Neutron-proton final-state interaction in πd breakup: Differential cross section

W. List, E. T. Boschitz, H. Garcilazo,* W. Gyles, C. R. Ottermann, R. Tacik, M. Wessler, and U. Wiedner
Kernforschungszentrum Karlsruhe, Institut für Kernphysik und Institut für Experimentelle Kernphysik der Universität Karlsruhe, D-7500 Karlsruhe, Federal Republic of Germany

R. R. Johnson
TRIUMF and University of British Columbia, Vancouver, Canada, V6T 2A3
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Threefold differential cross sections $\sigma(\theta_\pi,\theta_p,P_p)$ have been measured in a kinematically complete experiment. The experiment has been designed to extend earlier measurements into the kinematic region of the np final-state interaction. The data are compared with the predictions from the new relativistic Faddeev theory of Garcilazo.

I. INTRODUCTION

The final-state interaction between two nucleons has been of considerable interest for a long time. In low energy nuclear physics experiments the main effort was directed towards the extraction of nucleon-nucleon scattering parameters.[1] At higher energies the final state interaction has been considered responsible for discrepancies between quasifree NN scattering data and calculations based on simple knockout models.

The first direct observation of the neutron-proton final state interaction above 200 MeV came from the pd breakup reaction at $T_p=585$ MeV.[2] Later, this work was extended to 800 MeV.[3] In these kinematically complete experiments triple differential cross sections were measured for several proton-proton pairs, particularly in the region of phase space where the relative energy of the neutron-proton subsystem was low. The strong enhancement of the cross section in this region was analyzed applying the final state interaction formalism of Goldberger and Watson.[4] The spectra were fit with the incoherent sum of the final state interaction factor for singlet and triplet np final-state interaction plus a constant term. From this the authors extracted the individual contributions of the $^1S_0$ and $^3S_1$ np states and found a large $^3S_1/^1S_0$ ratio.

Strong effects due to the nucleon-nucleon final state interaction were also observed in nucleon-nucleon collisions above the pion production threshold. In the zero-degree measurements of the inclusive reaction $np\rightarrow pX$ between 400 and 800 MeV,[5] pronounced peaks were seen in the double differential cross section $d^2\sigma/d\Omega_p dP_p$ plotted as a function of the proton momentum. Similarly the exclusive cross section measurement of the $pp-\pi^+pn$ reaction[6] displayed strong np final state interaction peaks. The first theoretical calculations of these reactions did not include final state interaction effects with the exception of the field-theoretical peripheral model of VerWest,[7] which included the NN final state interaction only qualitatively and phenomenologically. Recently, Dubach, Kloet, and Silbar extended their unitary, unified model of NN and πNN interactions to include final state interaction corrections.[8] This was done following the Watson-Migdal final state interaction prescription by multiplying their NN-πNN reaction T matrix by a factor which incorporates the final state interaction in relative S waves. The authors were able to explain the peaks in the cross sections using $^1S_0$ and $^3S_1$ final state interactions. More recently, a unitary meson exchange calculation of the NN-πNN reaction was published by Matsuyama and Lee[9] in which the final state interaction was treated rigorously, but it was limited to the region near the final state peak. There the relative motion of the outgoing NN subsystem is low, and it is therefore sufficient to include only the $^3S_1-^3D_1$ and $^1S_0$ NN channels in defining the quasiparticle state "d." This calculation was able to reproduce both the shape and the position of the final state interaction peaks, but underestimated their magnitudes. It must be noted, however, that these results were not renormalized, as in the calculation of Dubach, Koet, and Silbar which involved an adjustable parameter to fit the data.

The np final state interaction in the πd breakup reaction was first observed by Bayukov *et al.*[10] Negative pions of 870 MeV were scattered by a CD_2 target, and pions and protons were detected by optical spark chambers. Due to the low count rate, the data were plotted as a single differential cross section as a function of neutron momentum. At large neutron momenta a simple quasifree πp scattering model failed, and the phenomenological addition of a np final state interaction was required. Similar effects were seen in a πd breakup experiment by Dakhno *et al.*,[11] who utilized a liquid deuterium bubble chamber for the detection of the pion and proton in the final state. The first kinematically complete measurement of πd breakup was performed by Hoftiezer *et al.*[12] Two extreme kinematical situations were emphasized in the experiment, one in which the outgoing neutron momentum is small and therefore the impulse term is expected to be dominant, the other where the outgoing neutron momentum is large in comparison to the deuteron internal momentum, and consequently processes other than the impulse term are expected to be important. But, no pronounced final state interactions were seen in this particular choice of phase space. Recently, Gyles et al.[13] measured the πd breakup cross section over a much larger region of phase space. The data were compared with calculations by Garcilazo[14] which were based on the relativistic Faddeev theory of Aaron, Amado, and Young.[15] In general, good agreement was found within the experimental uncertainties, even in the low cross section regions. (Recently, a numerical error was found in the theoretical calculation reported in Ref. 13, and almost simultaneously an error in the data reduction program was discovered, both of which cancel to a large extent in the OFS region.) Since then a novel relativistic Faddeev theory of the πNN system was developed by one of us,[16] which uses a variable-mass ansatz for the πN and NN amplitudes and the requirement that the spectator particles always be on the mass shell. Utilizing this theory a number of recent calculations showed that the np final state region is most sensitive to different theoretical descriptions.[17]

The motivation of the present work was to extend some of the existing data at 294 MeV into the region of low proton momentum where effects due to np final state interactions (FSI) are expected to be large, and compare them with theoretical predictions from Garcilazo.[16]

II. EXPERIMENTAL TECHNIQUE

The experimental setup is shown in Fig. 1. Pions from the $\pi M1$ beam line of the Swiss Institute for Nuclear Research (SIN) impinged on a liquid deuterium target. The outgoing pions and protons were detected in coincidence by scintillation counters. The arrangement specified the momentum of the incident pion, the azimuthal and polar angles of the outgoing pion and proton, and the momentum of the proton by a time-of-flight measurement. Therefore, the experiment was kinematically complete. The energy of the incident pions was $T_\pi = 294$ MeV. The average beam intensity during the experiment was 1.3×10^7 pion/s. The incident pions were detected by a scintillation counter hodoscope $S1$ and a beam defining counter $S2$. The hodoscope consisted of five scintillation strips ($0.2\times 1.0\times 10.0$ cm^3) and was placed 1.5 m upstream from the target. The beam defining counter with a 3 cm diameter hole in the center was operated as veto counter. A beam event was defined by BEAM$=S1\cdot S2\cdot$rf where rf is a radio frequency pickup signal from the accelerator. For a continuous stability check of the position, shape and intensity of the pion beam, two types of monitors were used: a 10 cm$\times$10 cm multiwire chamber as a beam profile monitor and a set of scintillation counters $M1$–$M3$. The profile monitor with an integrating readout was connected to an oscilloscope on which the X and Y profile of the beam was continuously displayed. The scintillation counters $M1$–$M3$ were arranged as a triple counter telescope and viewed the hodoscope $S1$ from an angle above the scattering plane.

The liquid deuterium target cell was disc shaped, 0.5 cm thick, and 10.6 cm in diameter. Deuterium gas ballast chambers on both sides of the cell separated the liquid target from the vacuum. The 36 μm Mylar foils of the target walls were prestretched. In a separate experiment it was shown that the deformation of the foils due to the hydrostatic pressure of the liquid deuterium was negligible.

The outgoing pions were detected at $\theta_\pi = 110.0°$, 125.0°, and 141.0° by scintillation counter telescopes. Each telescope consisted of a counter $\pi1$ ($0.3\times 6.0\times 16.0$ cm^3) at a distance of 50 cm and a counter $\pi2$ ($0.5\times 10.0\times 30.0$ cm^3) at 100 cm from the target center.

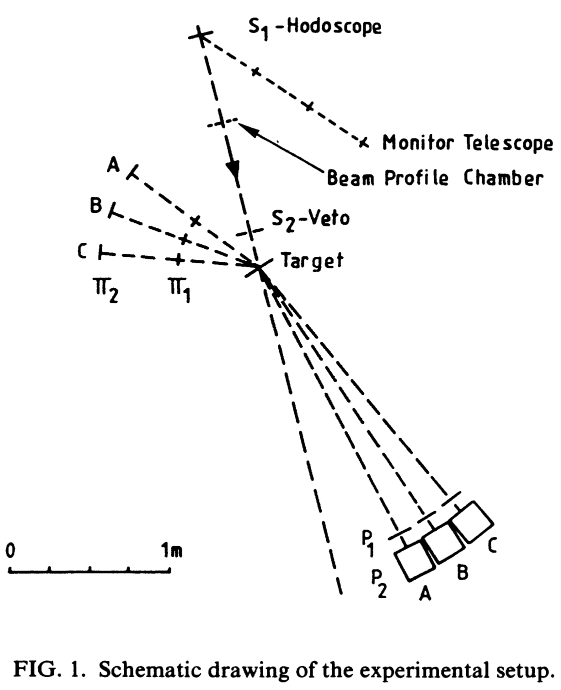

FIG. 1. Schematic drawing of the experimental setup.

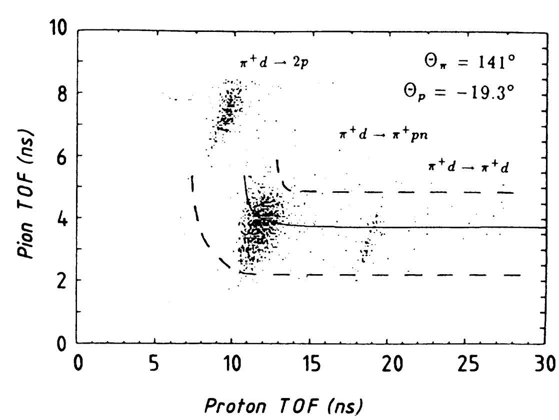

FIG. 2. Density plot of the scattering events. The solid line presents the kinematic locus for the πd breakup reaction, the dashed lines show the kinematic cuts applied for the data reduction.

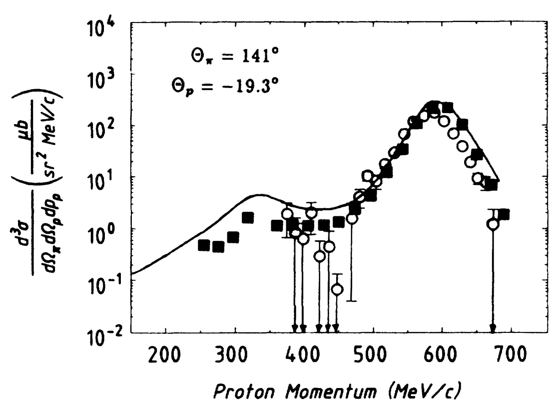

FIG. 3. Comparison of the cross section data from this experiment (solid squares) with the ones from Ref. 13 (open circles).

The latter one defined the time of flight. Therefore this scintillator was viewed by two photomultipliers, one on each end.

The outgoing protons were detected at $\theta_p = -13.3°$, $-19.3°$, and $-25.3°$ (the conjugate angles for πp kinematics) by detectors each composed of two scintillation counters. Counter $p1$ ($0.5\times20.0\times70.0$ cm^3) positioned at a distance of 1.88 m from the target and counter $p2$ ($20.0\times20.0\times70.0$ cm^3) 12 cm behind formed a detection system with E and ΔE information in addition to the time of flight. The counters were viewed by two photomultipliers each. This system permitted a clean separation of competing reactions like $\pi^+ d \to \pi^+ d$ or $\pi^+ d \to 2p$. The detection angles for pions and protons were chosen in such a way as to produce an overlap with earlier data taken with a different setup,[13] and to completely cover the final state interaction region at low proton momenta. The electronics setup permitted coincidences between each proton and each pion arm. The time of flight was calibrated using the πp elastic scattering reaction from the hydrogen in the Mylar foils. The time-of-flight resolution amounted to 0.8 ns FWHM. The data analysis was performed similar to the one described in the earlier publication.[13] Figure 2 shows a typical two-dimensional event plot. After extracting the yield for the appropriate proton momentum bins the cross section was calculated from the expression

$$\frac{d^3\sigma}{d\Omega_\pi d\Omega_p dP_p} = \frac{\text{Yield}}{N_{\text{beam}} N_{\text{tgt}} \epsilon \Delta\Omega_\pi \Delta\Omega_p \Delta P_p} ,$$

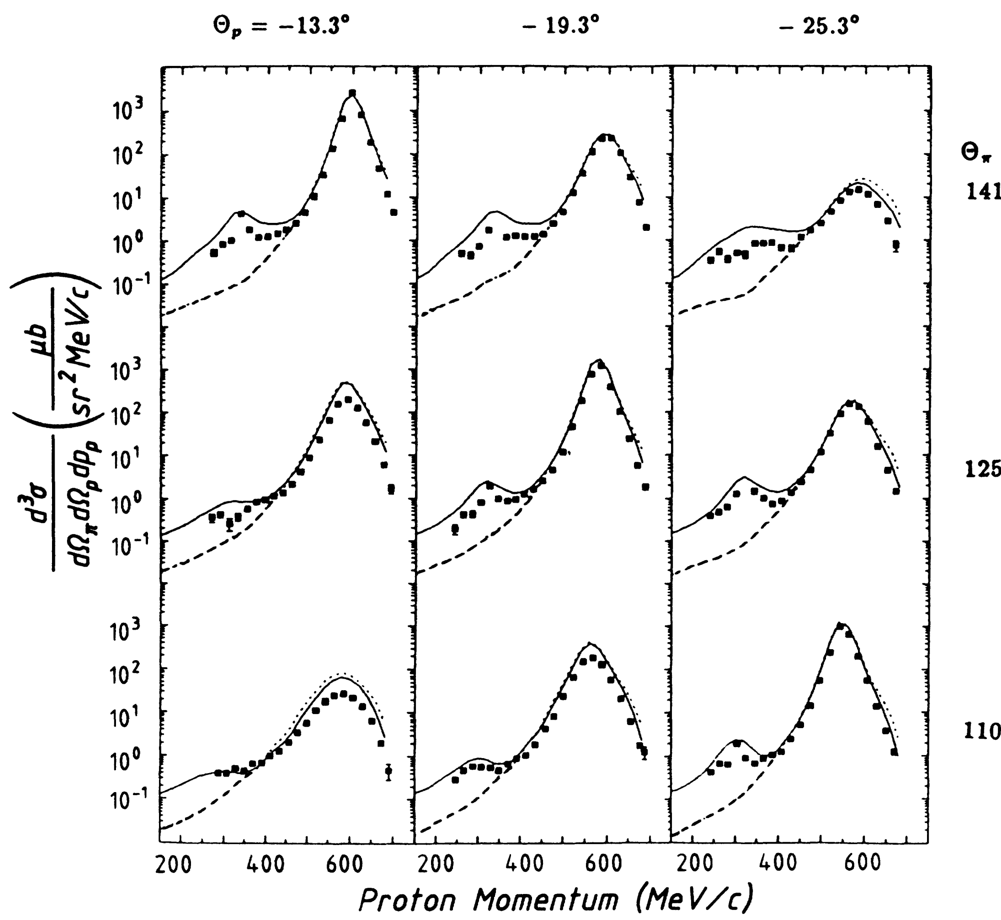

FIG. 4. Triple differential cross sections obtained for nine proton-pion angle pairs. The solid line represents the prediction from the new theory of Garcilazo (Ref. 16), the dashed line corresponds to the impulse approximation.

where N_{beam} is the number of incident pions, N_{tgt} is the number of deuterons per cm^2 in the target, ϵ is the combined efficiency of the detectors and the data acquisition system, measured during the experiment (0.7–0.8), $\Delta\Omega_\pi$ and $\Delta\Omega_p$ are the pion and proton solid angles (29.9 msr and 39.8 msr, respectively); and ΔP_p is the proton momentum bin (20 MeV/c).

The data were corrected with the use of a Monte Carlo calculation for the effect of averaging over the finite detector sizes and the momentum binning of the data. A detailed description of the Monte Carlo correction procedure will be given in a forthcoming publication. It raises the cross section in the quasifree πp scattering region, and lowers it on the sides. In the np final state interaction region the correction amounted to less than 10%, again raising the peak and lowering the sides.

The systematic uncertainties in the measurement of the cross section consist of a 5% error from the determination of the polynomial of the Monte Carlo correction, of 4% in the target thickness, 2% in the solid angles of the detectors, and 1% in the incident beam intensity. This results in a systematic error of 14% which is not included in the statistical uncertainties presented in the figures. To show the typical consistency of this data with the earlier measurements[13] the cross sections from both experiments are compared in Fig. 3 for one angle pair. There is good agreement in the quasifree πp scattering region.

III. RESULTS AND DISCUSSIONS

Before comparing the experimental results with the theoretical predictions, a brief description of the theoretical developments previous to the present theory seems appropriate.

One of the first things with which a theorist is confronted when dealing with the πNN system at intermediate energies is the fact that this system requires, one way or another, a relativistic treatment. Due to its small mass, a pion of say 300 MeV kinetic energy is a highly relativistic particle, while if this same pion is absorbed, the two nucleons emitted have kinetic energies which are not much smaller than the nucleon's rest mass. Thus, in the development of the theoretical description of this system, one can notice a clear trend in which additional relativistic features are put into the calculations. The starting point of this trend is, of course, the pioneering work of Afnan and Thomas[18] in which pion-deuteron elastic scattering, pion-deuteron absorption, and nucleon-nucleon scattering at energies not very much above the pion threshold, were all described simultaneously using the nonrelativistic Faddeev equations in which the nucleon was assumed to be a bound state of a pion and a nucleon.

Semirelativistic versions of the Faddeev equations were later introduced in order to use them in the description of pion-deuteron elastic scattering. For example,

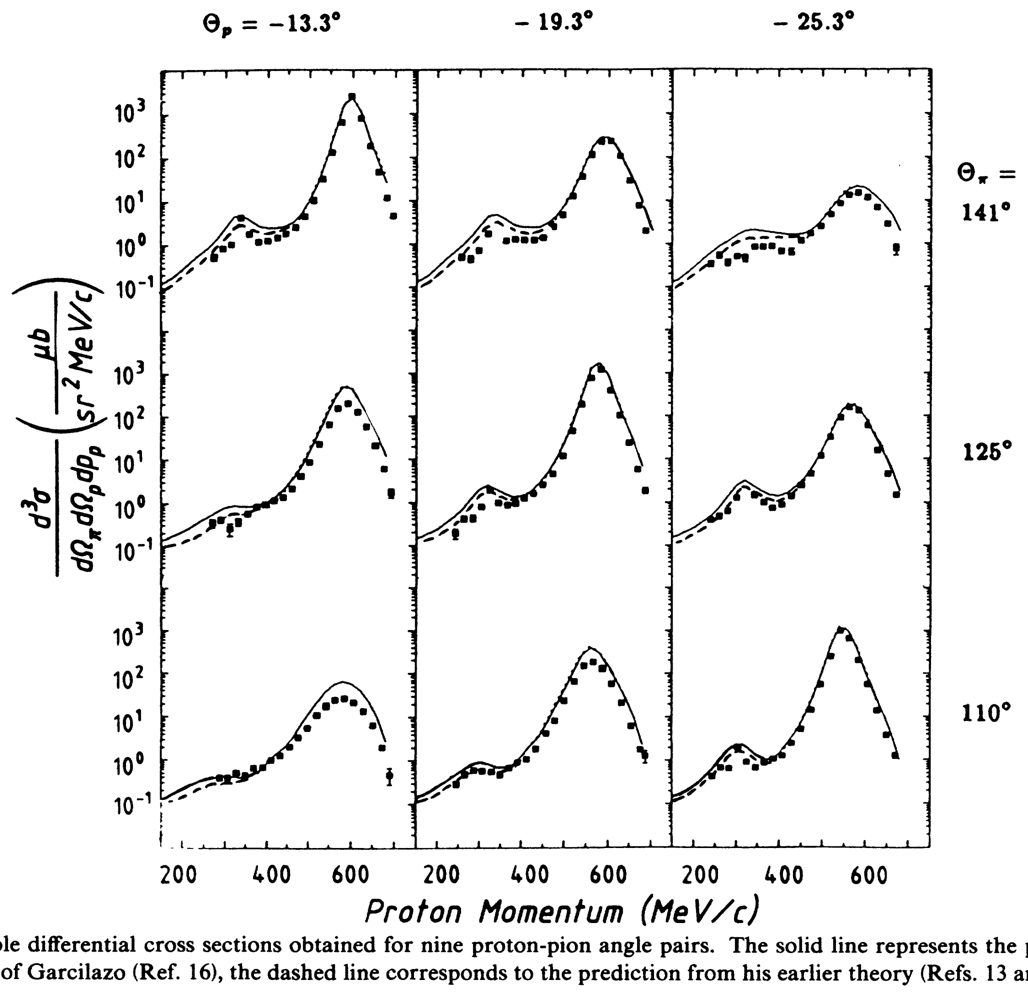

FIG. 5. Triple differential cross sections obtained for nine proton-pion angle pairs. The solid line represents the prediction from the new theory of Garcilazo (Ref. 16), the dashed line corresponds to the prediction from his earlier theory (Refs. 13 and 14).

Madelzweig, Garcilazo, and Eisenberg used a relativistic phase space and a relativistic Faddeev propagator but evaluated the three-body recoupling coefficient with nonrelativistic kinematics,[19] while Thomas treated the two nucleons nonrelativistically and used relativistic kinematics only for the pion.[20]

In order to treat the kinematics of the three particles fully relativistically, a number of calculations were performed[21–24] in which the basic framework was the relativistic three-body formalism of Aaron, Amado, and Young,[15] in which the kinematics of the three-body system corresponds to having all three particles on their mass shells. A further advancement of this theoretical framework was the inclusion of relativistic treatment not only for the space variables but for the spin variables as well,[25–27] which followed from the application of Wick's three-body helicity formalism.[28]

A very serious drawback, however, of using on-mass-shell kinematics in all intermediate states of three particles is that in general one does not have conservation of total four-momentum at every vertex. In order to remedy this situation, one of us[16] has recently developed a new relativistic Faddeev theory of the πNN system in which all the spectator particles are on the mass shell and all exchanged particles are off the mass shell, while the pion-nucleon and nucleon-nucleon amplitudes with any number of particles off the mass shell are represented by sums of isobars of variable mass. As a result of having allowed some of the particles to go off the mass shell, one guarantees conservation of total four-momentum, and in addition, one is able to describe correctly processes where there is an emission or absorption of a real or virtual pion.

There are two stable isobars in the πNN system, the nucleon in the πN subsystem and the deuteron in the NN subsystem. Thus, the integral equations of the spectator-on-mass-shell theory[16] give the amplitudes for all the processes which start with one free particle and one of the stable isobars and end up with another free particle and either a stable or an unstable isobar, so that they correspond, respectively, to two-body–two-body processes (like $\pi d \rightarrow \pi d$, $\pi d \rightarrow NN$, and $NN \rightarrow NN$) or two-body–three-body processes (like $\pi d \rightarrow \pi NN$ and $NN \rightarrow \pi NN$). The two-body input to these equations are the off-shell amplitudes for the pion-nucleon S_{11}, S_{13}, P_{11}, P_{13}, P_{31}, and P_{33} channels and the nucleon-nucleon ${}^3S_1$-${}^3D_1$ and ${}^1S_0$ channels as described in Ref. 16.

In Fig. 4 the πd breakup cross section is plotted as a function of the proton momentum for the nine proton-pion angle pairs. The cross section distribution is dominated by quasifree πp scattering. In the region of $P_p \approx 300$ MeV/c a strong enhancement of the cross section is observed which is due to the np final state interaction. The solid and dashed lines are theoretical predictions of the new theory of Garcilazo.[16] The solid line corresponds to the full calculation, the dashed one to the impulse approximation. As one would expect, both predictions are identical in the quasifree πd scattering region, but deviate drastically in the final state interaction region. While the full calculation reproduces the final state interaction qualitatively, the impulse approximation falls short by more than an order of magnitude.

The disagreement between the full calculation and the data in the region of the final state interaction is consistent with the discrepancies observed in large angle πd scattering. We have no explanation for this effect at the moment.

In Fig. 5 we compare predictions from the earlier calculations of Garcilazo[13,14]—dashed lines—with the ones of his new theory Ref. 16)—solid lines. Differences between the two theories are in the treatment of the two-body vertex functions and of the propagator of the exchanged particle that is allowed to be off the mass shell. The differences between the two theories are expected to be larger for the FSI region than for the quasifree (QF) region due to the fact that the QF process is a single scattering mechanism while the FSI process is a double scattering mechanism. Thus, while for the QF diagram the exchanged particle is reasonably close to the mass

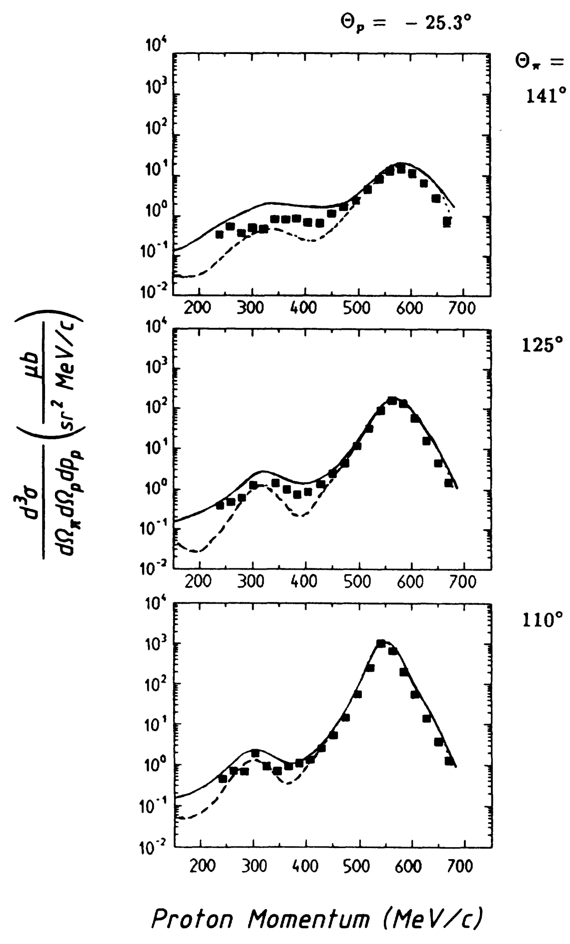

FIG. 6. Investigation of the effect of the D state of the deuteron on the calculated cross sections. The solid line represents the full calculation, the dashed line is the extreme case in which the D state is not included at all. More realistic variations between 4.25% D state (Bonn potential) and 5.8% (Paris potential) show differences too small to be seen in the figure.

shell, in the FSI diagram, on the other hand, one has to carry out a loop integration in which one picks up contributions where the exchanged particles are very far off the mass shell.

At this point it might be interesting to study the sensitivity of different parts of the πN or NN input in the theory. For this study we arbitrarily restrict ourselves to the right column of Fig. 4. The gross features of the πd breakup reaction are dominated by the deuteron wave function. It may be interesting, therefore, to see the effect of the D state on the cross section. In Fig. 6 we first show the extreme case when the D state is completely neglected in the deuteron wave function. The comparison with the full calculation shows that the effect is sizable only in the np final state interaction region. It is smallest where the relative proton-neutron momentum approaches a minimum. A more realistic comparison of different D-state components can be achieved by comparing the Paris potential with the Bonn potential as NN input in the calculation. While the D-state component in the Paris potential amounts to 5.8%, it is only 4.25% in the Bonn potential. The predictions show essentially no difference.

A further comparison shows the influence of the ${}^1S_0$ and (${}^3S_1$-${}^3D_1$) NN channels on the cross section in the final state interaction region (Fig. 7). The dotted line corresponds to the case where no final state interaction is included in the calculation, the dashed line corresponds to only including the ${}^1S_0$ channel, while the solid line corresponds to including also the ${}^3S_1$-${}^3D_1$ channel. As one well sees, the effect of the ${}^1S_0$ channel is negligible in comparison with that of the ${}^3S_1$-${}^3D_1$ channel. The very small sensitivity to the nucleon-nucleon final-state interaction in the ${}^1S_0$ channel is the special case of a general feature of the πd system. It was first noticed in the elastic channel by Rivera and Garcilazo,[22] while this behavior was later confirmed by Rinat *et al.*[29] A simple explanation for this behavior can be obtained if one

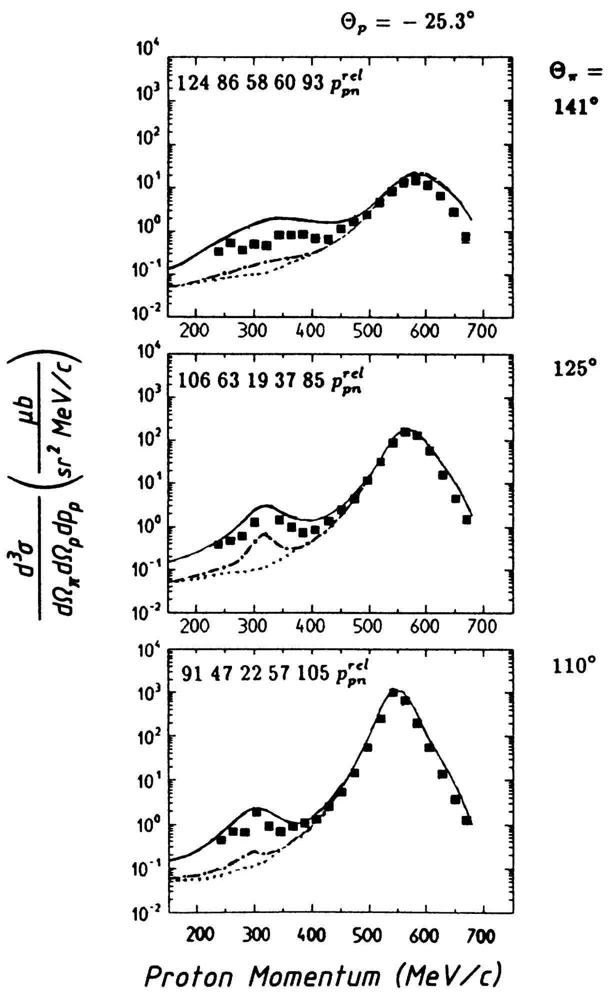

FIG. 7. Effects of the singlet and triplet NN channels on the cross sections in the final-state interaction region. The dotted line corresponds to "no FSI," the dot-dashed one to the ${}^1S_0$ channel only, and the solid curve corresponds to both singlet and triplet contributions included.

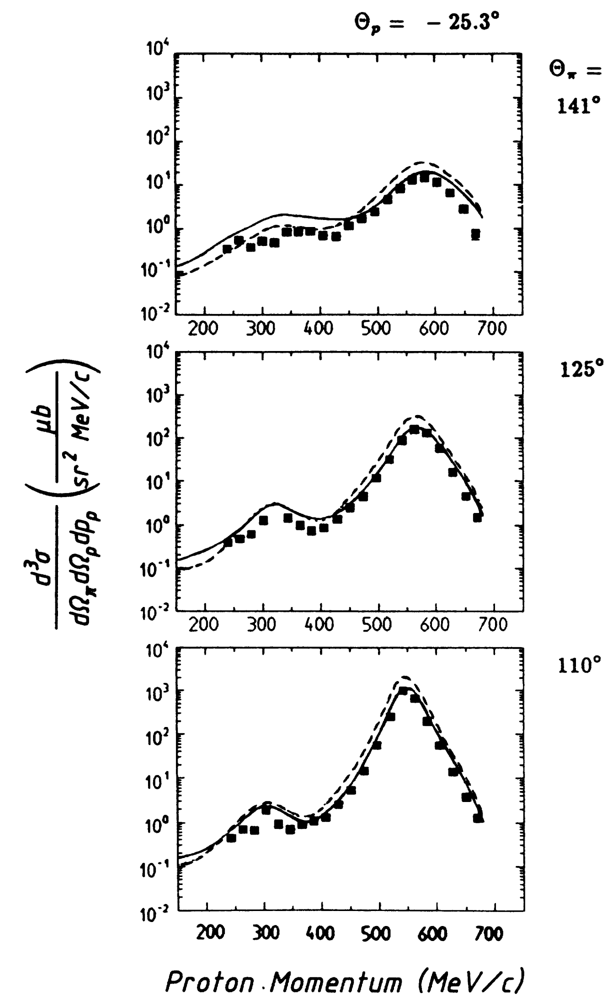

FIG. 8. Effects due to the nonresonant πN partial waves in the two-body input into the theory. The solid line corresponds to the full calculation, the dashed one to the Δ dominance (P_{33} πN partial wave only).

remembers that the pion-deuteron system is dominated by the $J^P=2^+$ state, in which the $\Delta(3,3)$ and the nucleon are in a relative S state while their spins are parallel to each other. Thus, it is easy to see that this state will couple very strongly to the three-body configuration where the two nucleons are in the ${}^3S_1$ channel (spins parallel) while the pion is in a relative P wave with respect to the two nucleons, since in order to get the quantum numbers of the $J^P=2^+$ state, this configuration requires also that all the spins and orbital angular momenta be parallel to each other. On the other hand, if the two nucleons are in the ${}^1S_0$ channel (spins antiparallel), in order to have total angular momentum $J=2$ the pion must be in a relative D state with respect to the two nucleons, and this implies that the state has quantum numbers $J^P=2^-$ since the state $J^P=2^+$ is not allowed. Thus, the small effect of the nucleon-nucleon ${}^1S_0$ channel is due to the fact that this channel does not contribute to the dominant configuration of the πd system, which is $J^P=2^+$.

Finally we show the effect of the small πN waves. In Fig. 8 again the solid line is the full calculation, while the dashed one corresponds to the calculation with only the P_{33} partial wave taken for the πN input (Δ dominance). A sizable effect is observed over the entire momentum range. The experimental data seem to prefer the full calculation.

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*On leave from Escuela Superior de Física y Matemáticas, Instituto Politécnico Nacional, México 14 D.F., Mexico.

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