Neutron-proton final-state interaction in πd breakup: Vector analyzing power

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The vector analyzing power iT_{11} has been measured for the πd breakup reaction in a kinematically complete experiment. The dependence of iT_{11} on the momentum of the proton has been obtained for 36 pion-proton angle pairs at $T_\pi = 134$ and 228 MeV. The data are compared with predictions from the new relativistic Faddeev theory of Garcilazo. The sensitivity of the observable iT_{11}, in particular in the np final-state interaction region, to details of the theory is investigated.

I. INTRODUCTION

In the preceding paper we have shown how sensitive the theoretical description of the cross section is in the region of the np final state interaction. It is well known, on the other hand, that spin-dependent observables provide a more stringent test of theoretical models since they contain additional information on the phases of the reaction amplitudes. For this reason, it would be interesting to investigate polarization effects in this kinematical region.

The first polarization effects in the NN final state interaction were those observed by Arvieux *et al.*[1] in pd breakup at 10.5 MeV. A few years later similar measurements were performed at somewhat higher energies,[2] and recently the analyzing power of the n-p final state interaction was measured in n-d breakup.[3] In those low energy experiments an analyzing power up to $A_y = 0.15$ was found, and the angular distributions showed a remarkable similarity to those of the corresponding elastic scattering.

At intermediate energies the only final state interaction effect which has so far been seen experimentally in a spin observable is the reduction of a large negative A_{y0} in the $\vec{p}\vec{p} \to pn\pi^+$ reaction at 500 MeV.[4] Other spin observables have been measured for the $NN \to \pi NN$ reaction,[5] but unlike the large final state interaction peaks in some of the pion production cross sections[6] there is no apparent final state interaction structure in the spin observables. As mentioned in our preceding paper, the pion production reaction was studied recently by two theoretical groups.[7–9]

Dubach *et al.*[7] investigated the model dependence of unitary isobar model treatments of the pion production reaction by comparing the Aaron, Amado, and Young (AAY) model[10] and the van Faasseu-Tjon (vFT) model.[11] Predictions were shown for the (spin averaged) exclusive differential cross section and five representative spin observables. In a separate paper Dubach *et al.*[8] studied explicitly the effects of the NN final state interaction on polarization observables. In their calculation narrow spikes were predicted in the spin-spin correlations A_{yy}, A_{zz}, and A_{zx} in the region of lowest NN relative momentum. These spikes were caused by a delicate interplay between amplitudes which are enhanced (differently) by the singlet and triplet final state interactions.

Matsuyama and Lee[9] treated the NN final state interaction within their unitary meson exchange model more rigorously than the phenomenological parametrization employed by Dubach *et al.* However, their calculation of the final state interaction was also limited to the region near the final state interaction peak. The contribution of the ${}^3S_1-{}^3D_1$ channel was included exactly in solving the coupled Faddeev–Alt-Grassberger-Sandhas equation, while the ${}^1S_0$ interaction was treated only perturbatively. The influence of the final state interaction on the observable A_{y0} was investigated, but no improvement was found over the calculation keeping only the direct Δ (3.3) production term.

In the π^+d breakup reaction (which leads to the same final state as the $pp \to \pi^+ pn$ reaction) the first spin-dependent cross sections were obtained by Mathie *et al.*[12] and Gyles *et al.*[13] The vector analyzing power iT_{11} was measured in a kinematically complete experiment over a large part of the phase space. The data were compared with theoretical calculations from Garcilazo[14] which were based on the AAY theory.[10] In general, good agreement was found within the experimental uncertainties. A more recent calculation from Garcilazo[15] using a novel relativistic Faddeev theory[16] was compared with a subset of the same data which contained the quasifree point, that is, a set of pion and proton angles and proton momentum for which the neutron is left almost at rest in the lab system. Also in this case the calculation gave a good description of the data within the experimental errors. Thus, it seems that in order to to able to use the breakup reaction to distinguish between theoretical prescriptions, one has to carry out new calculations and measurements far from the quasifree point.

The motivation of the present work was to extend existing data at 228 MeV into the region of smaller proton and larger pion angles were effects due to np final state interaction are expected to be large (Fig. 8 in Ref. 13) and compare them with theoretical predictions from Garcilazo. The measurement at 134 MeV was performed to investigate if the dramatic discrepancies from theoretical predictions found in a polarization observable for large angle πd scattering (Ref. 22) would also occur in the kinematically related np final state interaction (FSI) region of πd breakup.

II. EXPERIMENTAL TECHNIQUE

Similar to our earlier experiment,[12,13] a kinematically complete experiment was performed for the reaction $\pi^+ d \rightarrow \pi^+ pn$. In addition to the momentum and the angles of the incident pion, the reaction angles of the final state pion and proton and the momentum of the proton were specified. The reaction was limited to the horizontal scattering plane. The target consisted of dynamically polarized deuterons. The pions and protons in the final state were detected in a multiple arm time-of-flight spectrometer which has been described earlier. The experimental setup is shown in Fig. 1.

The experiment was conducted at the Swiss Institute for Nuclear Research (SIN) on the $\pi M1$ channel. This pion beam line has considerable advantages over the $\pi M3$ channel which was used for some earlier measurements. As a channel designed for high resolution pion scattering experiments it produces a small beam spot on the target, typically 1 cm FWHM in the horizontal and vertical direction. The channel also contains an electrostatic separator which removes the largest part of the protons in the beam, so that energy degraders are no longer required in the beam line to eliminate the protons. For this experiment a momentum resolution of the incident pion beam of $\pm 1\%$ was adequate. Therefore, the scintillator hodoscope at the intermediate focus which defines the pion momentum was replaced by lead collimators. In order to eliminate beam halo at the polarized target cell (2×2 cm^2 in area and positioned at 45° to the incident pion beam) a thin beam defining counter was positioned 25 cm upstream from the target in the converging beam. One meter further upstream a five-strip scintillator hodoscope was placed to monitor beam shifts. The incident pion energies were 134 and 228 MeV. At 134 MeV the six proton and six pion angles were chosen to be conjugate pairs of the πp kinematics in the range $39° > \theta_p > 15°$ and $87° < \theta_\pi < 141°$, respectively. At 228 MeV the corresponding angular ranges were $33° > \theta_p > 9°$ and $96° < \theta_\pi < 154°$. At this energy four proton-pion angle pairs matched corresponding ones from the earlier measurements[13] to provide a consistency check.

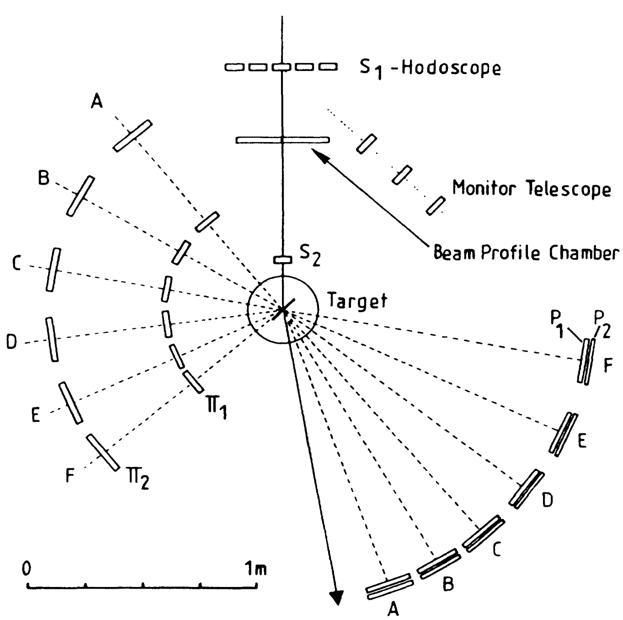

FIG. 1. Schematic drawing of the experimental setup.

The polarized target was the same as in the earlier experiment. Unfortunately, the positive and negative target polarizations were unusually low during this experiment, namely $P^+ = 0.145 \pm 0.014$ and $P^- = 0.153 \pm 0.012$. The vector analyzing power iT_{11} was calculated from the expression

$$iT_{11} = \frac{1}{\sqrt{3}} \frac{\sigma^+ - \sigma^-}{\sigma^+ P^- + \sigma^- P^+} ,$$

where σ^+ and σ^- are the background corrected threshold differential cross sections $d^3\sigma^{\pm}/d\Omega_\pi d\Omega_P dP_P$ for the two polarization states P^+ and P^- of the polarized deuteron target with the quantization axis perpendicular to the scattering plane. Following the Madison convention the sign of the target polarization is defined to be positive for $\hat{n} = \mathbf{k}_\pi \times \mathbf{k}'_\pi$.

The 2.5 T magnetic field surrounding the polarized target acts like a momentum analyzer which distorts the pion and proton trajectories. For a particular counter at a specific angle, the scattering angle with respect to the incident beam at the target center depends on the momentum of the detected particle. The trajectories and the mean times of flight of the particles (including the effects of energy losses in the target materials) were calculated with a ray tracing program. For further experimental details on the data taking procedure and the data analysis see Ref. 13.

III. RESULTS AND DISCUSSION

All experimental data at $T_\pi = 134$ MeV and 228 MeV are presented in Figs. 2(a) and (b) and Figs. 3(a) and (b) respectively. The vector analyzing power iT_{11} is plotted as a function of the proton momentum for the 36 proton-pion angle pairs. The solid and the dotted curves are predictions from the new relativistic Faddeev theory.[16] The solid curves correspond to the full calculation, the dotted ones to the impulse approximation. In Figs. 3(a) and (b) we also show the predictions from the earlier calculation from Garcilazo (Refs. 13 and 14) as dashed lines. As one can see, there are only small differences, mainly in the FSI region. A plausible reason

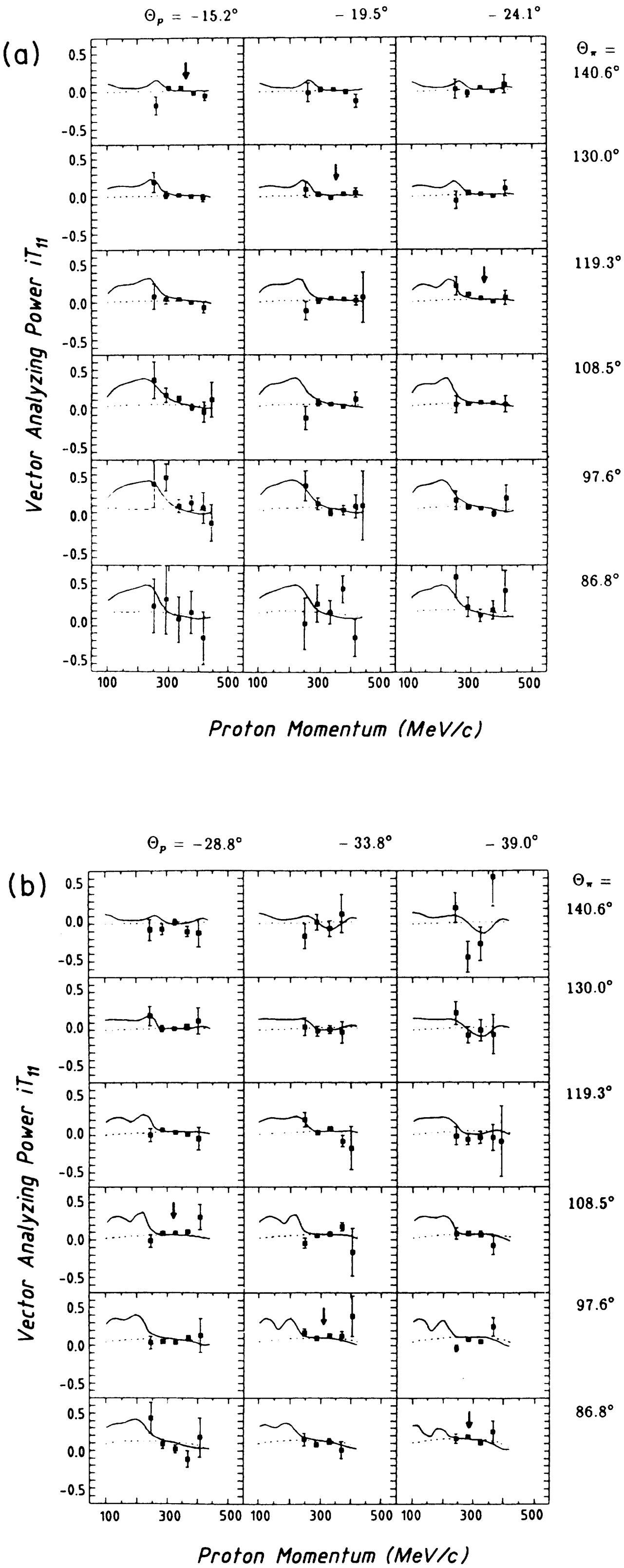

FIG. 2. (a) Values of iT_{11} vs proton momentum for various pion-proton angle pairs at incident pion energy of 134 MeV. The solid curves are the predictions from the full Faddeev calculation, the dotted ones from the impulse approximation. (b) The same as (a) at larger proton angles.

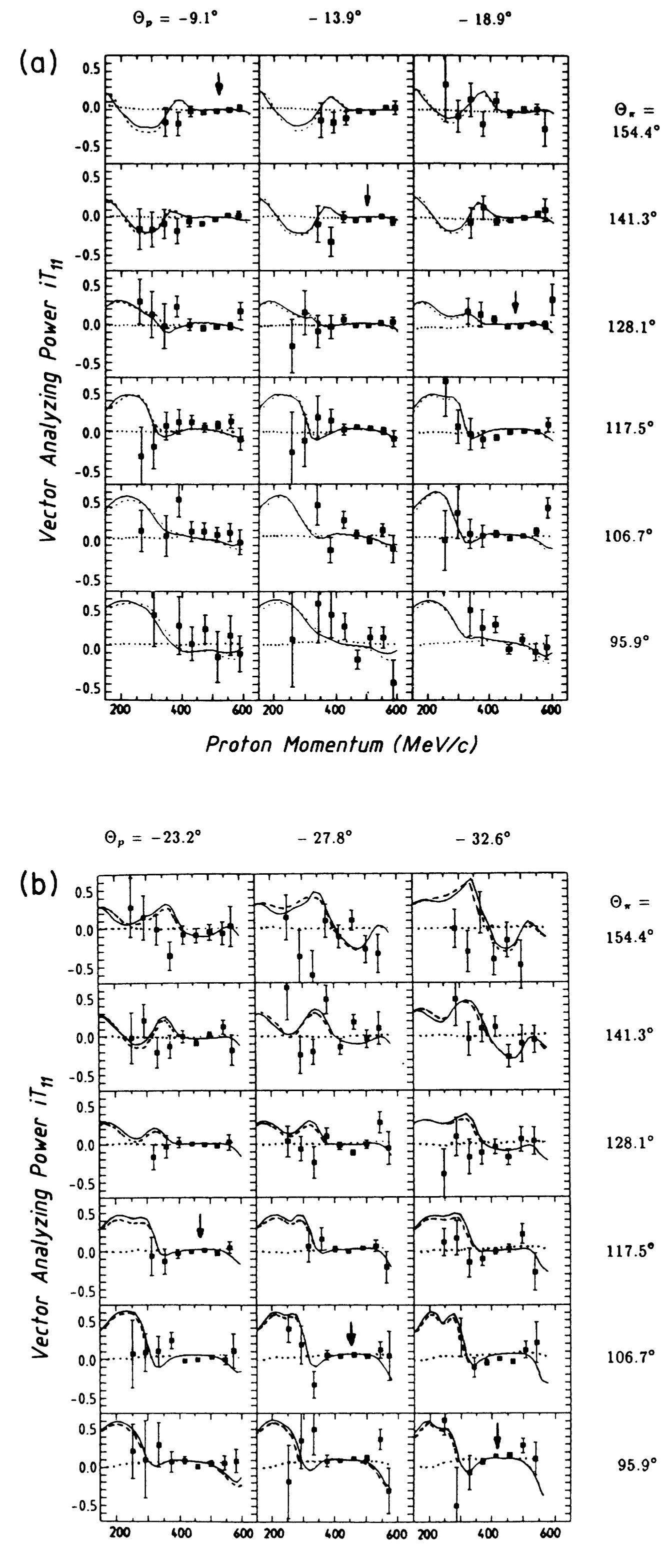

FIG. 3. (a) Values of iT_{11} vs proton momentum for various pion-proton angle pairs at incident pion energy of 228 MeV. The solid curves are the predictions from the new Faddeev theory (Ref. 15), the dotted ones from the impulse approximation, the dashed curves correspond to predictions from the earlier theory (Refs. 13 and 14). (b) The same as (a) at larger proton angles.

for this effect is given in the preceding paper. The proton-pion angle pairs on the diagonal line from the upper left to the lower right corners of the figures correspond to the free π-p scattering angles. In those particular plots the arrows mark the quasifree π-p scattering kinematics. There, one can compare the vector analyzing power iT_{11} of quasifree πp scattering with the analyzing power A_y of free πp scattering, neglecting effects due to the D state in the polarized deuteron. Similar to the findings in our previous publication (Ref. 13) the expected relationship $iT_{11}=A_y/\sqrt{3}$ is well reproduced in the present data. In a limited momentum range around this quasifree scattering kinematics the observable iT_{11} is almost constant. In this region the full calculation and the impulse approximation agree well with each other, and with the data. At lower proton momenta both predictions deviate increasingly from each other. In this region the uncertainties in the data increase due to the fact that the rapidly decreasing cross section for the πd breakup reaction eventually becomes equal to or even smaller than the background cross section from nuclei other than the deuterons in the polarized target material. There, it is more difficult to draw conclusions from the data. Nevertheless, quite a few interesting observations can be made by looking into some experimental and theoretical details.

First, it is interesting to show the energy dependence of the vector analyzing power in more detail. In Fig. 4 the vector analyzing power is displayed as a function of proton momentum for two proton-pion angle pairs, at four incident pion energies. The data at 180 and 294 MeV are taken from the earlier experiment.[13] The solid lines are theoretical predictions. The calculations show an increasingly richer structure in the polarization effects as the pion energy is raised. This is due to the opening of the phase space. Basically, there are three momentum regions of interest. For low proton momenta the theory predicts a large positive vector analyzing power. This is the region of the np final state interaction. The double-peaked pattern in the final state interaction region, which may be due to the interference of the singlet and triplet np final state interaction, moves to higher momenta with increasing energy. Beyond this region we find almost constant positive values for iT_{11}. Here, the quasifree πp scattering prevails as discussed above. Further, towards higher proton momenta iT_{11} finally turns negative. The proton momentum at which the crossover occurs increases with energy. The change in sign of iT_{11} corresponds to a change in the sign of the helicity amplitudes ($m=+1\rightarrow m=-1$). This can only be accomplished by a transition from the initial S state of the πNN system to a D state.

In order to investigate the different effects on the vector analyzing power, a subset of the data at 228 MeV is shown enlarged in Fig. 5. The two plots correspond to the momentum distributions of iT_{11} in the lower right corner of Fig. 3(b). This sample of the phase space was chosen because there the vector analyzing power is more sensitive to changes in the theoretical input. In Fig. 5 the solid line corresponds to the full calculation, the dashed one to the predictions when the D-state part of the deuteron wave function is turned off. Pronounced effects are seen at low and high proton momenta. The present data are not accurate enough to verify the change to negative values of iT_{11} at high momenta as predicted by the full calculation (solid line), but this has been seen in a number of distributions at 180 and 228 MeV in our earlier work.[13]

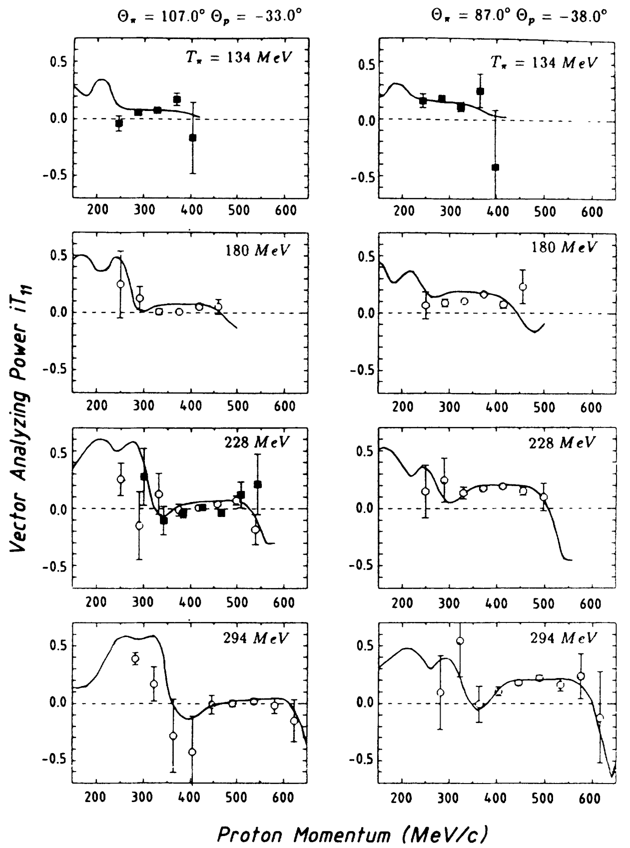

FIG. 4. Energy dependence of iT_{11} for two pion-proton angle pairs. The data (black squares from this experiment, open circles from our earlier experiment, Ref. 13) are compared with predictions from the Faddeev calculation. The largest values of iT_{11} are predicted for the np final-state interaction region. The dimple in the trapezoidally shaped curve corresponds to the minimum of the relative np momentum.

As shown in Figs. 2 and 3, the largest differences between the full calculation and the impulse approximation are predicted in the region of the np final state interaction (where the proton momenta are smaller than 250–300 MeV/c). It would be interesting to see whether the vector analyzing power, iT_{11}, shows these effects. Unfortunately, the data at each angle pair are not accurate enough to provide clear evidence for some final state interaction effects. Recognizing, however, that in certain regions of phase space the theoretical predictions do not vary greatly with proton angle, it may be justified to sum the data over several proton angles and compare these integrated data (with smaller errors) with the averaged theoretical predictions. For the two pion angles $\theta_\pi=95.9°$ and $\theta_\pi=106.7°$ the data were summed for $9.1°<\theta_p<32.6°$. The results are displayed in Fig. 6. The dotted curve corresponds to "no FSI," the dot-dashed

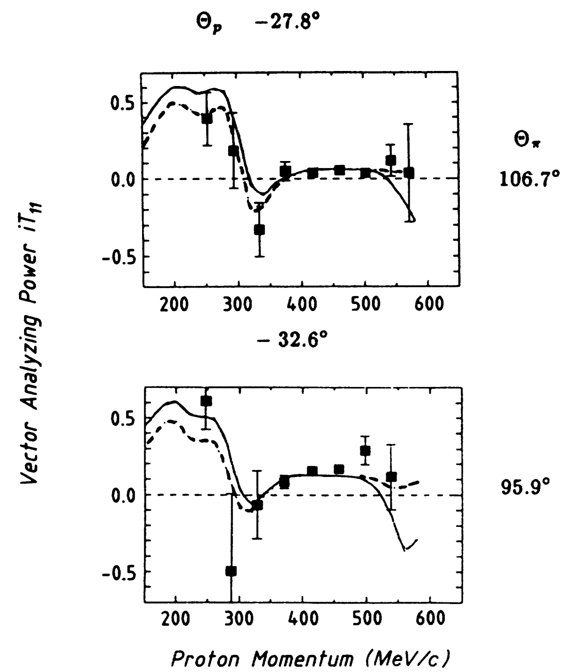

FIG. 5. Effect of the deuteron *D* state on iT_{11}. The solid curve corresponds to the full calculation. The dashed curve is the theoretical prediction, when the *D*-state component in the wave function is neglected.

one to $^1S_0$ FSI only, the dashed one to $^3S_1$-$^3D_1$ only, and the solid curve is the prediction when both singlet and triplet contributions are included. In spite of the large errors the averaged data clearly favor calculations which include the triplet contribution.

Most of the three-body calculations performed for the πNN system assumed that the πN interaction at medium energies ($120 < T_\pi < 250$ MeV) is dominated by the $\Delta(1236)$ resonance. An obvious question has been whether the inclusion of the nonresonating partial waves is important, and to what extent. Within the context of the three-body approach to πd elastic scattering, Giraud *et al.*[17] pointed out the importance of including the minor πN partial waves for the observable iT_{11}. This has been verified experimentally by Bolger *et al.*,[18] and more extensively by Smith *et al.*[19] It appears, however, that within an essentially nonrelativistic coupled channel model one obtains a vector analyzing power iT_{11} which is comparable to the three-body results without including those small πN waves.[20] Therefore, it is interesting to see the importance of the small πN partial waves on iT_{11} in the πd breakup reaction. This is shown in Fig. 7. The solid line corresponds to the full calculation, the dashed one to the assumption of Δ dominance (all small πN partial waves neglected). Effects on the vector analyzing power are observed in the final state interaction region, and also where the quasifree πp scattering dominates. From this comparison one would conclude that the small πN partial waves should be included in the πN input of the Faddeev calculation for the πd breakup reaction.

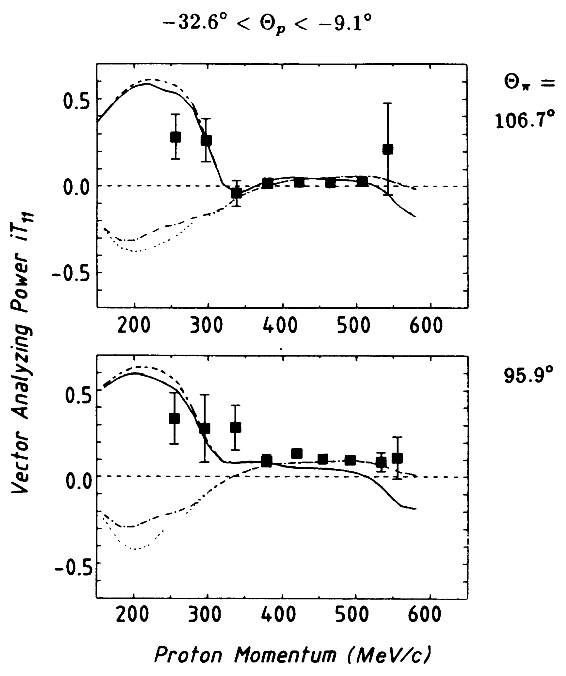

FIG. 6. Effect of the singlet and triplet np final state interactions on iT_{11}. The dotted curve corresponds to "no FSI," the dot-dashed one to $^1S_0$ FSI only, the dashed one to $^3S_1$-$^3D_1$ only, and the solid curve is the prediction for the full calculation (including both singlet and triplet contributions).

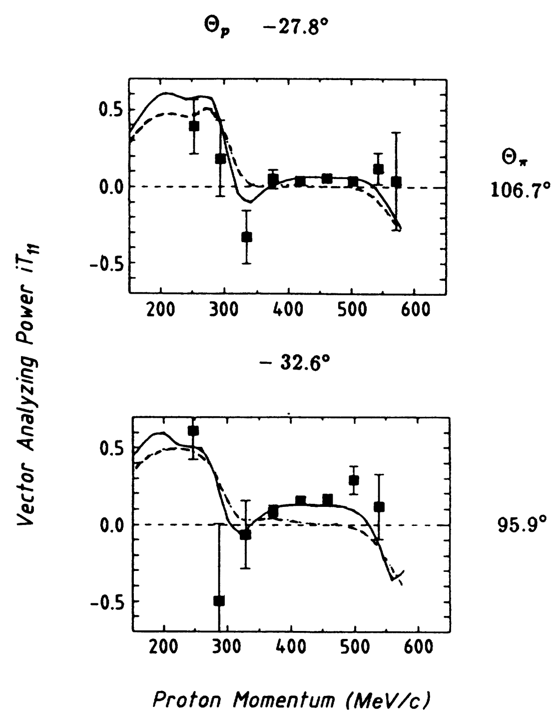

FIG. 7. Effect of neglecting the nonresonanting *S* and *P* πN partial waves on iT_{11} (dashed curve) in comparison to the full calculation (solid curve).

The πd breakup reaction involves a number of reaction mechanisms, each of which becomes dominant under different kinematical conditions. there is the quasifree πp scattering (the neutron having a small momentum), the πp final-state interaction (the neutron having a large momentum), and the np final-state interaction when the relative momentum between neutron and proton is small. In addition, one can think of more complicated reaction dynamics including exotics such as dibaryons. This latter contribution has been discussed by Hoftiezer *et al.* (Ref. 21).

In our earlier survey experiments we investigated the kinematical region of the first and partially of the second reaction mechanism. In the present two papers we focused on the np final state interaction. This kinematics corresponds to large angle π"d" scattering where the "d" stands for the unbound np system with small relative momentum. This kinematical condition may be compared to πd elastic scattering at large angles. There, all theories have notorious difficulties in describing cross section, vector analyzing power, and the tensor observables above pion energies of 180 MeV. It is, therefore, interesting that under rather similar kinematical conditions also the πd breakup cross section is overpredicted by the same factor, while the gross features of iT_{11} are described.

Possibly, much more accurate polarization measurements must be performed before systematic deviations from the theoretical predictions can be observed. This should be possible in the future. Since the time when this experiment was performed there has been a breakthrough in the technology of polarized deuteron targets. The vector polarization of the target has increased form $P_z \simeq 0.15$ (in the present experiment) to $P_z \simeq 0.45$, and even larger values may be obtained with novel target materials and higher magnetic fields. The target thickness may be reduced by a factor 2 allowing low energy protons to leave the target. In addition, when operating the target in the "frozen spin" mode where the magnetic field is lowered to a holding field of 0.5 T some of the problems in the iT_{11} measurements (described in detail in our earlier iT_{11} paper, Ref. 13) will be less severe.

From the theoretical predictions presented in these papers, and from calculations of the tensor observables (not shown here) the kinematic region of the np FSI appears to be the most sensitive to details of the theoretical models. It is unfortunate that, at present, no other calculations are available for comparing the sensitivity of different theories.

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