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TENSOR POLARIZATION IN PION-DEUTERON ELASTIC SCATTERING

by

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R. J. Holt

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ABSTRACT

The angular dependence of the tensor polarization t_{20}^{lab} of recoiling deuterons in π-d elastic scattering was measured as a function of incident pion energy in the range 134 to 256 MeV. No evidence was found for rapid energy or angular dependences in t_{20}^{lab}. The results agree most favorably with theoretical calculations in which the P_{11} π-N amplitude has been removed altogether. This agreement is consistent with a small effect of pion absorption on the elastic channel.

I. INTRODUCTION

During the past few years interest in the pion-deuteron system has been spurred by questions regarding the existence of dibaryon resonances, true pion absorption in nuclei and the quadrupole form factor of the deuteron. Another more recent development involves the effect of a quark bag model on the πNN and πNΔ components which enter the theoretical models.

Presently, the theoretical calculations of the π-d system have achieved a high level of sophistication. These calculations are typically three-body in nature and include both the absorptive channel πd → NN and pion scattering. The results of the latest theoretical calculations are summarized in Fig. 1. Here, the calculations of Blankleider and Afnan[1] (Flinders), Betz and Lee[2] (Argonne), Fayard et al.[3] (Lyon), and Rinat and Starkand[4] (Weizmann) are compared with measurements of the differential cross section[5,6] and the vector analyzing power[7] iT_{11} for π-d elastic scattering. The results shown here are for three pion energies T_π = 142, 180 and 256 MeV which represent the Δ resonance region as well as the energy region where dibaryon resonance effects might be present. Although none of the calculations agree with the data in quantitative detail, the work of Refs. 1, 3 and 4 agree reasonably well with both the cross sections and vector analyzing powers at the lower energies. Of course, the calculation of Betz and Lee do not give reasonable values for the vector analyzing power since only the P_{33} channel is included in the π-N amplitudes and for the most part the vector polarization in π-d scattering arises from the interference between S and P waves in the π-N amplitudes in this energy region. This consideration of only the Δ channel may be responsible for the failure of this model to give an adequate account of the differential cross section.

The discrepancy between the experiment and theory is greatest at T_π = 256 MeV. The vector analyzing power iT_{11} becomes negative at forward angles and this is not predicted by present three-body calculations, although the prediction of Blankleider and Afnan is remarkably close in shape to the data. However, these new data do not exhibit negative values near θ = 130° as suggested by earlier data. The less oscillatory behavior of iT_{11} weakens the argument for dibaryon resonance behavior in this energy region. No other evidence for dibaryon resonance effects exists in the π-d system.

Pion absorption in nuclei has emerged as a major issue in medium energy physics. Although many measurements involving the πd → NN reaction have been performed, the absorption process has not been explained adequately and the effect of pion absorption on the elastic amplitudes is poorly understood. In order to further investigate the effect of absorption on the elastic channel it is essential to focus on the P_{11} π-N amplitude since this amplitude is necessary for pion absorption. Mizutani et al.[8] have emphasized that the composition of the P_{11} π-N amplitude into the pole and non-pole pieces is not known at present. The pole term is necessary for pion absorption while the non-pole amplitude contributes to pion rescattering in the nucleus. Experiments in π-N scattering give a measurement of the sum of these two terms, while the relative strength of these two amplitudes is important in π-nucleus scattering. The uncertainties in the composition of the P_{11} phase shift was demonstrated by Mizutani et al. and is illustrated in Fig. 2. Here, one can see that two very different sets of pole and non-pole phase shifts can give rise to essentially the same π-N P_{11} phase shift. Previous experiments have imposed very little constraint on the pole and non-pole components of the P_{11} amplitude. However, measurements of t_{20}^{lab} in π-d scattering are expected to place an important restriction on the P_{11} amplitude. The sensitivity of t_{20}^{lab} to the P_{11} amplitude can be seen from lower half of Fig. 3. Here, the angular dependence of t_{20}^{lab} is shown for T_π = 256 MeV for several calculations. The primary differences among these calculations is the manner in which the P_{11} amplitude is treated, i.e., all of these calculations are in good agreement as shown in the upper half of Fig. 3 if the P_{11} amplitude is made to vanish! Examples of the differences are that Rinat et al. use both a P_{11} πN as well as a ρN amplitude, whereas Blankleider and Afnan and Fayard et al. employ only πN amplitudes. Moreover, the πNN coupling constants vary widely among the calculations. More discussion of this issue will be given later in light of the present measurements of t_{20}^{lab}.

The prospect of measuring the quadrupole form factor of the deuteron by observing t_{20} in π-d scattering was discussed[9] with regard to multiple-scattering and early three-body calculations and led to an early interest in measuring t_{20}. The sensitivity of t_{20} to the quadrupole form factor can be seen readily from a simple expression based on an impulse approximation. The expression is given in terms of the π-N non-flip $g(\theta)$ and spin-flip $h(\theta)$ amplitudes as well as the ratio x of the quadrupole F_2 to the monopole form factor F_0:

$$t_{20} = -(2)^{-1/2} \left[\frac{3|g|^2 (2^{3/2} + x)\, x + |h|^2 y^2}{3|g|^2 (1 + x^2) + 2|h|^2 y^2}\right]$$

where $x = F_2/F_0$ and $y = F_1/F_0$. Here, F_1 is the dipole form factor. At large scattering angles where $|g|^2 >> |h|^2$, then t_{20} is given by

$$t_{20} \approx -(2)^{-1/2}\, x \left[\frac{2^{3/2} + x}{1 + x^2}\right] ,$$

and thus, depends critically upon x the ratio of the quadrupole to monopole form factor. It is this dependence that led several authors to suggest that t_{20} in π-d scattering at an angle of 180° would provide a measurement of the deuteron d-state probability. Since the calculated values of t_{20} in π-d scattering appear to depend strongly on the absorption it is likely that the ratio x might be best determined from t_{20} measurements in e-d elastic scattering and experiments[10] of this type have begun already at MIT-Bates. However, if the absorption effect can be determined, then π-d elastic scattering would offer complimentary information to e-d scattering, particularly at high momentum transfer, $q \gtrsim 3\ fm^{-1}$.

Unfortunately, there is some controversy[11] concerning the measurements of t_{20}^{lab} which Willi Grüebler expressed in the previous talk, and I now shall discuss the experimental method and the results.

II. EXPERIMENTAL METHOD

The key feature for performing measurements of t_{20}^{lab} in π-d scattering is the development of a high-efficiency deuteron tensor polarimeter. A prototype of the present polarimeter was used to perform the first measurement of t_{20} in π-d scattering and it is described in detail in Ref. 12. The present polarimeter was employed to measure (i) the first angular dependence[13] of t_{20}^{lab} in π-d scattering, (ii) t_{20}^{lab} in e-d scattering[10] for the first time, and (iii) the angular and energy dependence of t_{20}^{lab} in π-d scattering. Experiments and calibration procedures involving the new polarimeter are summarized in Table I.

A. Calibration of Polarimeter

The polarimeter employs the $^3He(d,p)^4He$ reaction which has a large cross section and tensor analyzing power T_{20} at forward angles and has a large Q-value, 18.4 MeV. The polarimeter was calibrated in a separate experiment at the Berkeley 88" cyclotron. The polarization of the deuteron beam was measured with respect to the well-known tensor analyzing power of $\vec{d}$-^4He elastic scattering at T_d = 35.0 MeV. The calibration of the polarimeter was determined as a function of incident deuteron energies, position and angle of incidence on the polarimeter. Typical results for the calibration are shown in Fig. 4. Here, the analyzing power T_{20} and efficiency ε_o of the polarimeter for nonpolarized deuterons is shown as a function of energy for deuterons incident along the central axis of the polarimeter. The calibration was checked two years after the primary calibration by measuring ε_o again (see Table I) at the Los Alamos three-stage tandem Van-de-Graaff. These results are shown as the open circles in Fig. 4. We conclude from this test that the measurement of the efficiency ε_o is reproducible to ~ 2%.

B. Electron-Deuteron Elastic Scattering

Further confidence in the present method can be gained by examining the results of the t_{20} measurement in e-d elastic scattering which was mentioned in Table I. The measurement with the present polarimeter was performed at low values of momentum transfer, q = 1.74 and 2.03 fm^{-1}, at the MIT-Bates Linear Accelerator Center. These measurements were performed as a feasibility study of the problems associated with performing polarization experiments in electron scattering at high momentum transfer. At low values of momentum transfer reasonable models (Paris, Reid soft core, Hamada-Johnson, Feshbach-Lomon) of the deuteron yield values of t_{20} which are in good agreement with one another. For example, effects such as meson exchange currents and relativistic wave functions are expected to be relatively minor. It is especially gratifying that the present work agrees very well with these calculations as shown in Fig. 5. This work provides additional confidence that the present method of measuring t_{20} really is working.

C. Pion-Deuteron Elastic Scattering

The tensor polarization t_{20}^{lab} of the recoil deuterons from π-d elastic scattering was determined by measuring the efficiency ε of the polarimeter for the scattered deuterons. Then, t_{20}^{lab} is related to ε and the calibration parameters E_o and T_{20} by the expression:

$$t_{20}^{lab} = \frac{1}{T_{20}} \left(\frac{\varepsilon}{\varepsilon_o} - 1\right) .$$

The experimental apparatus designed to measure ε is illustrated schematically in Fig. 6. Pions from the P^3 East channel at LAMPF were focused onto a liquid deuterium target of thickness 2.5 mm or 5.0 mm. Recoil pions were detected in an array of three plastic scintillators, while the recoil deuterons were focused onto the polarimeter with a QQD system. It is essential to clearly define the deuterons before they enter the ^3He volume and to separate protons for the $^3He(d,p)^4He$ reaction from other sources of protons. The deuterons are defined by dE/dx signals in the S1 and S2 detectors and by the time-of-flight between the pion arm and S2. A contour plot of S1 vs. S2 is shown in Fig. 7 for π-d scattering at T_π = 134 MeV and θ_d = 18.0°. This kinematic condition was selected for illustration since the results of the previous talk in this energy and angular range show remarkable disagreement with the present work. The contour plot shows that there is a clear separation between protons and deuterons incident on the polarimeter. The separation is even more dramatic than illustrated since the deuterons shown in the figure are prescaled by a factor of 100 compared with the background protons. The protons from the $^3He(d,p)^4He$ reaction are identified by first requiring a deuteron event and then dE/dx in the S3 scintillator, energy in the E scintillator and time-of-flight between S2 and S3. This time-of-flight vs. E is shown in the contour plot in Fig. 8. The upper part of Fig. 8 indicates the results if no requirement is placed on the event being associated with a deuteron. Then, three distinct ridges emerge in the time-of-flight spectrum: (i) the $^3He(d,p)^4He$ events are in the smallest ridge, (ii) protons which have a random pion in the pion arm lie in the center ridge, and (iii) the largest component are protons from the $(\pi,\pi'p)$ reactions which occur in time near the edge of the coincidence window of the pion and deuteron signals. Since these latter events occur near the edge the timing is shifted relative to the proton peak by ~ 15 ns, the width of the S1-S2 pulse. A contour filter on S1 and S2, our most powerful filter, eliminates both components of background protons and only the $^3He(d,p)^4He$ ridge remains as shown in the lower part of Fig. 8. (We note that the filters which define the deuteron events in the SIN experiment are made by hardware discriminator thresholds on their Q and R detectors and time-of-flight signals.) These spectra exhibit little background and further software cuts on S3, E or pion time-of-flight are redundant. This redundancy is lost for the data at T_π = 256 MeV and these filters become significant. The final results at $\theta_d = 18.0°$ are shown in Fig. 9. There is no dramatic energy dependence in the data from 134 to 256 MeV. The results[11,14] $\theta_d = 15.0$ and 20.0° from SIN are shown also in the figure for comparison. Clearly, there is remarkable disagreement between the present work and that of the previous speaker.

Although the exact cause of the discrepancy has not yet been determined, it is useful to compare the two methods in more detail. The main differences between our method and that of the ETH group reside in the polarimeter itself. Here, I will only highlight two major differences. First, the aperture of the SIN polarimeter (3.0 cm) is approximately three times smaller than the LAMPF polarimeter (8.9 cm). Since the deuteron beam size at SIN is comparable with the polarimeter aperture it is possible that particles identified as deuterons entering the polarimeter hit a wall and never enter the ^3He volume. This would result in a low efficiency ε and a more positive t_{20}^{lab}. Clearly there is a geometry dependent correction to be made in the SIN experiment. Since the deuteron trajectories are not measured in the actual experiment, this effect might lead to the observed disagreement. This problem is avoided in the LAMPF experiment in two ways: (i) the aperture of the polarimeter is approximately three times larger as mentioned and (ii) two x-y wire chambers measure the trajectory of each deuteron entering the polarimeter. Also, the wire chambers are used at the beginning of each run in order to tune the QQD system and to align the polarimeter with respect to the deuteron beam. Secondly, the energies of the deuterons incident on the LAMPF polarimeter are measured by scanning the polarimeter aperture with 2.0 and 3.0-cm diameter Si(Li) detectors. The importance of measuring the deuteron energy accurately can be seen from the rapid energy dependence of ε_o in Fig. 4. In the SIN experiment the deuteron energies are determined by allowing the deuterons to range out in aluminum foils. Although this method is generally accepted for finding the centroid of the deuteron energy spectrum, it is somewhat problematic to determine the spectrum of deuteron energies. This is important since the width of the deuteron energy spectrum at T_d = 20 MeV, is typically 6 MeV in the SIN experiment. Of course, with the use of Si(Li) detectors this problem is avoided in the LAMPF experiment.

III. RESULTS AND DISCUSSION

The final work is shown in Fig. 10 for T_π = 142, 180, 220 and 256 MeV. The results are compared with the theoretical calculations of Blankleider and Afnan,[2] Betz and Lee,[2] Fayard et al.[3] and Rinat and Starkand.[4] In addition, the dotted curve in the figure represents the Blankleider-Afnan calculation with no P_{11} π-N channel. Omitting this channel has the effect of both removing absorption and P_{11} π-N rescattering from the calculation. The remarkable result is that the present work is in best agreement with the calculations which have no P_{11} channel. This observation is supported by the measurements of differential cross section and iT_{11} at T_π = 142 MeV. The available data for π-d elastic scattering at T_π = 142 MeV are shown in Fig. 11. The solid curve in the figure represents the full calculation of Blankleider and Afnan and the dotted curve, the calculation with no P_{11} π-N amplitude. Clearly, the calculation with no P_{11} gives better agreement with the data. A similar result is obtained with the calculations of Fayard et al. and Rinat and Starkand. At higher energies the result is not as striking as at 142 MeV. In fact, at 256 MeV there is worse overall agreement if the P_{11} channel is removed from the Blankleider-Afnan calculations. This may be an indication that the energy dependence of the P_{11} amplitude is in error as well as the magnitude. Unfortunately, there are many open questions at this high energy and no firm conclusions can be drawn. On the other hand, at T_π = 142 MeV one might expect the theoretical calculation to be more reasonable since the momentum transfer is relatively small $q < 2\ fm^{-1}$ and the deuteron wave function and N-N interaction are then reasonably well known. Moreover, dependence of the deuteron wave function on relativistic corrections is not substantial at the lower energy.

Although, omitting the P_{11} channel from the calculation is a somewhat drastic measure, especially since absorption is removed, may not be as unreasonable as it appears. Afnan and Blankleider have shown that true pion absorption can be expected to proceed primarily through the $L_{N\Delta} = 0$ and $J^\pi = 2^+$ channel; whereas, the absorptive amplitude that is believed to have the dominant effect on the elastic channel occurs in $L_{N\Delta} = 2$, $J^\pi = 0^+$ channel. Thus, in terms of the calculation elastic scattering data indicate that the 0^+ absorptive channel is in error, while no claim is made about the 2^+ channel which gives rise to most of the true absorptive cross section. A question which naturally arises from this work is whether or not π-d elastic scattering would be sensitive to possible dibaryon resonance effects since elastic scattering appears to be weakly dependent on the absorption channel and since the predicted dependence favors low relative orbital angular momentum in the intermediate N-N channel. In fact, Afnan and Blankleider predict that the intermediate NN channel with $L_{NN} = 0$ should have the dominant effect on elastic scattering. At present, the evidence indicates that π-d elastic scattering channel is not well suited for studies of possible dibaryon resonances. Another question which may now be asked is whether or not the quadrupole form factor of the deuteron can be measured in π-d scattering if absorption has a small effect on elastic scattering.

IV. CONCLUSIONS

The energy dependence of t_{20}^{lab} was measured in the range T_π = 134 to 256 MeV. There is remarkable disagreement with the work at SIN: near T_π = 140 MeV we observe a negative $t_{20}^{lab} \simeq -0.6$, while the ETH group observes a positive $t_{20}^{lab} \simeq 0.2$. In the present work no unusually dramatic energy dependence of t_{20}^{lab} was observed. At present there is no apparent evidence for dibaryon resonance effects in π-d scattering. The measurements of t_{20}^{lab} are in best overall agreement with the calculations in which the P_{11} π-N amplitude has been omitted. This suggests that the effects of pion absorption are not properly taken into account by the existing theories.

Clearly, more theoretical effort is necessary in order to understand this simplest π-nucleus process, π-d elastic scattering. Future measurements of π-d scattering should focus on polarization studies which cover a broader angular range and achieve a higher accuracy.

The collaborators for this experiment are W. S. Freeman, D. F. Geesaman, J. R. Specht, E. Ungricht, B. Zeidman, E. J. Stephenson, J. D. Moses, M. Farkhondeh, S. Gilad and R. P. Redwine. In addition, we thank K. Stephenson, J. S. Frank and M. J. Leitch for their substantial part in developing the new polarimeter. This work was supported by the U. S. Department of Energy under Contract W-31-109-Eng-38.

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TABLE I
Summary of Experiments with New Polarimeter

Experiment	Location	Completion Date
Calibration	Berkeley 88" cyclotron	July 1980
$\pi d \rightarrow \pi \vec{d}$ (exp. no. 483)	LAMPF (LEP)	August 1980
$ed \rightarrow e\vec{d}$ (exp. no. 7920)	MIT/Bates	June 1982
calibration check	LANL three-stage tandem Van-de-Graaff	November 1982
$\pi d \rightarrow \pi \vec{d}$ (exp. no. 673)	LAMPF (P^3)	February 1983

Fig. 1. Comparison of current three-body calculations with measured differential cross sections and analyzing powers for π-d elastic scattering.

Fig. 2. Comparison of two different sets of pole and nonpole P_{11} π-N phase shifts (from Ref. 8) which give rise to essentially the same total π-N scattering phase shift at low energies.

Fig. 3. The upper panel indicates the results of three-body calculations for t_{20}^{lab} with no P_{11} π-N amplitude, while the lower panel illustrates the same calculations with the P_{11} amplitude. This indicates the sensitivity of t_{20}^{lab} to the P_{11} amplitude, and consequently, to pion absorption.

Fig. 4. The results for the polarimeter efficiency for unpolarized deuterons is given in the upper panel for two separate calibrations which were two years apart and performed at two different laboratories. The analyzing power of the polarimeter is given in the lower panel. These results are for deuterons which enter along the central axis of the polarimeter.

Fig. 5. The results of a measurement of t_{20} for e-d elastic scattering are in good agreement with existing calculations.

Fig. 6. Schematic diagram of the apparatus to measure t_{20}^{lab} .

Fig. 7. Contour plot of dE/dx signals in scintillators S1 and S2. The deuterons incident on the polarimeter are clearly separated from background protons. (No previous software cuts are placed on this spectrum.)

Fig. 8. Countour plot of the time-of-flight between detectors S2 and S3 vs. the pulse height in detector E. The upper part indicates the proton spectra before any software cuts are placed on the S1-S2 spectrum shown in Fig. 7. the protons from the $^3He(d,p)^4He$ are clearly visible without the software filter on deuterons. The lower figure illustrates the results with a filter only on S1 and S2.

Fig. 9. The darkened circles indicate present measurements of t_{20}^{lab} for a deuteron recoil angle of 18.0°. These are compared with the work of Refs. 11 and 14 at θ_d = 15.0 and 20.0°.

Fig. 10. Present measurments of t_{20}^{lab} are indicated by the darkened points while the previous measurements of Ref. 13 are represented by the open circles. The results agree best with the calculations which contain no P_{11} π-N amplitude, the dotted curve.

Fig. 11. The data points represent measuremnts of the differential cross section (upper panel) and vector analyzing power (lower panel) at $T_\pi \approx 142$ MeV. Again, the data seem to be in best agreement with the calculations with no P_{11} π-N amplitude.

ANL-P-17,281

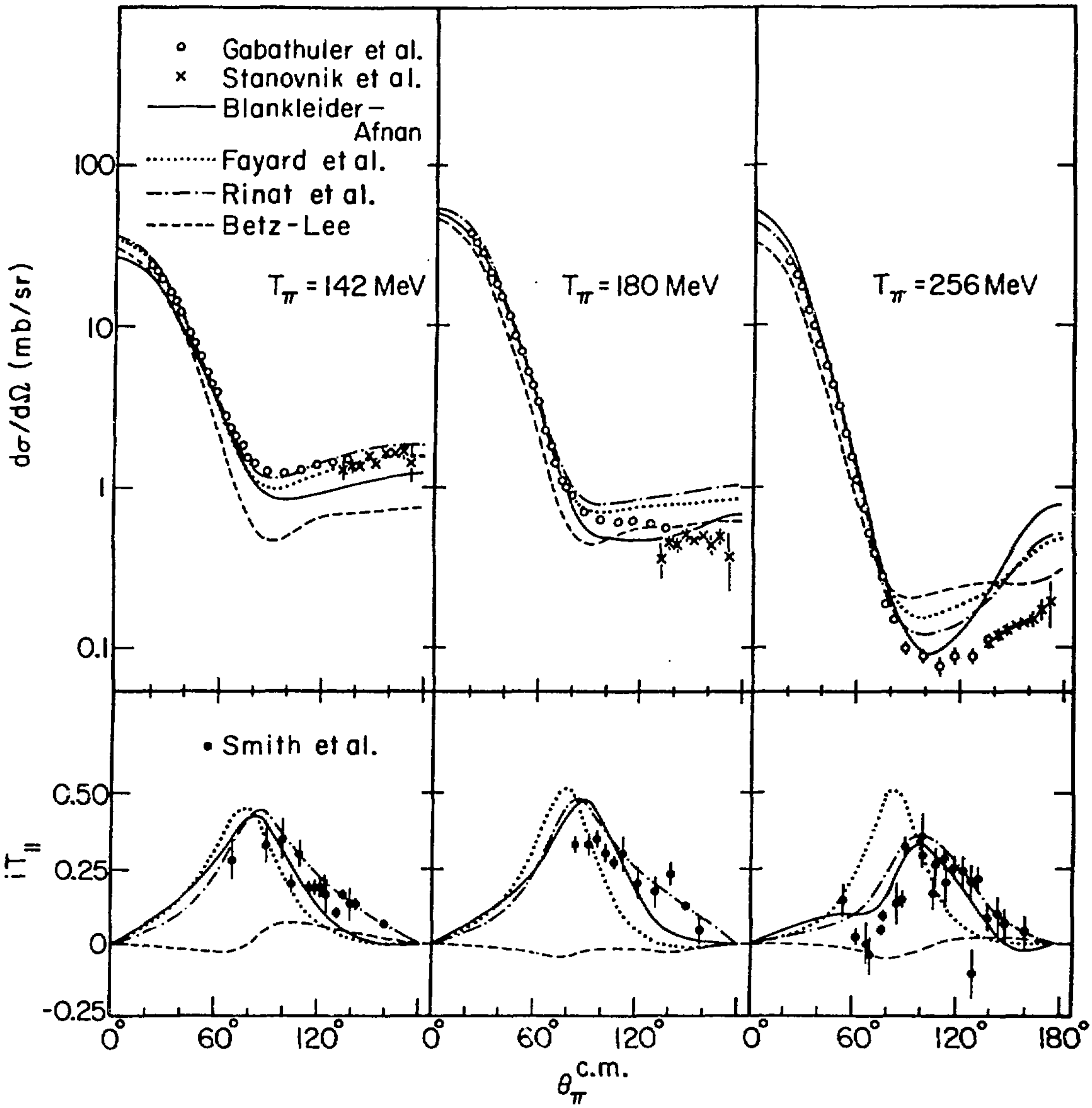
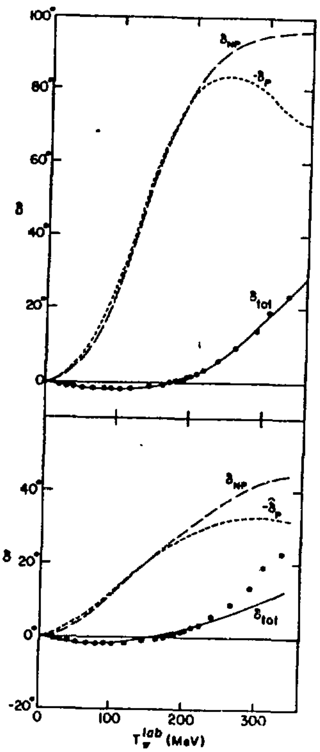


Fig. 1



100°
80°
60°
40°
20°
0
δ
δ_{NP}
$-\delta_P$
δ_{tot}
40°
20°
0°
-20°
δ
δ_{NP}
$-\hat{\delta}_P$
δ_{tot}
0
100
200
300
T_π^{lab} (MeV)

Fig. 2

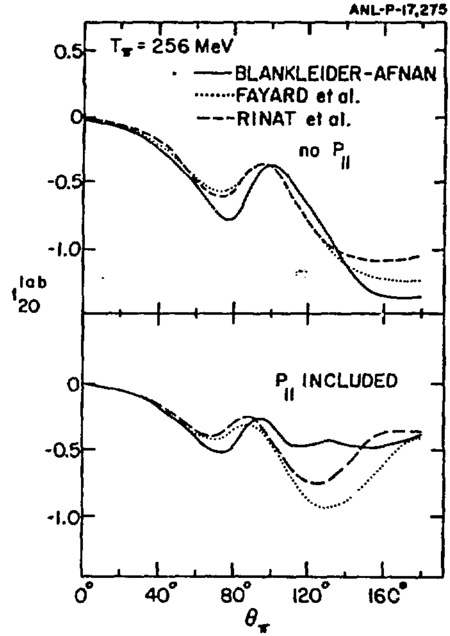

ANL-P-17,275
T_π = 256 MeV
BLANKLEIDER-AFNAN
FAYARD et al.
RINAT et al.
no P_{11}
P_{11} INCLUDED
t_{20}^{lab}
0.5
0
-0.5
-1.0
0°
40°
80°
120°
160°
θ_π

Fig. 3

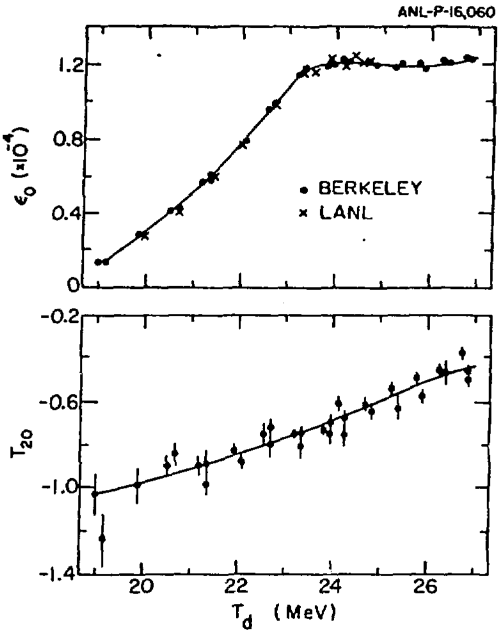
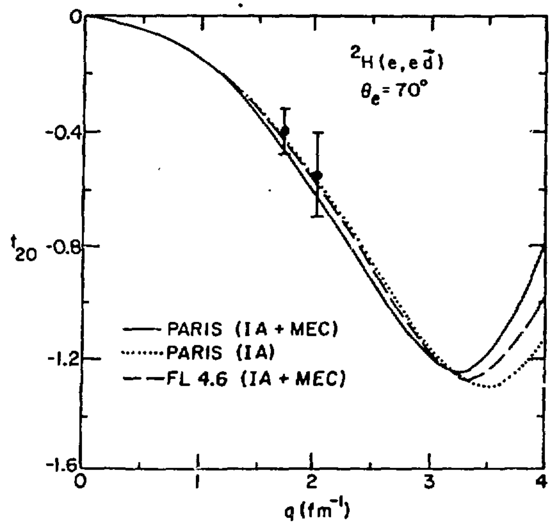

ANL-P-16,060
1.2
0.8
0.4
0
ϵ_0 (×10^{-4})
• BERKELEY
× LANL
-0.2
-0.6
-1.0
-1.4
T_{20}
20
22
24
26
T_d (MeV)

Fig. 4



$^2H(e,e\vec{d})$
$\theta_e = 70°$
PARIS (IA + MEC)
PARIS (IA)
FL 4.6 (IA + MEC)
t_{20}
0
-0.4
-0.8
-1.2
-1.6
0
1
2
3
4
q (fm^{-1})

Fig. 5

ANL-P-16,974

APPARATUS TO MEASURE t_{20} IN $\pi - d$ SCATTERING

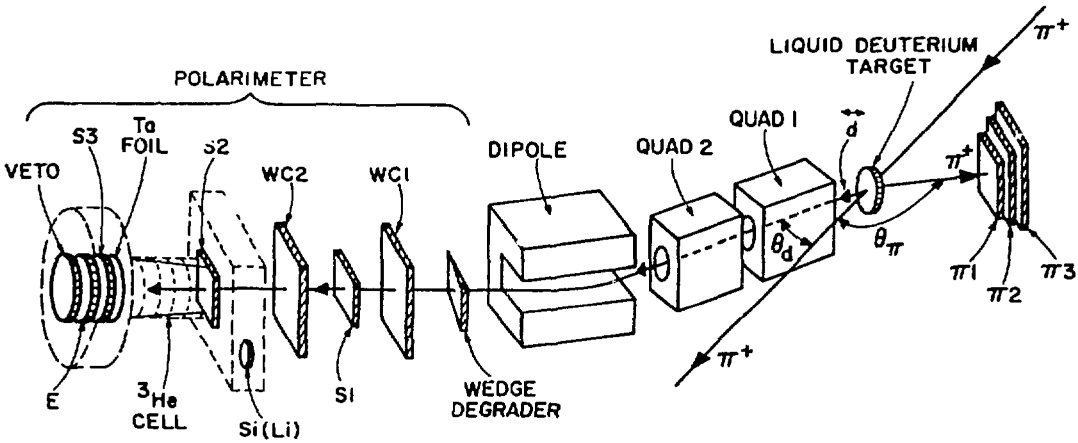


Fig. 6

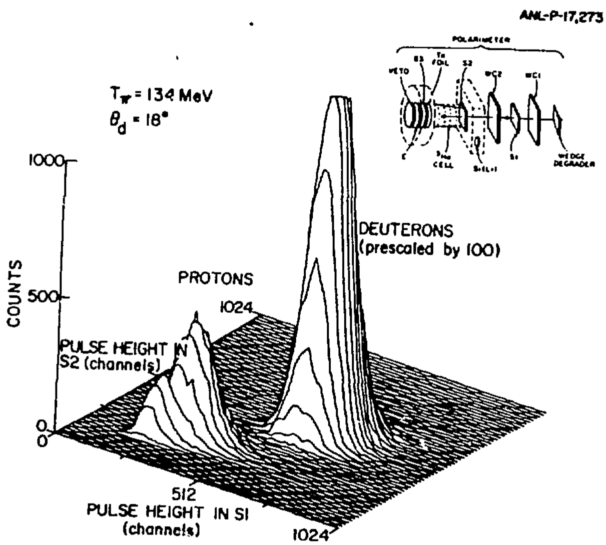

ANL-P-17,273
T_π = 134 MeV
θ_d = 18°
1000
500
0
COUNTS
PROTONS
DEUTERONS
(prescaled by 100)
1024
PULSE HEIGHT IN
S2 (channels)
512
PULSE HEIGHT IN S1
(channels)
1024
POLARIMETER
VETO
S3
WC2
WC1
S1
CELL
WEDGE
DEGRADER

Fig. 7

ANL-P-17,274

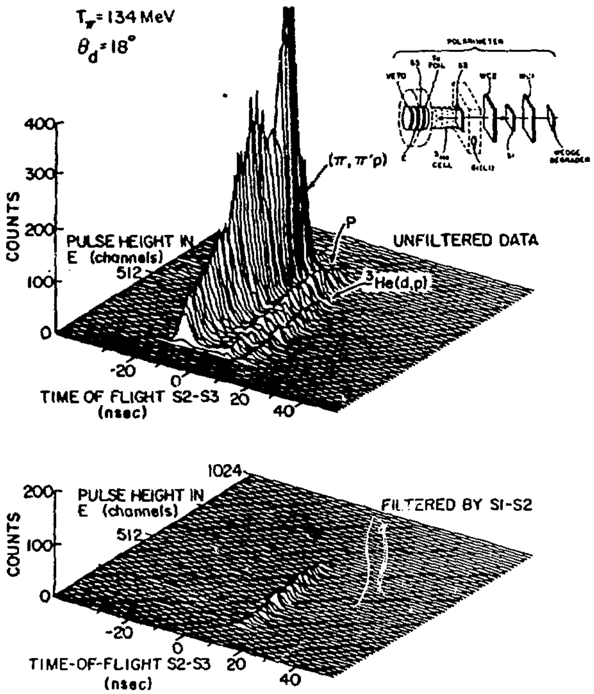


Fig. 8

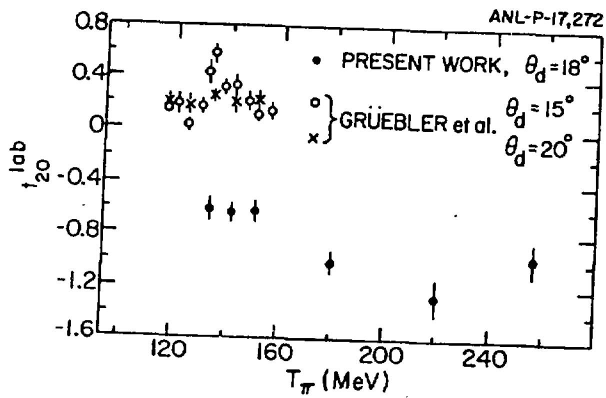
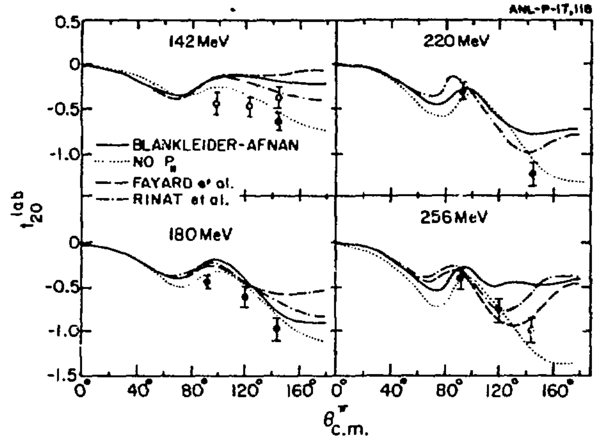
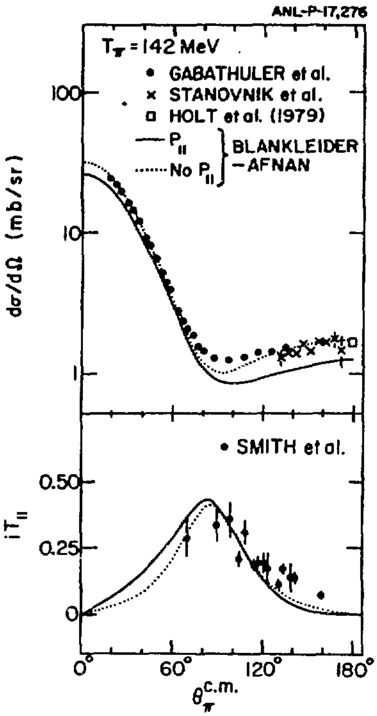

ANL-P-17,272
0.8
0.4
0
-0.4
-0.8
-1.2
-1.6
t_{20}^{lab}
• PRESENT WORK, $\theta_d = 18°$
o
x
GRÜEBLER et al.
$\theta_d = 15°$
$\theta_d = 20°$
120
160
200
240
T_π (MeV)

Fig. 9



ANL-P-17,118
142 MeV
220 MeV
180 MeV
256 MeV
BLANKLEIDER-AFNAN
NO P11
FAYARD et al.
RINAT et al.
t_{20}^{lab}
$\theta_{c.m.}^{\pi}$

Fig. 10



ANL-P-17,276
T_π = 142 MeV
GABATHULER et al.
STANOVNIK et al.
HOLT et al. (1979)
P11
No P11
BLANKLEIDER -AFNAN
100
10
1
dσ/dΩ (mb/sr)
SMITH et al.
0.50
0.25
0
iT11
0°
60°
120°
180°
θπ c.m.

Fig. 11