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POLARIZATION PHENOMENA IN THE THREE-NUCLEON SYSTEM

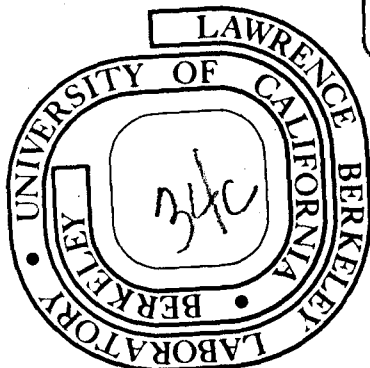
H. E. Conzett

August 1974

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POLARIZATION PHENOMENA IN THE THREE-NUCLEON SYSTEM

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1. Introduction

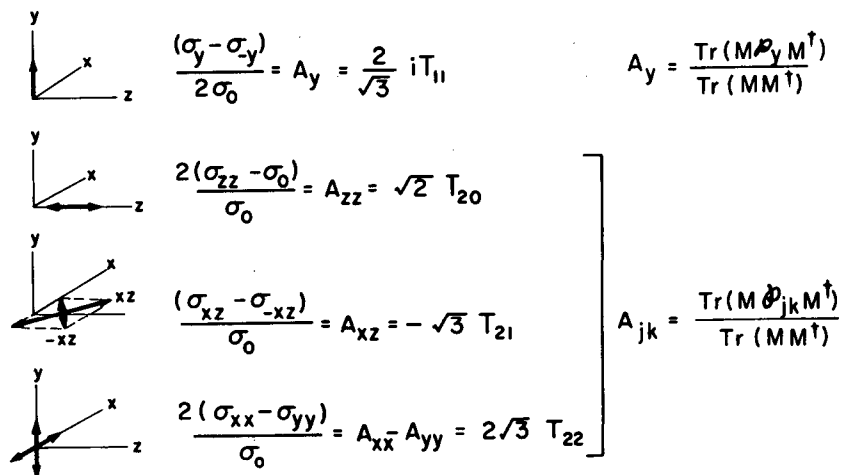
There has been an impressive quantity and quality of polarization data acquired during the past few years on the mass 3 to mass 6 systems, essentially with beams of polarized protons and deuterons. I have chosen, in this paper, to limit the discussion of polarization effects to those of the three-nucleon system. I do this for two reasons: 1) There is now a rather extensive variety of experimental results on this system, and the ever more detailed three-body calculations of these polarization effects have been remarkably successful. Thus, a description of the past developments and present status of this research, in the detail that is warranted by this substantial progress, will take my allotted time. 2) Certainly a central role in this and in the past few-body conferences has been that of the "exact" three-body theory, which calculates the three-nucleon observables from the two-nucleon interaction. Thus, there is, so far, a natural separation between descriptions of three-nucleon data and those of mass 4 and higher. Polarization results are certainly important in the latter systems, but the appropriate theoretical descriptions are generally those of R-matrix analysis, and the direct connection to the nucleon-nucleon force is not made.

2. Terminology

Since the community of experimentalists involved in investigations of polarization phenomena is rather small, let me begin with some definitions and terminology.¹ Fig. 1 summarizes everything I will use in this discussion. For the analyzing powers I list an "experimental" definition along with its theoretical counterpart. We follow the Madison convention² throughout; the incident beam is along the z axis and the y axis is taken along $\vec{k}_i \times \vec{k}_f$, i.e. perpendicular to the reaction plane. In direct analogy with the spin 1/2 case, the fully vector-polarized deuteron beam (indicated in the top figure by the single-headed arrow) has zero population of the $m = -1$ deuteron magnetic substate and twice the normal population of the $m = +1$ state, where normal means the population in an unpolarized beam. The $m = 0$ state, which is not indicated, has its normal population. The vector analyzing power A_y (cartesian form) or

iT_{11} (spherical form) is given as shown, where σ_y and σ_{-y} are differential cross sections with the vector polarization oriented in the $+y$ and $-y$ directions, respectively, and σ_0 is the spin-averaged, or unpolarized, cross section. In the theoretical expression for A_y , M is the transition matrix and ρ_y is a basic spin-one 3×3 matrix operator. A fully tensor polarized beam is one with zero population of the $m = 0$ substate and normal populations of the $m = \pm 1$ substates. The vector polarization is zero, and this tensor polarization corresponds to an alignment of the deuteron indicated by the double-headed arrows in Fig. 1. The tensor analyzing powers A_{zz} , A_{xz} , and $A_{xx} - A_{yy}$ are given then by the differences in cross-sections for deuterons with the alignment axis oriented in the different directions shown with respect to the beam direction. The ρ_{jk} are the corresponding matrix operators.

Deuteron analyzing powers



Polarization transfer coefficients (\bar{p} to \bar{d})

$$p_{i'} = (P_{i'} + \sum_k K_k^{i'} p_k) I_0 / I \quad K_k^{i'} = \frac{\text{Tr}(M\sigma_k M^\dagger \rho_{i'})}{\text{Tr}(MM^\dagger)}$$

$$p_{i'j'} = (P_{i'j'} + \sum_k K_k^{i'j'} p_k) I_0 / I \quad K_k^{i'j'} = \frac{\text{Tr}(M\sigma_k M^\dagger \rho_{i'j'})}{\text{Tr}(MM^\dagger)}$$

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Fig. 1

The polarization transfer coefficients for the case of proton-to-deuteron polarization transfer are defined in the bottom two lines. In the first expression, $P_{i'}$,

is the deuteron vector polarization resulting from N-d scattering with an initial nucleon beam of polarization components p_k, P_i , is the deuteron vector polarization produced in the scattering of an unpolarized beam, I_0 and I are the cross sections for scattering of unpolarized and polarized nucleons, respectively, and $K_k^{i'}$ are the vector-to-vector polarization transfer coefficients. For example, with $P_{i'} = 0$, $I = I_0$, and for a nucleon beam polarized along the y-axis, $p_{y'} = K_y^{y'} p_y$. As shown in the second expression, the vector-to-tensor polarization transfer coefficients $K_k^{i'j'}$ are defined in the same manner. Here $p_{i'j'}$ are the tensor polarizations of the scattered deuterons and $P_{i'j'}$ are the tensor polarizations that occur in the scattering with unpolarized nucleons.

3. Analyzing Powers in Nucleon-Deuteron Elastic Scattering

The first comparison, some 10 years ago, between the calculated³ and experimental⁴ proton analyzing power in N-d scattering below 100 MeV is shown in Fig. 2. This was at 40 MeV.

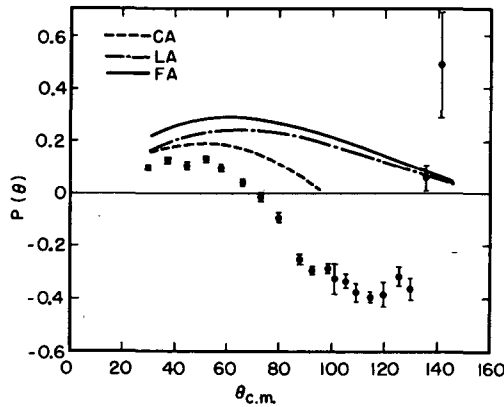


Fig. 2

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This impulse-approximation calculation was quite inadequate to explain the data. In fact, the discrepancy between the experimental and calculated results increased in going to the more complete versions of the calculation. Soon thereafter the early three-nucleon calculations, based on the Faddeev equations with simple S-wave nucleon-nucleon potentials, were very successful in fitting the elastic N-d differential cross section data up to about 50 MeV. Since only S-wave forces were used, those calculations could not provide the observed polarizations. There was already a substan-

tial amount of nucleon analyzing-power data up to 50 MeV⁵ and a few measurements of the deuteron vector and tensor analyzing powers at lower energies.⁶ Only within the past three years have more realistic N-N potentials been used in efforts to fit the polarization data. Aarons and Sloan⁷ used a two-body force with separable terms corresponding to both the 1S_0 and the coupled 3S_1 - 3D_1 (tensor) interactions. This calculation gave deuteron tensor polarizations in qualitative agreement with experiment over the range $E_N = 3$ -11 MeV. Fig. 3 shows the comparison near 11 MeV. The solid and dashed curves are for the percentage D-state in the deuteron of 7% and 2%, respectively.

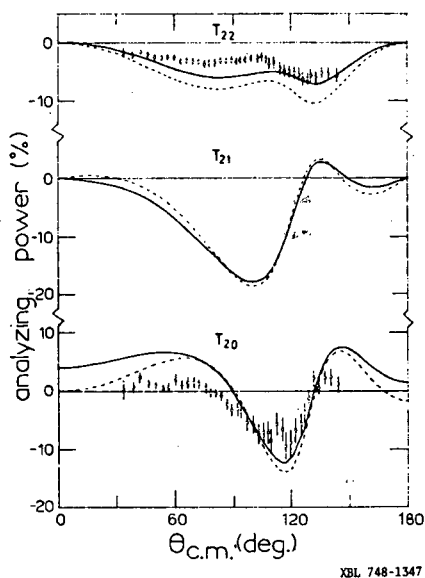


Fig. 3

vious calculations of the vector polarizations was dramatic. The nucleon polarizations were in excellent agreement with the experimental data up to 14 MeV, and qualitative agreement was achieved beyond that to 40 MeV. As an example, Fig. 5 shows Pieper's comparison with the nucleon polarization near 23 MeV. Sets C and E correspond to different P-wave potentials, and set D adds D-wave forces to set C. The agreement with the available deuteron vector analyzing-power data was not as good, as is shown in Fig. 6 near $E_d = 20$ MeV. It soon proved, however, that the absolute normalization of these data was in error by about a factor of two, due to an uncertainty in the value of the beam polarization. These were some of the first measured deuteron

and dashed curves are for the percentage D-state in the deuteron of 7% and 2%, respectively. In contrast to this agreement, the calculated nucleon and deuteron vector polarizations were much too small, as shown in Fig. 4. Soon thereafter Pieper⁸ and Doleschall⁹ independently included S- and P-wave interactions, and the improvement over the pre-

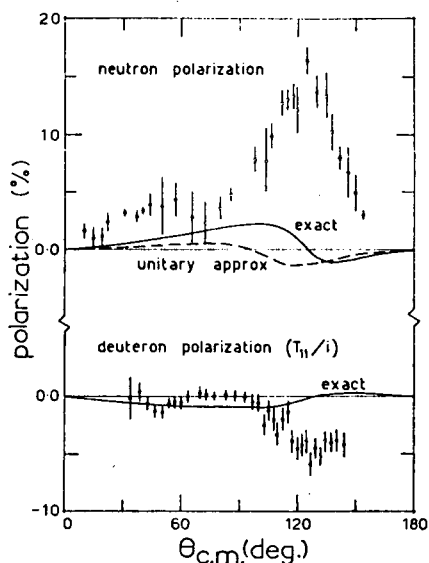


Fig. 4

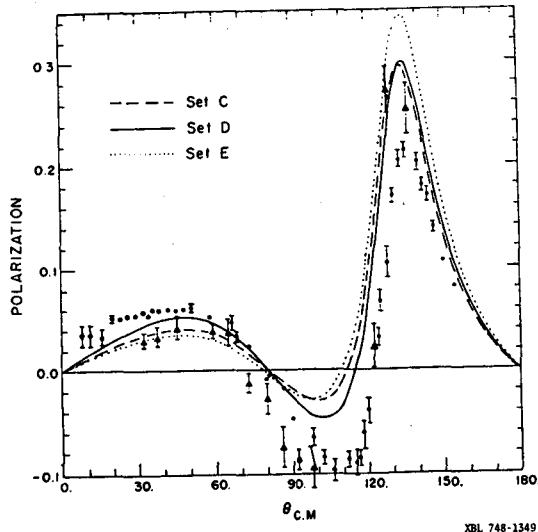


Fig. 5

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with separable N-N potentials for the 1S_0 , 3S_1 - 3D_1 , and P-wave components of the two-nucleon interaction. Pieper's calculation (solid line) included D-waves, but not the 3S_1 - 3D_1 tensor force. Also, his calculation treated the S-wave part exactly in the Faddeev equations, while the part containing the P- and D-wave N-N input information was treated in first-order perturbation theory. Thus, one could not conclude that the

analyzing powers, and there had not yet been established any standard analyzer with which to determine and to monitor deuteron beam polarizations. Almost concurrently with these calculations, more precise determinations were made of the deuteron vector analyzing powers at $E_d = 20$ and 30 MeV,¹⁰ and these are shown in Figs. 7 and 8. The dashed line in Fig. 7 represents the data of Fig. 6. The solid curve is Pieper's prediction. In Fig. 8 the curves are the calculated results at $E_d = 28.2$ MeV. Doleschall's calculation (dashed line) was an exact one

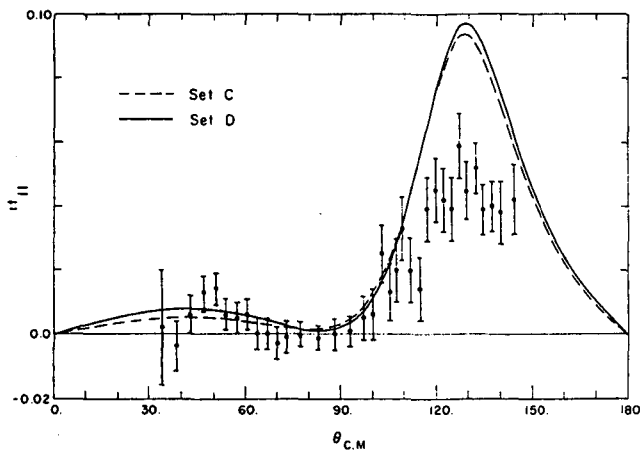


Fig. 6

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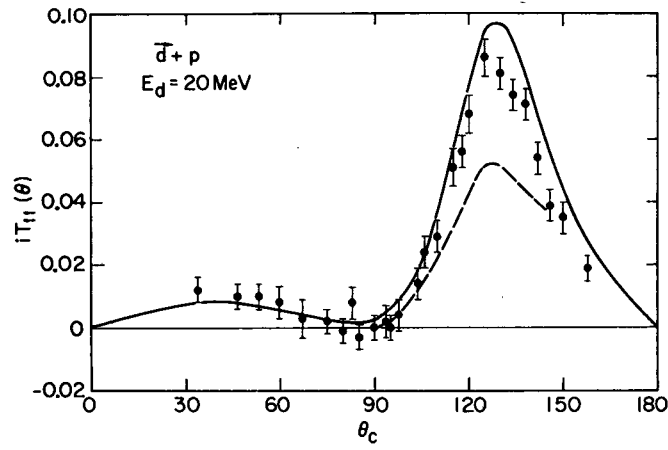


Fig. 7

differences seen in Fig. 8 were due mainly to the additional D-wave interactions in Pieper's calculation. In fact, in a subsequent paper Pieper¹¹ compared his perturba-

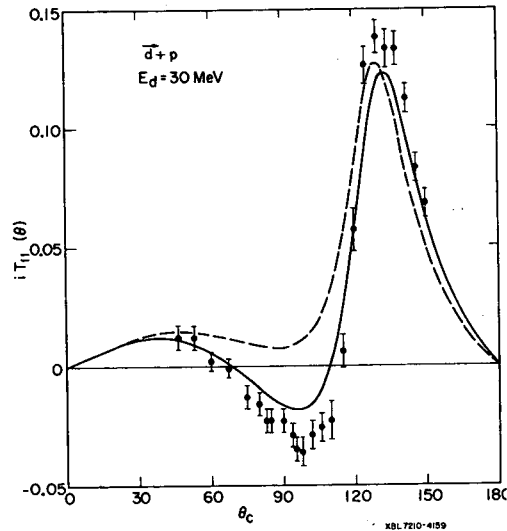
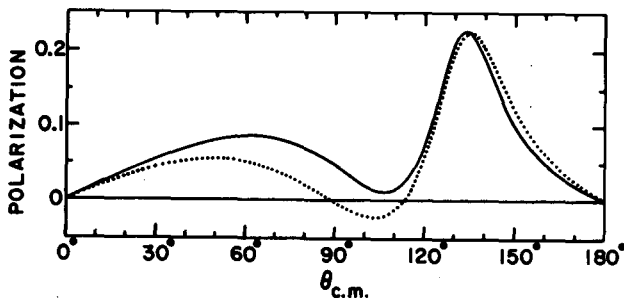


Fig. 8

tive calculation with the exact result of Doleschall for the same N-N input interactions, and he found that significant differences, as shown in Fig. 9 for the nucleon polarization near 23 MeV, were indeed due to the different methods of calculation.

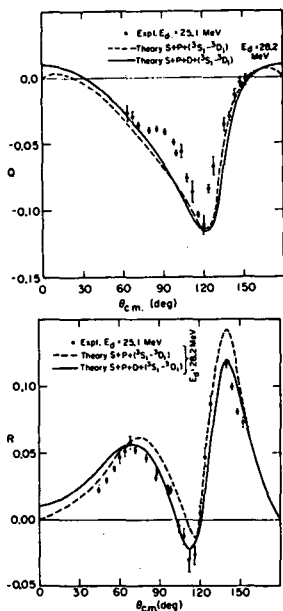
The dotted curve is the perturbative calculation, so the fact that it agrees better with the data than does the exact calculation appears to be a fortuitous result.



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Fig. 9

These calculations have also provided very good fits to the recently measured tensor analyzing powers.¹² Examples near $E_d = 25$ MeV are shown in Fig. 10. The predictions, which preceded the data, are for $E_d = 28.2$ MeV. The dashed line is Dole-schall's result, and the solid line is that of Pieper¹³, which now includes the (3S_1 - 3D_1) tensor force. Q and R are linear combinations of T_{20} and T_{22} [$Q = (1/2\sqrt{2})(T_{20} + \sqrt{6} T_{22})$, $R = (1/2\sqrt{2})(T_{20} - \sqrt{6} T_{22})$].



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Fig. 10

At this point, then, these three-nucleon calculations had shown very considerable success in fitting the several available N-d elastic scattering observables. It was, also, clear that the polarization data required the use of the more realistic, i.e. more detailed and more complicated, N-N interactions, and thus provided the more sensitive and significant tests of the calculations. The conclusions then were that 1) the N-N P-wave interactions were chiefly responsible for the observed vector polarizations, whereas 2) the 3S_1 - 3D_1 tensor force was the source of the N-d tensor polarizations.

The stage was now ready for an examination of the sensitivity of the calculated N-d observables to changes in the N-N input interactions. Certainly, the first goal of the three-body theory has been to reproduce three-nucleon data with calculations that use

two-nucleon forces. Clearly, a second goal is to pursue the possibility of deducing, from

N-d scattering and the three-body calculations, information on the N-N interaction which has not been available from N-N scattering itself. Very recent investigations have suggested that this possibility exists. In contrast to the two quite definite conclusions noted above, there have been conflicting opinions concerning the effect of the N-N tensor force on the N-d vector polarizations. Pieper¹³ reported only slight changes with the addition of the tensor force, and he suggested¹¹ that changes in the 3S_1 - 3D_1 potential would have little effect on the nucleon polarization. This conjecture was based on Sloan and Aarons result,¹⁴ which demonstrated that none of the N-d polarizations were very sensitive to reasonable changes in the tensor interaction. However, that calculation did not include P-waves, so the vector polarizations were unrealistically small. Doleschall's earlier calculation⁹ showed a substantial change in the vector polarizations with the addition of the tensor force to the S- and P-wave interactions, and his most recent calculation¹⁵ demonstrates that the vector polarizations are quite sensitive to the details of the 3S_1 - 3D_1 potential used. First of all, as shown in Fig. 11, his P-wave interactions were improved to give a better representa-

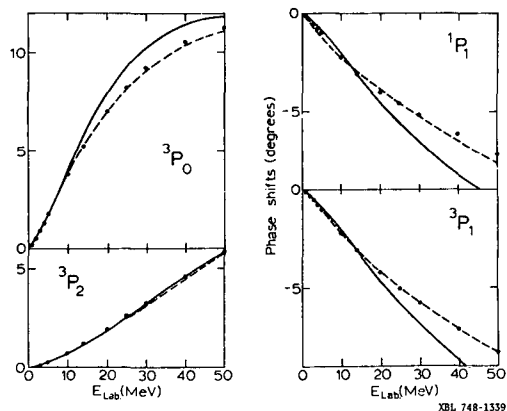


Fig. 11

tion of the N-N P-wave phase shifts, which are shown as the dots. This had the effect shown in Fig. 12, where the solid and dashed curves correspond to the solid and dashed P-wave curves of Fig. 11. Also, he constructed rank-2 tensor interactions in an attempt to simultaneously reproduce the 3S_1 and 3D_1 phase shifts, the corresponding mixing parameter ϵ_1 , and the deuteron properties. As seen in Figs. 13 and 14, it was not possible to find a single rank-2 tensor force which satisfied all of these criteria, so two such potentials were used. One, the T4D force, reproduced the low energy (≤ 100 MeV) 3D_1 phase shifts but gave larger values of ϵ_1 than have been deduced from n-p

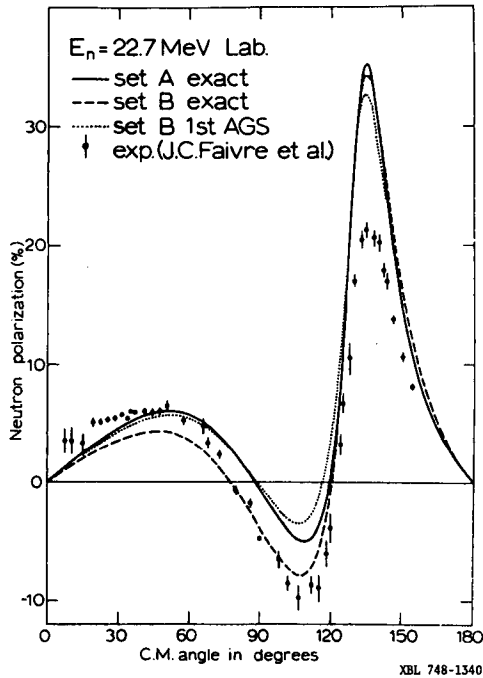
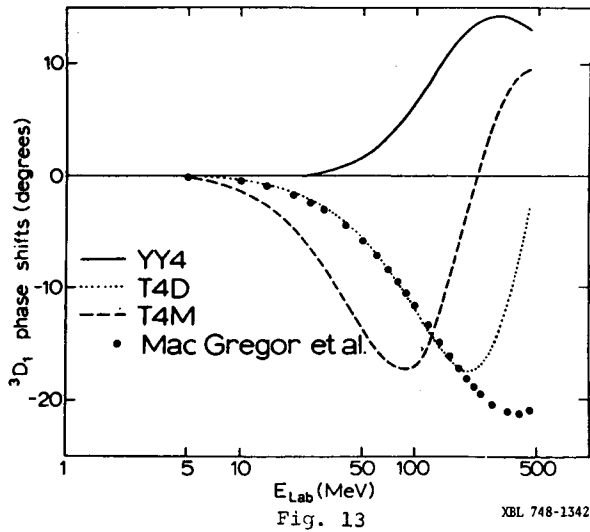


Fig. 12

the same energy, so we very recently at Berkeley made measurements¹⁷ of the deuteron vector analyzing power, iT_{11} , in \vec{d} -p scattering at $E_d = 45.4 \text{ MeV}$ for direct comparison

scattering.¹⁶ The other, the T4M force, reproduced the low energy ϵ_1 behavior but not that of the 3D_1 phase shift. Fig. 15 shows the separate effects of these two different tensor interactions on the nucleon polarization in N-d scattering at 22.7 MeV. It is clear (compare with Fig. 11) 1) that the tensor interaction has a substantial effect on the (vector) polarization, and 2) that the addition of the T4M force gives an excellent fit to the data at angles larger than $\theta_c = 80^\circ$. In a further effort to improve the agreement with the data, Doleschall also included a 3D_2 interaction. Computational limitations precluded the addition of a complete set of D-wave interactions. The result is shown in Fig. 16 as the solid curve, which shows some improvement in the fit to the forward angle data. Doleschall also calculated deuteron vector polarizations at



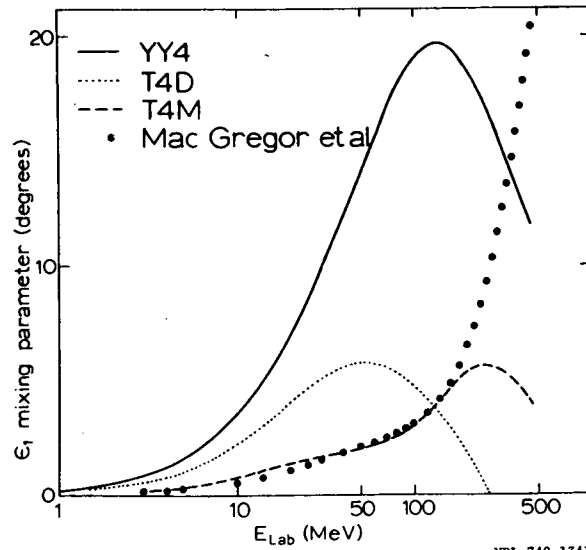


Fig. 14

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with the calculated vector polarization at the equivalent nucleon energy of 22.7 MeV. Our data are compared in Fig. 17 with the calculated results for the different N-N interactions. The dotted curve is the result with S- and P-waves plus the T4D tensor potential; the dashed line, with T4M in place of T4D; and the solid line, with the addition of the 3D_2 terms to the T4M case. Just as with the nucleon polarization, this final step gives improved agreement with the forward angle data at the expense of a slightly poorer fit in the region $\theta_c = 85^\circ$ to 115° .

The angular region forward of $\theta_c = 120^\circ$, wherein the remaining discrepancies between experiment and theory exist, is just the region of greatest sensitivity to the details of the 3S_1 - 3D_1 tensor interaction. Clearly, it would be most interesting and useful to do the calculation with a tensor force which simultaneously reproduces the N-N 3D_1

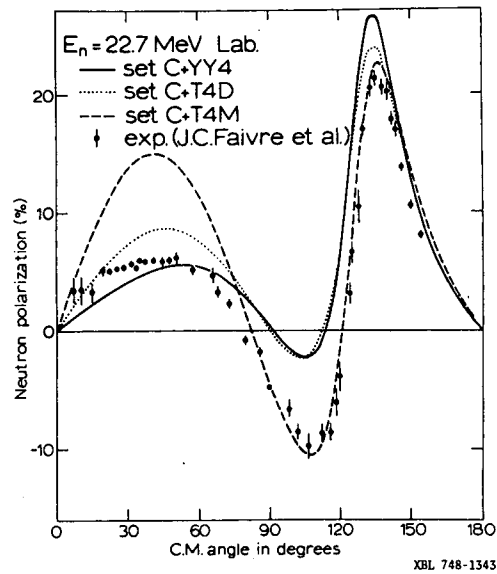


Fig. 15

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phase shift and the mixing parameter ϵ_1 . For example, the rank-4 potential recently constructed by Pieper¹⁸ does just that.

I must now digress momentarily in order to connect these results with a problem of rather long standing in n-p scattering. MacGregor et al., in their phase shift analyses of n-p data five years ago, found that the 1P_1 phase shift $\delta(^1P_1)$ and the mixing parameter ϵ_1 were strongly correlated and poorly determined below 80 MeV.¹⁶ Neither, in fact, was near the theoretical expecta-

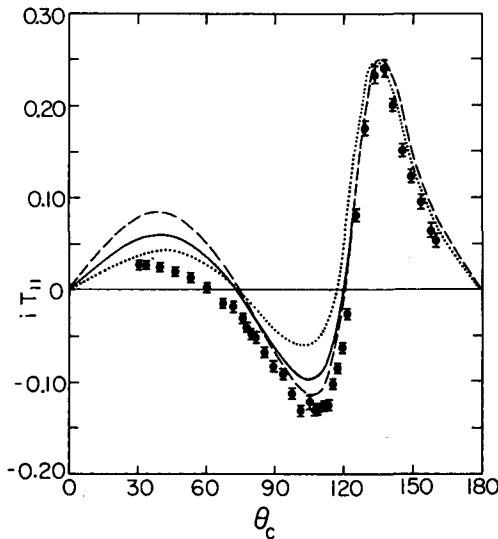


Fig. 17

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most sensitive to that phase shift. They conclude that the existing forward angle data are suspect, and they recommend that forward angle absolute $d\sigma/d\Omega$ measurements, accurate to $\pm 1\%$, be made in order to pin down $\delta(^1P_1)$. Concerning ϵ_1 , they show (Fig. 18) that the present n-p data (σ_{TOT} , $d\sigma/d\Omega$, $P(\theta)$) near 50 MeV leave ϵ_1 undetermined between -10° to $+3^\circ$. They also examine the sensitivity of other experimental observables to ϵ_1 , and they find that the neutron-to-proton polarization transfer coefficient D_t (our $K_{y'}^{y'}$) combines fairly high sensitivity with reasonable experimental feasibility. Fig. 18 also shows the effectiveness of adding to the data set presumed values of D_t , which were taken from a calculation with ϵ_1 fixed at a theoretical expectation near 2.8° . One sees that ϵ_1 is determined to about $\pm 1^\circ$ in each case. Note, also, the assumed

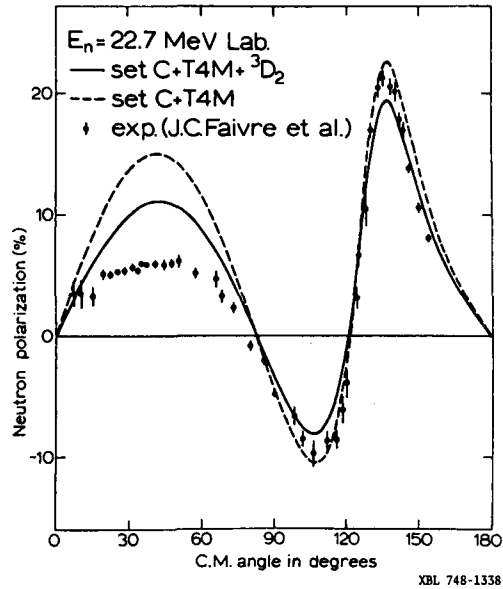


Fig. 16

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tion. Arndt, Binstock, and Bryan¹⁹ have recently examined this problem in considerable detail near 50 MeV, including in their analyses some more recently available n-p data. They did not find a strong $\epsilon_1 - \delta(^1P_1)$ correlation. Concerning $\delta(^1P_1)$, they reemphasize that the differential cross section is the observable

± 0.01 absolute error on D_t , and be assured that such an experiment, if reasonable, is difficult.

Let us return now to the three-nucleon calculation. In view of the demonstrated sensitivity of the vector polarizations to the N-N tensor interaction, it

should be possible, with a tensor force which simultaneously reproduces the N-N $\delta(^3D_1)$ and ϵ_1 , to vary ϵ_1 in a search for improved fits to the N-d vector analyzing power data. It seems possible that this procedure could more easily provide a better determination of the low energy values of ϵ_1 than is possible via the more difficult measurement of D_t . If this should prove to be so, one would indeed have deduced from the three-nucleon investigations specific information about the two-nucleon interaction that has not yet been attainable.

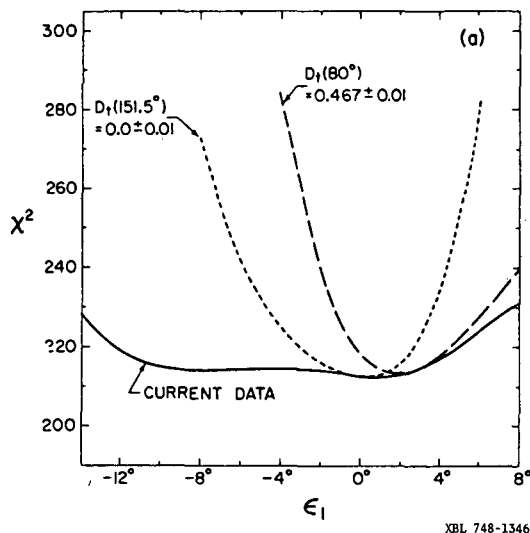


Fig. 18

4. Polarization Transfer in Nucleon-Deuteron Elastic Scattering

The first of the other N-d spin observables measured at energies below 100 MeV were the Wolfenstein spin rotation parameters²⁰ D , R , and A (our $K_y^{y'}$, $K_x^{x'}$, $K_z^{z'}$). These describe the reorientation of the projectile nucleon's spin in the scattering process, and are included in the more general class (Fig. 1) of polarization-transfer coefficients. Measurements had been made of them near 50 MeV,²¹ and Pieper's perturbative three-body calculation⁸ of these spin rotation parameters were in qualitative agreement with the data. The experimental errors of 10% or larger did not encourage any attempt to fit the data in greater detail. At the Los Angeles Few Particle Conference two years ago Ohlsen²² pointed out that polarized beams and experimental techniques have been sufficiently perfected that these more difficult measurements of polarization transfer coefficients could be made. At the same time, the Los Alamos group reported the first determinations of vector-to-tensor polarization transfer coefficients in p-d elastic scattering.²³ Their measurements were made at two angles at energies between 5 and 9 MeV, and the values were consistent with zero within a typical error of ± 0.05 .

Pieper's later three-body calculation,¹¹ an example of which is shown in Fig. 19, gave predicted values of these coefficients to be less than 0.1 for energies below 10 MeV, in essential agreement with the data. Of particular interest was his result that the

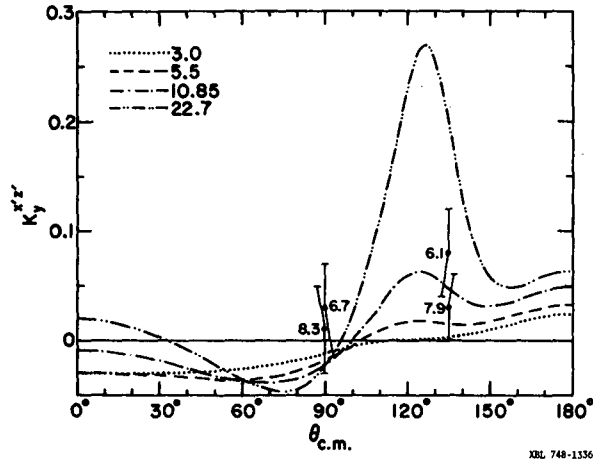


Fig. 19

calculated vector-to-vector transfer coefficients differed more substantially from zero, so his suggestion was that measurements of those could be a fruitful area for experiments. A single measured value of $K_{xx}^{x'x'}$ at 9 MeV.²⁴ was two standard deviations from the calculated value, but it was clear that more data were required for a significant comparison with the predictions. Now, in a contribution to this conference, the Berkeley group reports on measurements of $K_{yy}^{y'y'}$ (θ) at $E_p = 22.7$ MeV.²⁵ Fig. 20 shows these data along with Pieper's predicted curve. The agreement is certainly very good. Since this provides the first significant comparison between experimental and calculated vector-to-vector polarization transfer coefficients, this agreement represents yet another substantial success of the three-body calculations.

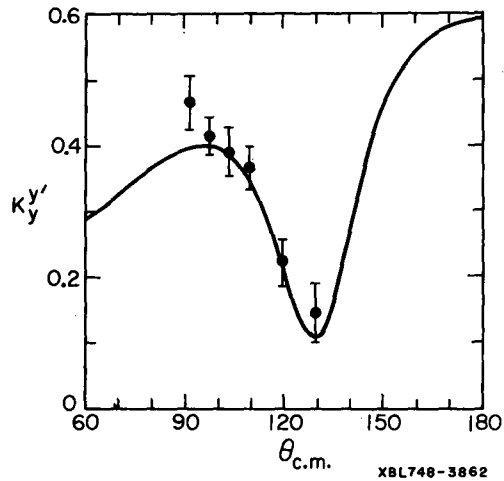


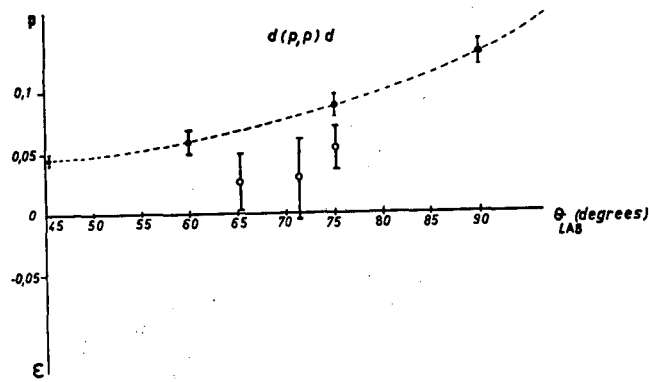
Fig. 20

We have noted the considerable progress that has been made during the past two years in both the experimental and theoretical determinations of polarization observables in N-d elastic scattering. It seems to me that an important undertaking now is to specifically examine the sensitivities of the various analyzing powers and transfer coefficients to the details of the input two-body interactions; for example, sensitivity to variations of $\delta(^1P_1)$ and ϵ_1^i , and to the addition of a complete set of D-wave interactions in the exact calculation. This would provide invaluable guidance in the choice of further experiments, since it is clear that many of the polarization observables can now be measured to just about whatever accuracy is required for specific and detailed comparison with predictions.

5. Polarization effects in the N-d Breakup Reaction

The present status of studies of polarization phenomena in the N-d breakup transition to three-nucleon final states is comparable to that which existed for the elastic channel almost ten years ago. That is, only a few experiments have been done which even show the presence of polarization effects, and theoretical interpretation and predictions via exact three-body calculations have not, as yet, been made. Such calculations²⁶ have been successful in fitting N-d breakup cross-sections, but they have so far been limited to S-wave N-N input interactions. It appears that experimental evidence of significant polarization effects in the breakup channel are required in order to encourage, or even compel, the addition of the tensor force and P-wave contributions to these calculations.

Perhaps the first polarization effects seen in the breakup reaction below 100 MeV were those observed by Arvieux et al. in the reaction $D(\vec{p}, 2p)n$ at 10.5 MeV.²⁷ Their results are shown in Fig. 21. The open circles are their measurements of the proton analyzing power for the transition to the np final-state-interaction region of the 3-body continuum spectrum, in their case selected to be the region of relative np energies $E_{np} \leq 0.5$ MeV. They noted, for comparison, the similarity of the trend of these data to that of the elastic channel analyzing power at 11 MeV, as shown by the solid dots connected by the dashed line. In a contribution to this conference, Blyth et al.²⁸ report an investigation of the deuteron vector analyzing power at several angles in the same reaction $H(\vec{d}, 2p)n$, but now induced with a beam of 12.2 MeV vector polarized deuterons. Their reported values are all consistent with zero, within errors of ± 0.01 to ± 0.03 , but it should be noted that in this case the elastic channel analyzing power at the nearby deuteron energy of 11.5 MeV has a maximum value of less than 0.05.²⁹ We have very recently obtained at Berkeley some results for the deuteron vector analyzing power in the same inelastic transition at $E_d = 45.4$ MeV.³⁰ These are shown in Fig. 22. Again, for comparison, the elastic scattering analyzing power is



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Fig. 21

shown as the smooth curve. Here the similarity between the inelastic and elastic analyzing powers is quite definite. This similarity is rather unexpected in view of the results that were reported by Brückmann et al., in their analysis of cross section data

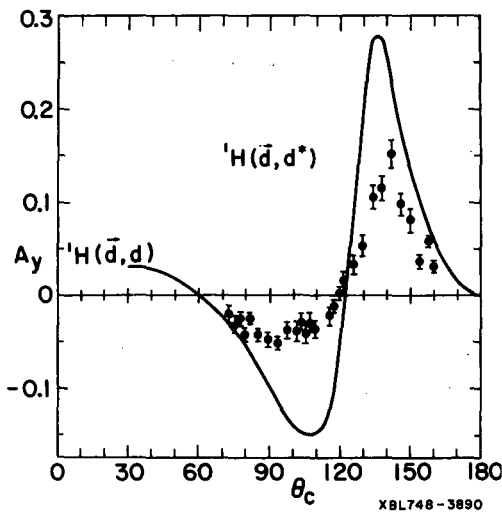


Fig 22

in this reaction at the slightly higher energy $E_d = 52.3 \text{ MeV}$.³¹ Their findings are displayed in Fig. 23. In their analysis they determined the separate contributions of n-p singlet and triplet pairs to the observed final-state-interaction peak at the relative n-p energy $E_{np} = 0$. These separate contributions are shown in the figure. The solid curve, which is in excellent agreement with the cross section for production of n-p triplet pairs, represents a Born approximation calculation in which the final state n-p wave function used was effectively that of a deuteron with binding energy $E_B = 0$. If triplet n-p production were the major contribution to the cross section, we could expect the similarity between inelastic and elastic vector ana-

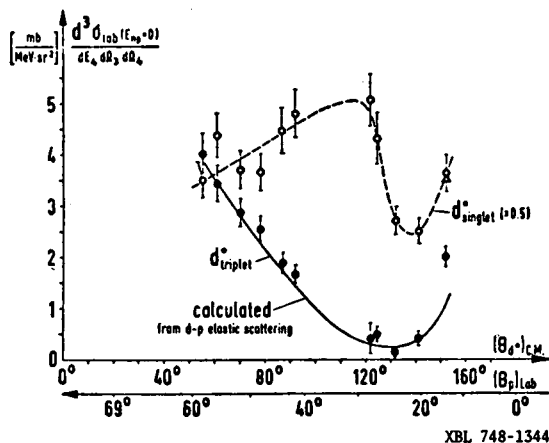


Fig. 23

lyzing powers. However, in just the backward angular region of maximum analyzing-powers, Fig. 23 shows that the major cross-section contribution is the production of n-p singlet pairs. Thus, one is led to the conclusion that the contribution to the inelastic analyzing power from the production of n-p singlet pairs has an angular distribution similar to that of the elastic analyzing power; and that is surprising. Since Ebenhöh's three-body calculation²⁶ quite successfully reproduces the form of the singlet n-p contribution to the cross section shown in Fig. 23, it would be of considerable interest to add to such a calculation the N-N spin dependent interactions that are necessary for the calculation of these analyzing powers.

Another study of polarization effects in the breakup reaction was that of Rad et al.³² in their measurement of the neutron polarization in p + d breakup at $E_p = 21.4$ MeV and $\theta_L = 18^\circ$. Fig. 24 shows some of their results, here d on p at $E_d = 42.8$ MeV. The n-p quasifree scattering (QFS) contribution occurs in the region of the maximum polarization values of about -0.05. Indeed, the corresponding polarization in n-p scattering has essentially the same magnitude but is opposite in sign. Their conclusion then is that predictions based on QFS near this energy can not be reliable. So here again is a polarization result which awaits a three-body calculation for its explanation.

In a contribution to this conference Walter et al.,³³ report measurements of the proton-to-neutron polarization transfer in the ${}^2\text{H}(p, n)2p$ breakup reaction at $\theta = 0^\circ$ and at several energies between 10.5 and 15 MeV. They found $K_Y^{Y'}$ (0°) to be near -0.2 for the production of p-p singlet pairs of relative energy near zero. Associated with the

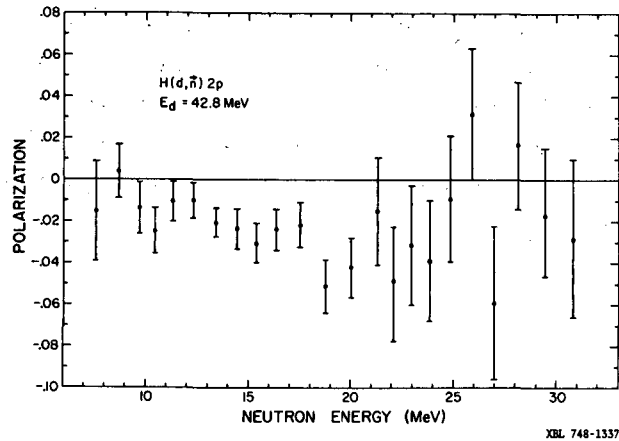


Fig. 24

production of p-p pairs of several MeV relative energy they found $K_Y^{y'}(0^\circ)$ reaching values of +0.5. The negative values are qualitatively understood in a simple knockout process, because the singlet p-p pairs would have been formed from the incident polarized proton and protons of opposite spin from the target deuteron; then the correlated neutron spin would be opposite to that of the incident proton. If one includes the deuteron $m = 0$ magnetic substate, this qualitative argument³⁴ yields $K_Y^{y'}(0^\circ) = -1/3$. This description neglects the deuteron D-state and nucleon-nucleon spin exchange terms; thus, a three-body calculation is again indicated in order to examine the connection between the behavior of this observable and the specific components of the nucleon-nucleon force.

6. Summary

The three-body calculations have been impressively successful in reproducing and predicting the cross-sections and spin-observables in elastic N-d scattering below 50 MeV. We have reached the point where the distinct possibility exists that specific information on the two-nucleon ^{interaction}, i.e., on the mixing parameter ϵ_1 , may be obtained from these three-nucleon studies. We clearly need calculations which investigate the sensitivities of the various N-d observables to the details and to the complexity of the input N-N interaction; the 3S_1 - 3D_1 separable potential used should reproduce all of the parameters of that channel. I can only imagine the difficulty, and cost, of such calculations. However, the theorists' suggestion to measure D_t in n-p scattering at 50

MeV to an accuracy of ± 0.01 allows me considerable latitude in my suggestion.

The situation concerning the N-d breakup to three-nucleon final states is reminiscent of that which existed with respect to the elastic channel several years ago. As we have seen here, there are now several experimental determinations of spin observables in this breakup reaction, and an appropriate three-body calculation is required for their quantitative interpretation. When the more complicated spin-dependent N-N interactions are included and spin observables are calculated, be assured that more such data will become available.

REFERENCES

1. See, for example, S. E. Darden, Polarization Phenomena in Nuclear Reactions, edited by H. H. Barschall and W. Haeberli (Univ. of Wisc. Press, Madison, 1971) p. 39; G. G. Ohlsen, Rep. Prog. Phys. 35 (1972) 717.
2. Ibid., p. xxv.
3. K. L. Kowalski and D. Feldman, Phys. Rev. 130 (1963) 276.
4. H. E. Conzett, H. S. Goldberg, E. Shield, R. J. Slobodrian, and S. Yamabe, Phys. Lett. 11 (1964) 68.
5. W. Haeberli, Proc. Int. Conf. on Three-Body Problem, edited by J. S. C. McKee and P. M. Rolph (North-Holland, Amsterdam, 1970) p. 188.
6. P. Extermann, Nucl. Phys. A95 (1967) 615; R. E. White, W. Gruebler, V. König, R. Risler, A. Ruh, P. S. Schmelzbach, and P. Marmier, Nucl. Phys. A180 (1972) 593; J. Arvieux, R. Beurtey, J. Goudergues, B. Mayer, A. Papineau, and J. Thirion, Nucl. Phys. A102 (1967) 503.
7. J. C. Aarons and I. H. Sloan, Nucl. Phys. A182 (1972) 369.
8. S. C. Pieper, Nucl. Phys. A193 (1972) 529.
9. P. Doleschall, Nucl. Phys. A201 (1973) 264.
10. J. S. C. McKee, H. E. Conzett, R. M. Larimer, and Ch. Leemann, Phys. Rev. Lett. 29 (1972) 1613.
11. S. C. Pieper, Phys. Rev. C8 (1973) 1702.
12. A. Fiore, J. Arvieux, Nguyen Van Sen, G. Perrin, F. Merchez, J. C. Gondrand, C. Perrin, J. L. Durand, and R. Darves-Blanc, Phys. Rev. C8 (1973) 2019.
13. S. C. Pieper, Phys. Rev. C6 (1972) 1157.
14. I. H. Sloan and J. C. Aarons, Nucl. Phys. A198 (1972) 321.
15. P. Doleschall, Nucl. Phys. A220 (1974) 491.
16. M. H. MacGregor, R. A. Arndt, and R. M. Wright, Phys. Rev. 182 (1969) 956.
17. F. N. Rad, J. Birchall, H. E. Conzett, S. Chintalapudi, R. M. Larimer, and R. Roy, Bull. Amer. Phys. Soc. 19 (1974) 476, and to be published.
18. S. C. Pieper, Phys. Rev. C9 (1974) 883.
19. R. A. Arndt, J. Binstock, and R. Bryan, Phys. Rev. D8 (1973) 1397; J. Binstock and R. Bryan, Phys. Rev. D9 (1974) 2528.
20. L. Wolfenstein, Ann. Rev. Nucl. Sci. 6 (1956) 43.
21. N. M. Stewart and W. R. Gibson, Polarization Phenomena in Nuclear Reactions, edited by H. H. Barschall and W. Haeberli (Univ. of Wisc. Press, Madison, 1971) p. 455; N. M. Stewart, W. R. Gibson and F. G. Kingston, Nucl. Phys. A171 (1971) 225; N. M. Stewart, W. R. Gibson, and J. H. P. C. Megaw, Nucl. Phys. A174 (1971) 338.
22. G. G. Ohlsen, Few Particle Problems in the Nuclear Interaction, edited by I. Slaus, S. A. Moszkowski, R. P. Haddock, and W. T. H. van Oers (North-Holland,

Amsterdam, 1973), p. 585.

23. G. G. Ohlsen, C. K. Mitchell, and G. C. Slazmann, *ibid.*, p. 460.
24. G. G. Ohlsen, C. K. Mitchell, G. C. Slazmann, J. L. Gammel, D. C. Dodder, and K. Witte, *Bull. Am. Phys. Soc.* 17 (1972) 922.
25. F. N. Rad, J. Birchall, H. E. Conzett, and R. Roy, *These Proceedings*.
26. R. T. Cahill and I. H. Sloan, *Nucl. Phys.* A165 (1971) 161; W. Ebenhöf, *Nucl. Phys.* A191 (1972) 97.
27. J. Arvieux, J. L. Durand, J. C. Faivre, D. Garreta, A. Papineau, J. Sura, and A. Tarrats, *Nucl. Phys.* A150 (1970) 75.
28. C. O. Blyth, N. T. Okumasoglu, N. Berovic, and J. S. C. McKee, *These Proceedings*.
29. R. E. White et al., reference 6.
30. J. Birchall, H. E. Conzett, F. N. Rad, and R. Roy, to be published.
31. H. Brückmann, W. Kluge, H. Matthäy, L. Schänzler, and K. Wick, *Nucl. Phys.* A157 (1970) 209.
32. F. N. Rad, L. C. Northcliffe, D. P. Saylor, J. G. Rogers, and R. G. Graves, *Phys. Rev.* C8 (1973) 1248.
33. R. L. Walter, P. W. Lisowski, R. C. Byrd, and T. B. Clegg, *These Proceedings*.
34. G. G. Ohlsen, reference 1.

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