units)	
151.49	0.772	0.974	0.030
154.47	0.814	0.929	0.031
156.07	0.835	0.952	0.118
157.45	0.853	0.967	0.035
160.49	0.888	0.940	0.035
166.44	0.945	0.868	0.043
169.42	0.966	0.927	0.034
172.40	0.982	0.970	0.043
175.38	0.994	1.000	0.060
178.02	0.999	0.937	0.027

C. Tests for symmetry about 90° c.m.

The results of Cheung's calculations at 800 MeV lead to any asymmetry about 90° c.m. which can be parametrized

$$\begin{aligned}\Delta\sigma(\theta) &= [\sigma(\theta) - \sigma(\pi-\theta)] \\ &= [0.277P_1 + 0.204P_3 + 0.036P_5] \\ &\quad \times 10^{-3}\text{mb}/sr \ ,\end{aligned} \tag{4}$$

where P_i are normalized Legendre polynomials. Bartlett *et al.*[12] have argued that the important CSB transitions from the initial isospin 0 part of the np system to the final isospin 1 $\pi^0 d$ system are

$$\begin{aligned}a_1 &= {}^1P_1 \rightarrow {}^3S_1 \ , \\ a_2 &= {}^1P_1 \rightarrow {}^3D_1 \ , \\ a_3 &= {}^1F_3 \rightarrow {}^3D_3 \ .\end{aligned} \tag{5}$$

These transitions interfere with the dominant charge symmetry conserving transition $a_0 = {}^1D_2 \rightarrow {}^3P_2$, which gave the angular distribution the dominant shape of a second order Legendre polynomial. This interference gives rise to odd orders of Legendre polynomials in the angular distribution.

We have applied least squared fits to the present data using the functional form

$$\frac{d\sigma}{d\Omega} = \sum_i A_i P_i \ . \tag{6}$$

Odd powers of P_i, from one to five, as well as the form for $\Delta\sigma(\theta)$ from above, were used to search for asymmetry about 90° c.m. The result of the searches are tabulated in Table II as ratios of each Legendre coefficient to the zeroth order coefficient A_0. Each row in Table II contains the results from a separate least squares fit in which the free coefficients are those with nonzero entries. Data points near 90° c.m. were observed to have consistently high χ^2 contributions in the fits. All searches were repeated after removing four points from the data on either side of 90°. The results of these searches are presented as the last three entries in Table II. We observe no statistically significant odd order of Legendre polynomial, except perhaps for A_5/A_0 in the first group of coefficients. With the data points near 90° removed, A_5/A_0 is consistent with zero. The seventh column in Table II lists the degree with which the data agrees with the results for Cheung for $\Delta\sigma(\theta)$ at 800 MeV. A value of $+1.0$ would indicate complete agreement. For this comparison we have assumed that $\sigma(np \rightarrow d\pi^0) = \frac{1}{2}\sigma(pp \rightarrow d\pi^+)$ of Ref. 22. Note that the maximum predicted value of $\Delta\sigma(\theta)$ occurs at 0° and is equal to ~ 0.5 μb/sr. To detect an asymmetry of this size would require the coefficient ratio for the odd P_i to be determined to better than ± 0.005, about double the precision of the present experiment.

An asymmetry about 90° can also be expressed as a forward-to-backward cross section ratio A_{fb}, where

$$\begin{aligned}A_{fb} &= \left[\int_0^{\pi/2} \sigma d\Omega - \int_{\pi/2}^{\pi} \sigma d\Omega\right] \\ &\quad \times \left[\int_0^{\pi/2} \sigma d\Omega + \int_{\pi/2}^{\pi} \sigma d\Omega\right]^{-1} \ .\end{aligned} \tag{7}$$

The results for A_{fb} from the present experiment are also listed in Table II as percentages. Again, except for A_{fb} calculated from the A_5/A_0 coefficient of the

TABLE II. Legendre polynomial coefficient ratios to the zeroth order coefficient obtained from a least squares fit to the data of the present experiment. Each row in Table II contains the results from a separate least squares fit in which the free coefficients are those with nonzero entries. The last three entries are for the case where four data points on both sides of 90° were deleted. The column $A_{\Delta\sigma}$ indicates the extent of agreement with which the fore-aft asymmetry is described with Cheung's calculation at 800 MeV. A value of +1.0 would imply complete agreement. The column labeled χ^2/ν indicates the total chi-square of the fit divided by the number of degrees of freedom. The last column labeled A_{fb} lists the results for the total asymmetry parameter (in percent) calculated for each odd Legendre polynomial coefficient.

A_2/A_0	A_4/A_0	A_6/A_0	A_1/A_0	A_3/A_0	A_5/A_0	$A_{\Delta\sigma}$	χ^2/ν	A_{fb}
0.809 ± 0.011	-0.250 ± 0.013	0	0	0	0	0	1.27	0
0.827 ± 0.012	-0.247 ± 0.013	-0.071 ± 0.017	0	0	0	0	1.03	0
0.826 ± 0.012	-0.247 ± 0.013	-0.071 ± 0.017	-0.003 ± 0.010	0	0	0	1.06	-0.15 ± 0.50
0.824 ± 0.012	-0.249 ± 0.013	-0.071 ± 0.017	0	-0.011 ± 0.014	0	0	1.03	$+0.14 \pm 0.18$
0.824 ± 0.012	-0.244 ± 0.013	-0.067 ± 0.017	0	0	-0.019 ± 0.016	0	1.02	-0.12 ± 0.10
0.824 ± 0.012	-0.249 ± 0.013	-0.069 ± 0.017	-0.003 ± 0.010	-0.011 ± 0.014	0	0	1.05	
0.824 ± 0.012	-0.247 ± 0.013	-0.067 ± 0.017	-0.004 ± 0.010	0	-0.020 ± 0.016	0	1.03	
0.820 ± 0.012	-0.245 ± 0.013	-0.065 ± 0.017	0	-0.013 ± 0.014	-0.021 ± 0.016	0	1.02	
0.820 ± 0.012	-0.245 ± 0.013	-0.064 ± 0.017	-0.005 ± 0.010	-0.013 ± 0.014	-0.022 ± 0.016	0	1.04	
0.826 ± 0.012	-0.248 ± 0.013	-0.070 ± 0.017	0	0	0	-0.818 ± 1.602	1.05	-0.09 ± 0.18
0.831 ± 0.015	-0.257 ± 0.017	-0.057 ± 0.020	-0.007 ± 0.010	0	0	0	0.72	-0.35 ± 0.50
0.831 ± 0.015	-0.257 ± 0.020	-0.057 ± 0.020	0	$+0.002 \pm 0.014$	0	0	0.73	$+0.03 \pm 0.18$
0.831 ± 0.015	-0.257 ± 0.020	-0.057 ± 0.020	0	0	-0.002 ± 0.17	0	0.73	-0.01 ± 0.10

first group, we find in the worst case $A_{fb} = -(0.15 \pm 0.50\,\%)$ when a first order Legendre polynomial is used, that is, A_{fb} is consistent with zero. Bartlett *et al.*[12] quoted a determination of $A_{fb} = 1.0 \pm 2.8\,\%$, and Wilson *et al.*[13] averaged results taken at eight energies to obtain $A_{fb} = -(0.36 + 0.66\,\%)$, with A_{fb} determined at each energy to no better than 1.6%. Wilson's results for A_{fb} must be considered questionable in view of the disagreement between the shapes of the angular distributions of Wilson *et al.* with recent results for $\pi^+ d \to pp^+$ (Refs. 23 and 24) and $np \to d\pi^0$ (Ref. 25) measurements. Cheung, Henley, and Miller[8] deduced a theoretical value at 577 MeV of $A_{fb} = 0.16\%$, and at 800 MeV, Cheung's calculation predicts that $A_{fb} = 0.11\%$.

D. Comparisons with $pp \to d\pi^+$ angular distribution data near 800 MeV

If charge independence is valid, then at the same center-of-mass energy the differential cross sections at each angle for the $np \to d\pi^0$ reaction should be exactly one half that for the $pp \to d\pi^+$ reaction. Neutron-proton and $\pi^+ - \pi^0$ mass differences, and Coulomb effects would affect this equality. Absolute cross-section values were not determined in the present measurement. It is possible, though, to compare the shape of our $np \to d\pi^0$ angular distribution to $pp \to d\pi^+$ data sets near 800 MeV. In Fig. 7 are illustrated the $\pi^+ d \to pp$ data of Richard-Serre *et al.*,[26] which corresponds to an equivalent proton energy of 810 MeV (□), the 800 MeV $pp \to d\pi^+$ data of Mutchler *et al.* (◇),[27] and the 800 MeV $pp \to d\pi^+$ data of Nann *et al.* (○).[22] We have multiplied each data set by a normalization constant to provide a better visual comparison of the shape of the data sets to the solid curve. The solid curve represents the angular distribution of the present $np \to d\pi^0$ measurement and is calculated from the sixth order even coefficients of Table II. Qualitatively, there is excellent agreement between the curve and the $pp \to d\pi^+$ data sets. To make a more quantitative comparison we examine the coefficients of Legendre polynomial fits which describe these $pp \to d\pi^+$ data. Since the authors of Refs. 22 and 26 did not use a sixth order term to describe their data, we have refitted these data and list the resulting coefficient ratios in Table III. No further comparison with the data of Ref. 27 is made since the five data points are insufficient to support a sixth order fit.

The result of the comparison, displayed in Table III, shows that there is complete agreement between our $np \to d\pi^0$ data and the data of Richard-Serre *et al.*,[26] and small disagreements, just outside the errors, with the results of the more precise data of Nann *et al.*[22] These small differences may reflect effects due to the $n-p$ and $\pi^+ - \pi^0$ mass differences, and the Coulomb forces present in the initial and final states for the $pp \to d\pi^+$ reaction, but absent in the $np \to d\pi^0$ reaction. Kohler[28] has calculated such angle dependent effects on the value of the ratio for the cross sections $\sigma(pd \to {}^3\mathrm{H}\pi^+)/\sigma(pd \to {}^3\mathrm{He}\pi^0)$ at a proton energy of 600 MeV. A similar calculation for the present reactions would be valuable.

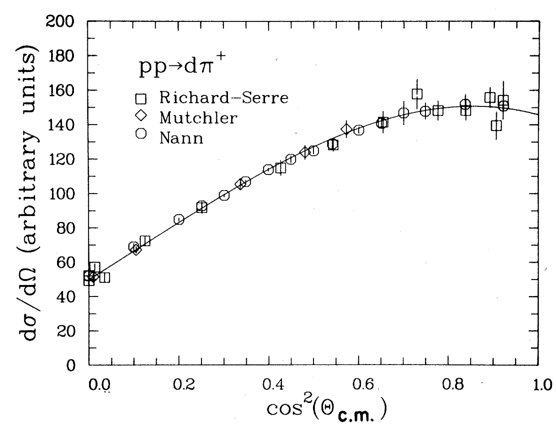

FIG. 7. Angular distributions for $\pi^+ d \to pp$ [Richard-Serre (Ref. 26)] and $pp \to d\pi^+$ [Mutchler (Ref. 27) and Nann (Ref. 22)] for proton energies near 800 MeV. The solid line represents the 6th order Legendre polynomial fit which best describes the $np \to d\pi^0$ data of the present experiment.

TABLE III. Legendre polynomial coefficient ratios to the zeroth order coefficient obtained from a least-squares fit to the data of Refs. 22 and 26, as well as for the present experiment.

A_2/A_0	A_4/A_0	A_6/A_0	Reference
0.805 ± 0.024	-0.188 ± 0.036	0	26
0.810 ± 0.024	-0.212 ± 0.040	-0.067 ± 0.048	
0.804 ± 0.015	-0.213 ± 0.016	0	22
0.795 ± 0.016	-0.213 ± 0.016	-0.047 ± 0.020	
0.809 ± 0.011	-0.250 ± 0.013	0	This work
0.827 ± 0.012	-0.247 ± 0.013	-0.071 ± 0.017	

TABLE IV. A, B, and C coefficients for the expression of even-powers of $\cos\theta$ which describe the $np \rightarrow d\pi^0$ angular distribution of the present experiment. Note the drastic change in the coefficients when the order of the fit is increased to include a $\cos^6\theta$ term.

A	B	C
0.232 ± 0.003	-0.510 ± 0.009	0
0.308 ± 0.004	$+0.239 \pm 0.060$	-0.650 ± 0.066

E. Comparisons with $NN - d\pi$ angular distribution data

Legendre polynomials including sixth order best describe the present data. Inclusion of an eighth order term destabilizes the solution, with the leading coefficients becoming poorly determined and changing drastically. Traditionally, a functional form involving powers of $\cos\theta$ has been used to fit the data below 1000 MeV.[29] With a $\cos^6\theta$ term included, the expression has the form

$$\frac{d\sigma}{d\Omega} = K(A + \cos^2\theta + B\cos^4\theta + C\cos^6\theta) \ . \quad (8)$$

Theoretical calculations have recently appeared which give the energy dependence of the A and B coefficients for the above expression.[30] To facilitate comparison of the present data with other data sets

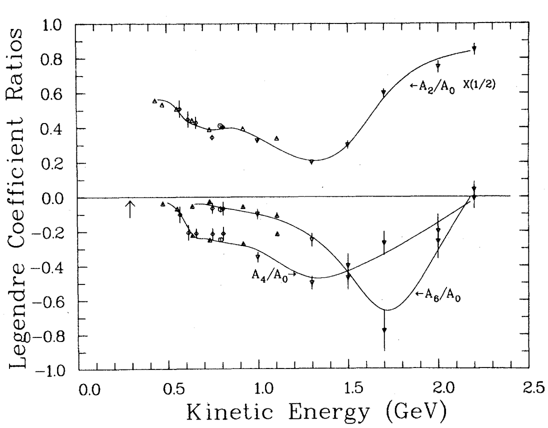

FIG. 8. The energy dependence of the Legendre polynomial coefficient ratios A_2/A_0, A_4/A_0, and A_6/A_0 for the best fits to data of Refs. 24 (Δ), 26 ($\square$), and 31 (∇) and the present experiment ($\circ$). The data of Refs. 24 and 26 have been converted to the equivalent $pp \rightarrow d\pi^+$ proton energy. The curves serve only to guide the eye.

and calculations we have fitted our data using the above functional form for both up to fourth and sixth orders, and list the results in Table IV. Note that the addition of the sixth order term to the series alters significantly the lower order terms—the B coefficient changes from -0.510 to $+0.239$. This dramatic change simply reflects the nonorthogonality of the series of powers of $\cos\theta$, and indicates that the use of such a series to parametrize the data and results of theoretical calculations is misleading. We strongly recommend that the use of a power series in $\cos\theta$ be discontinued.

The presence of a sixth order Legendre polynomial implies that deuteron-pion angular momentum states of a least $l = 3$ are present. The data of Heinz *et al.*[31] has indicated the presence of f-wave pions between 1000 and 3000 MeV. Recent precision measurements at LAMPF[24] for the $\pi^+ d \rightarrow pp$ reaction also require the presence of a sixth order Legendre polynomial. The energy dependence of the Legendre polynomial ratios for the data of Refs. 24, 26, and 31, as well as the present measurements, are shown in Fig. 8. We have refitted the data of Ref. 26 at 750 MeV including a sixth order Legendre coefficient. Note that the scale for the A_2/A_0 is compressed by a factor of 2 with respect to the other ratios. The curves serve only to guide the eye. The arrow near 275 MeV indicates the $d\pi^+$ threshold. The results from the present measurements are shown at 795 MeV with the symbol Φ. The agreement of the present data with the trends indicated by the previous data is apparent. The A_6/A_0 coefficient is clearly nonzero at 795 MeV, and from the trend exhibited, this coefficient could persist to rather low energies. Thus, f-wave pions may be significant at energies below 800 MeV, and analyses which assume only s, p, and d wave pions may also be incorrect.

IV. SUMMARY AND CONCLUSIONS

We find no evidence of an asymmetry in $np \rightarrow d\pi^0$ angular distribution data about 90° c.m. at 795 MeV to the order of $\pm 0.50\%$, and, therefore, no evidence for CSB forces. The recent calculations of Cheung, Henley, and Miller,[8] and of Cheung[9] indicate that an asymmetry might exist at the level of $0.11\% - 0.16\%$. The detection of an asymmetry at this level will require an experiment with more than double the precision of the present measurement. Our work can be compared with the result of Pedroni *et al.*[6] who deduce CSB effects at the 1%

level in the measurement of $\pi^+ d$ and $\pi^- d$ total cross sections near the Δ (1232) resonance. It would appear that the CSB mechanisms are different in the two experiments.

We observe small differences between the shape of our $np \to d\pi^0$ angular distribution data and the $pp \to d\pi^+$ measurements of Nann *et al.*[22] The differences might result from $n - p$ and $\pi^+ - \pi^0$ mass differences, as well as from Coulomb effects. We find definite evidence for the f-wave pion deuteron final state at 795 MeV, and from the trend of the A_6/A_0 Legendre polynomial coefficient ratio, speculate that f-wave pions persist to lower energies.

ACKNOWLEDGMENTS

We have benefitted greatly at all stages of setup and performance of this experiment from the support of the staff of LAMPF. We give special thanks to Paul Allison and Ralph Stevens for the design and development of the LAMPF chopped-beam system. We express our gratitude to J. E. Simmons, L. C. Northcliffe, J. C. Hiebert, and others who participated in the development of the spectrometer system of the LAMPF Nucleon Physics Laboratory. This work was supported by the U. S. Department of Energy.

---

*Present Address: Laboratoire National Saturne, 91190 Gif-sur-Yvette, Cedex, France.

[1]E. M. Henley and G. A. Miller, in *Mesons in Nuclei,* edited by M. Rho and D. H. Wilkinson (North-Holland, Amsterdam, 1979), p. 406.

[2]C. Y. Cheung, E. M. Henley, and G. A. Miller, Nucl. Phys. A305, 342 (1978).

[3]E. M. Henley, in *Isospin in Nuclear Physics,* edited by D. H. Wilkinson (North-Holland, Amsterdam, 1969), p. 15.

[4]R. A. Brandenburg, S. A. Coon, and P. Sauer, Nucl. Phys. A294, 305 (1978).

[5]J. L. Friar and B. F. Gibson, Phys. Rev. C 18, 908 (1978).

[6]E. Pedroni *et al.*, Nucl. Phys. A300, 321 (1978).

[7]F. Myhrer and H. Pilkuhn, Z. Phys. A 276, 29 (1976).

[8]C. Y. Cheung, E. M. Henley, and G. A. Miller, Phys. Rev. Lett. 43, 1215 (1979); C. Y. Cheung, E. M. Henley, and G. A. Miller, Nucl. Phys. A348, 365 (1980).

[9]C. Y. Cheung (private communication).

[10]C. N. Yang (unpublished) (see Ref. 11).

[11]R. H. Hildebrand, Phys. Rev. 89, 1090 (1953).

[12]D. F. Bartlett *et al.*, Phys. Rev. D 1, 1984 (1970).

[13]S. S. Wilson, *et al.*, Nucl. Phys. B33, 253 (1971).

[14]C. W. Bjork *et al.*, Phys. Lett. 63B, 31 (1976).

[15]G. Glass *et al.*, Phys. Rev. D 15, 36 (1977).

[16]C. L. Hollas *et al.*, in *Nucleon-Nucleon Interactions—1977, (Vancouver),* Proceedings of the Second International Conference on Nucleon-Nucleon Interactions, edited by H. Fearing, D. Measday, and A. Strathdee (AIP, New York, 1978), p. 550.

[17]D. Aebischer *et al.*, Nucl. Phys. B108, 214 (1976).

[18]Particle Data Group, UCRL 20000 NN, 1970.

[19]H. L. Anderson *et al.*, Phys. Rev. D 3, 1536 (1971).

[20]J. D. Seagrave, *Proceedings of the First International Conference on the Three Body Problem in Nuclear and Particle Physics,* edited by J. S. C. McKee and P. M. Rolph (North-Holland, Amsterdam, 1970), p. 41.

[21]J. C. Keck and A. V. Tollestrop, Phys. Rev. 101, 360 (1956).

[22]H. Nann *et al.*, Phys. Lett. 88B, 257 (1979).

[23]B. Preedom *et al.*, Phys. Rev. C 17, 1402 (1978).

[24]Jonathan S. Boswell, thesis, University of Virginia, 1980 and (to be published.)

[25]W. Hurster *et al.*, Phys. Lett. 91B, 214 (1980).

[26]C. Richard-Serre *et al.*, Nucl. Phys. B20, 413 (1970).

[27]G. S. Mutchler *et al.*, *Nucleon-Nucleon Interactions—1977, (Vancouver),* Proceedings of the Second International Conference of Nucleon-Nucleon Interactions edited by H. Fearing, D. Measday, and A. Strathdee (AIP, New York, 1978), p. 556.

[28]H. S. Kohler, Phys. Rev. 118, 1345 (1960).

[29]F. Mandl and T. Regge, Phys. Rev. 99, 1478 (1955).

[30]J. A. Niskanen, Nucl. Phys. A298, 417 (1978); O. V. Maxwell, M. Weise, and M. Brack, *ibid.* A348, 388 (1980); J. Chai and D. O. Riska, *ibid.* A338, 349 (1980).

[31]R. M. Heinz *et al.*, Phys. Rev. 167, 1232 (1968).