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POLARIZATION PHENOMENA IN FEW-BODY SYSTEMS*

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1. INTRODUCTION

Since the Quebec few-body conference [1] was held less than one and one-half years ago and the Zürich polarization symposium [2] took place only four months ago, it was anticipated that there would be rather few contributions on polarization phenomena at this conference. Therefore, this report includes, in addition, relevant material on the subject which either has been published since the Quebec conference or was reported at the Zürich symposium. My intention is to survey the recent developments in the study of polarization effects in the two-, three-, and several-nucleon systems. Since these measurements or calculations essentially have to do with cross sections for particular selected spin states, it is clear that these studies provide more detailed information and test more detailed calculations than is possible with the usual spin-averaged cross sections.

2. TWO-NUCLEON SYSTEMS

One of the nucleon-nucleon discussion sessions at the Quebec conference considered experiments for the next decade, with a stress on polarization experiments [3]. Included among the several suggestions for future experiments were: (1) a need for more accurate p-p cross section and polarization data below 20 MeV because of significant discrepancies among the existing data; (2) measurements of the neutron to proton polarization transfer (D_t) or the spin-correlation coefficient, C_{nn}, in n-p scattering at 50 MeV, in order to make a substantial improvement in the determination of ϵ_1, the $^3S_1$ - $^3D_1$ mixing parameter, since the available data left ϵ_1 undetermined between $-10°$ to $+3°$ at 50 MeV [4]; and (3) a general request for measurements above the inelastic threshold of total cross sections for various spin orientations of both beam and target, and for measurements of the analyzing powers and spin correlation coefficients, at the higher energies above the inelastic threshold. I am happy to report the significant progress that has already been made in these three areas at just the beginning of that decade.

Hutton et al. [5] have recently reported on measurements of the analyzing power in p-p scattering at 10 MeV. Their results as shown in Fig. 1. Note that the maximum (negative) value is 2×10^{-3} and the typical error is 10% of that, or 2×10^{-4}, so these are accurate data, with more than an order of magnitude better precision than had been attained previously. Traditionally, the low energy p-wave phase shifts have been obtained with phenomenological extrapolations from higher energies. The dot-dash curve in Fig. 1 is the analyzing power calculated from the phase shifts resulting from the 1-27.6 MeV analysis of Arndt et al. [6], in which the overall normalizations of the cross section data were kept fixed. That is clearly inconsistent with these data, whereas an analysis with the normalizations taken as adjustable parameters resulted in calculated analyzing powers that are in reasonable agreement

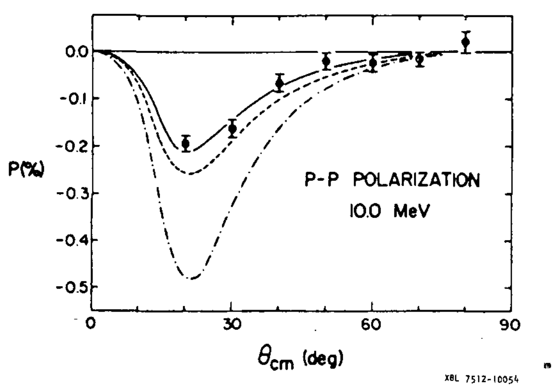

Fig. 1

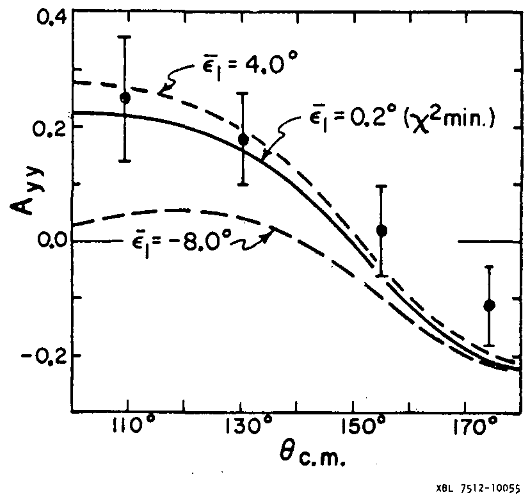

Fig. 2

with the data. The solid curve is the calculated analyzing power from a phase-shift analysis of these and nearby 9.9 MeV cross-section results. The s- and p-wave phase shifts determined in this analysis [5] are the first model independent determinations made below 25 MeV.

Proton-proton analyzing power data of similar accuracy at 16 MeV were reported at Zürich by Lovoi et al. [7], and the phase-shift prediction of MacGregor et al. [8] is in quite good agreement with them. Now that these two groups have shown that such accruacy is possible it seems clear that similar polarization measurements should be made at least at 25 and 50 MeV, the energies at which measurements of various p - p observables exist.

With respect to the n - p mixing parameter ϵ_1, Johnson et al. [9] reported at Zürich on their measurements at 50 MeV of the n - p spin correlation parameter A_{yy} (equal to C_{nn} for parity conserving or time-reversal invariant interactions). Their results are shown in Fig. 2, along with curves calculated from phase-shift solutions with the indicated values of ϵ_1. The -8° value seems to be ruled out, but an additional overall normalization uncertainty of $\simeq$ 25% leaves the error on ϵ_1 considerably larger than the ±1° envisioned by Binstock and Bryan. Their calculations, [4], in fact, with ϵ_1 = 2.8° gives A_{yy} (i.e. C_{nn}) = 0.38 at θ_{cm} = 120°, which is a value 35% larger than that shown as the calculated result in Fig. 2. This discrepancy between the two calculations must certainly be resolved, but these measurements, requiring both a polarized neutron beam and polarized proton target, clearly demonstrate an impressive experimental achievement. Hopefully, this experiment will be further pursued in order to reduce the experimental errors and thus reduce the uncertainty in ϵ_1.

Krisch [10] reported on several unanticipated, thus interesting, results from p - p experiments at the Argonne ZGS (proton synchrotron) with transverse polarization of both target and beam at momenta up to 6 GeV/c. Total cross section measurements showed σ_{TOT} (spins antiparallel) to be 6 mb. larger than σ_{TOT} (spins parallel) at 2 GeV/c. This difference is more than 10% of the spin-averaged σ_{TOT}, and, as yet, no explanation of this large difference exists. Fig. 3 shows elastic p - p cross sections for various spin states, divided by the spin-averaged corss section. Note, for example, that $\sigma(\uparrow\uparrow)$ is about

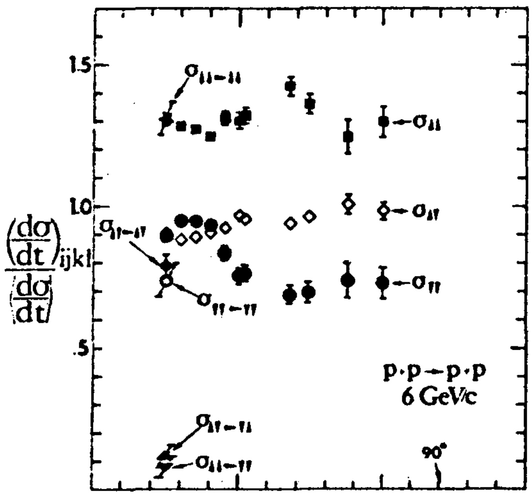

Fig. 3

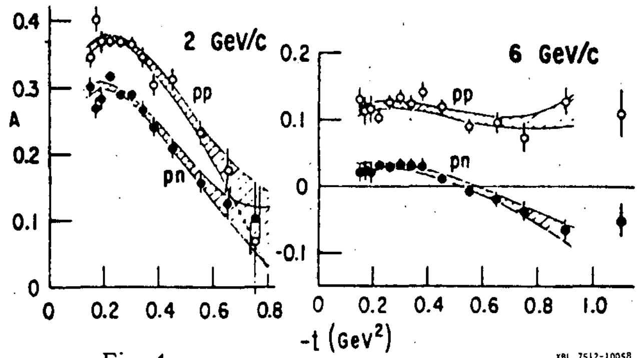

Fig. 4

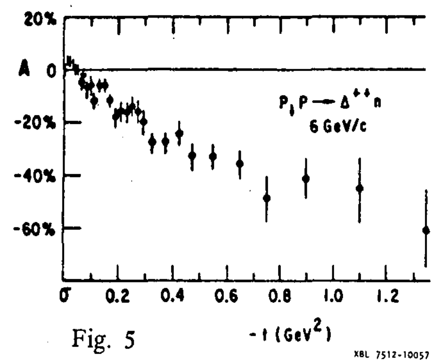

Fig. 5

twice $\sigma(\downarrow\downarrow)$ for the larger values of momentum transfer. Fig. 4 shows results of analyzing-power measurements in p-p and n-p elastic scattering at 2 and 6 GeV/c. Clearly the effects are substantial and they display a marked energy dependence. Finally, Fig. 5 shows analyzing-powers in the inelastic $p + p \rightarrow \Delta^{++} + n$ three-body final state reaction. Again the spin effects are large. There were no reported calculations of any of these observables, so the situation is reminiscent of that which existed with respect to elastic nucleon-deuteron scattering below 50 MeV several years ago. Some polarization measurements had been made, but the early exact three-body calculations were limited to s-wave N-N interactions, so they did not provide the observed polarizations. We can hope that the high energy theorists will provide calculations to reduce the present experimental-theoretical mismatch in as expeditious a manner as was accomplished by the lower energy three-body calculations.

3. THREE-NUCLEON SYSTEM

Since the three-nucleon polarization data and the relevant calculations were summarized at the Quebec conference, the work described here will serve as a natural extension of that report [11]. (See Fig. 1 of reference 11 for definitions of the spin-1 analyzing powers and of the polarization-transfer coefficients).

There is little new elastic N-d polarization data to discuss. Steinbock et al. [12] reported on their neutron analyzing power measurements in n-d scattering near 16 and 22 MeV, and their work confirmed that of Morris et al. [13] in finding good agreement with the p-d polarization data near those energies. There now remains only a single 35 MeV point at θ_{cm} = 120° for which the nucleon analyzing-powers in n-d and p-d scattering are reported to differ significantly [14]. All the other nucleon polarization data below 50 MeV agree, and thus support the principle of basic charge summetry of the nuclear interaction. On the theoretical side, Stolk and Tjon [15] have reported on their n-d elastic scattering calculations with the local Reid N-N potential, in contrast to the more generally used separable interactions. This is the first three-body calculation of polarization observables with local two-nucleon interactions. The s-wave contributions were calculated exactly, while the higher partial-wave contributions were calculated with a peturbative treatment. An example of their calculated polarizations, the neutron polarization at 14 MeV, is shown in Fig. 6. The indicated calculations included the following partial waves: dash ($^1S_0$, $^3S_1$ - $^3D_1$); dash-dot ($^1S_0$, $^3S_1$, $^1P_1$, $^3P_{0,1,2}$, no tensor); dash-dot-dot ($^1S_0$, $^3S_1$ - $^3D_1$, $^1P_1$, $^3P_{0,1,2}$); full curve adds $^1D_2$ and $^3D_2$ to the dash-dot-dot calculation. Note that the tensor interaction has a substantial effect (dash-dot to dash-dot-dot curve), as was found by Doleschall [16] in his exact calculation with separable potentials. Also, the effect was similar in depressing the back angle values and raising those at forward angles. The full-curve fit in Fig. 6 is not as good as that of Pieper's [17] analogous calculation with separable potentials, but at the higher energy of 46 MeV this local-potential calculation provides a better representation of the data than does the separable-potential model. So, there can be no claim yet of a better result from the local-potential calculation.

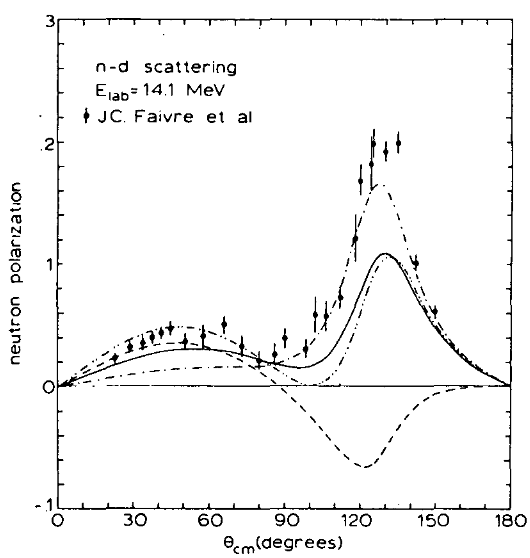

Fig. 6

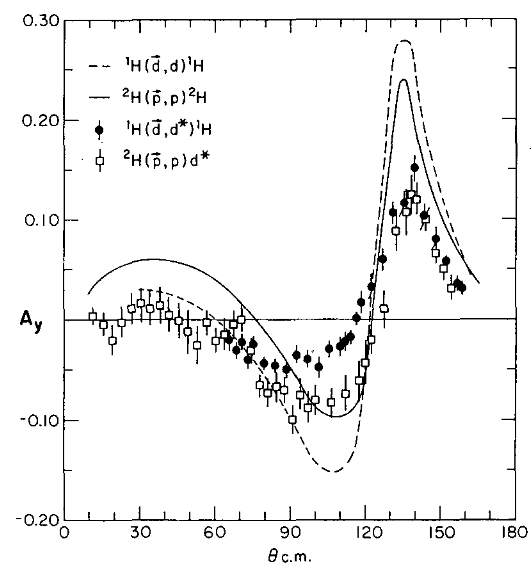

Fig. 7

Concerning polarization effects in the N-d breakup reaction, there have been recent noteworthy reports of both theoretical and experimental results. Rad et al. [18] have reported on measurements, at E_p = 22.7 MeV, of both the proton and deuteron (vector) analyzing powers in the p-d breakup transition to the np final-state interaction (FSI) region of the three-body spectrum. These data are shown in Fig. 7, where the smooth curves represent the elastic p-d proton and deuteron analyzing powers. The substantial values of these inelastic analyzing powers demonstrated a clear need for the exact N-d breakup calculations to include more than the simple s-wave N-N interactions that had been sufficient to fit the cross-section data. Such calculations are now underway. The first of these at E_n = 22.7 MeV, is reported in a contribution to this conference by Bruinsma and von Wageningen [19]. Their work shows that the tensor force affects the cross section in the region of the FSI peak but has little influence in the quasi-free scattering region. Their calculated deuteron tensor analyzing powers show very substantial values; an example is shown in Fig. 8. In particular, T_{20} exceeds 0.35 in the FSI region for the particular θ_1, θ_2 angle combination chosen here. These predictions of substantial tensor analyzing powers will certainly encourage experimentalists to measrue them. The calculated deuteron vector analyzing powers are less than 0.05 for this angle combination, so the situation seems to be comparable to that of the elastic N-d case, where the $^3S_1$ - $^3D_1$ tensor force was chiefly responsible for the observed tensor polarizations while the N-N p-wave interactions were the source of the vector polarizations. It is planned to next add the p-wave N-N interactions in these breakup calculations.

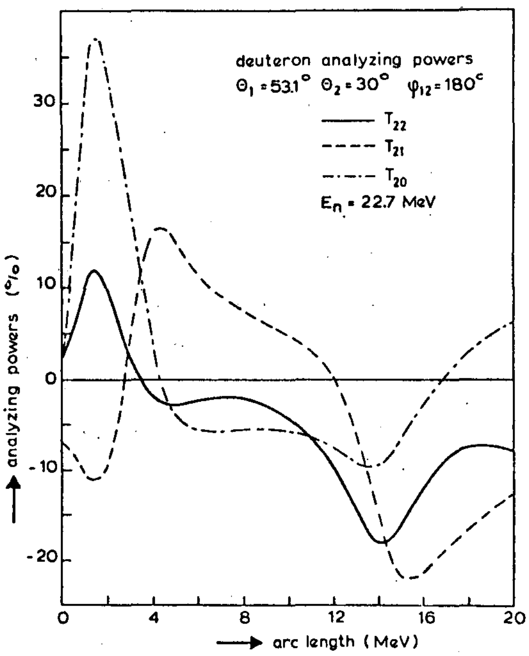

Fig. 8

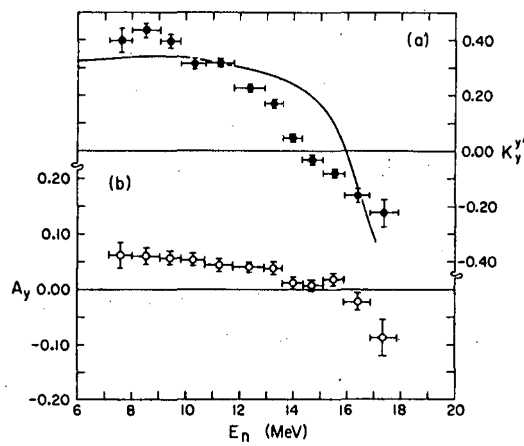

Fig. 9

Another polarization observable that has been measured recently in the p-d breakup reaction is the polarization transfer coefficient $K_y^{y'}(E_n)$ in the $D(\vec{p},\vec{n})2p$ reaction at E_p = 20.4 MeV and θ_n(lab) = 18°. These data are shown in Fig. 9, where the solid curve is the result from an exact three-body calculation limited to $^1S_0$ and $^3S_1$ separable N-N potentials [20]. Pieper [17] has shown that non-trivial values of $K_y^{y'}$ are obtained from such a calculation for N-d elastic scattering. Despite the qualitative agreement with the data in Fig. 9, the non-zero values of the analyzing power A_y, also shown in the figure, prove the necessity for other than s-wave interactions in the calculation.

There is now a real promise that the very fruitful interchange which occurred between theory and experiment with respect to polarization observables in elastic N-d scattering can now be repeated for the breakup reaction.

4. SEVERAL-NUCLEON SYSTEMS

There is such a wealth of polarization data on the mass 4, 5, and 6 systems that I will discuss here only selected examples of this work which seem to me to be particularly fruitful or unique. Most of these results were reported at the Zürich conference.

Dodder [21] described the Los Alamos group's program of multichannel R-matrix analysis of scattering and reaction data from few-nucleon systems. The aim of this program is to provide a simultaneous description of the experimental observables in all the reaction channels. As an example of the success of this work, Weitkamp [22] reported on measurements of three polarization-transfer coefficients in $\vec{p}$ - ^{3}He elastic scattering at three energies below 11 MeV. The R-matrix predictions of these coefficients, based on the previous analysis of several other observables in this mass-4 system, were in quite good agreement with the experimental data.

The Birmingham group [23] reported their measurements of analyzing powers in the elastic scattering of polarized ^{3}He from p, d, ^{3}He and ^{4}He at 32 MeV. These data are much more extensive and accurate than has been available from work using polarized ^{3}He targets, although the present limitation to a single energy restricts the utility of such data in an energy-dependent description of reactions involving these nuclei. However, there was no evidence of significant resonance effects in this energy region, and optical model analysis resulted in surprising good fits to these data, with spin-orbit potential strengths of 1 - 2 MeV. At the same time a Basel/Zürich group [24] reported on considerably improved and extended measurements in p + $^{3}\vec{\mathrm{He}}$ scattering between 2.3 and 8.8 MeV, using a polarized ^{3}He target. These ^{3}He analyzing-power data result in significantly better determinations of the p - ^{3}He phase shifts below 10 MeV.

The first measurements of polarizations in transitions to three-body final states of the mass-6 and mass-9 systems were discussed here by Slobodrian [25]. The final state proton polarizations were determined in the reactions ^{3}He(^{3}He, $\vec{p}$)pd and ^{6}Li(^{3}He, $\vec{p}$)$\alpha\alpha$. Fig. 10 displays their cross-section and polarization data for the first reaction, the (^{3}He, p) transition to the (unbound) ground state of ^{5}Li, at E(^{3}He) = 13.6 MeV. Significant proton polarization is seen. The solid curve which best fits the polarization data is a DWBA calculation for a deuteron-cluster transfer with J,L,S transfers of 2,1,1, respectively.

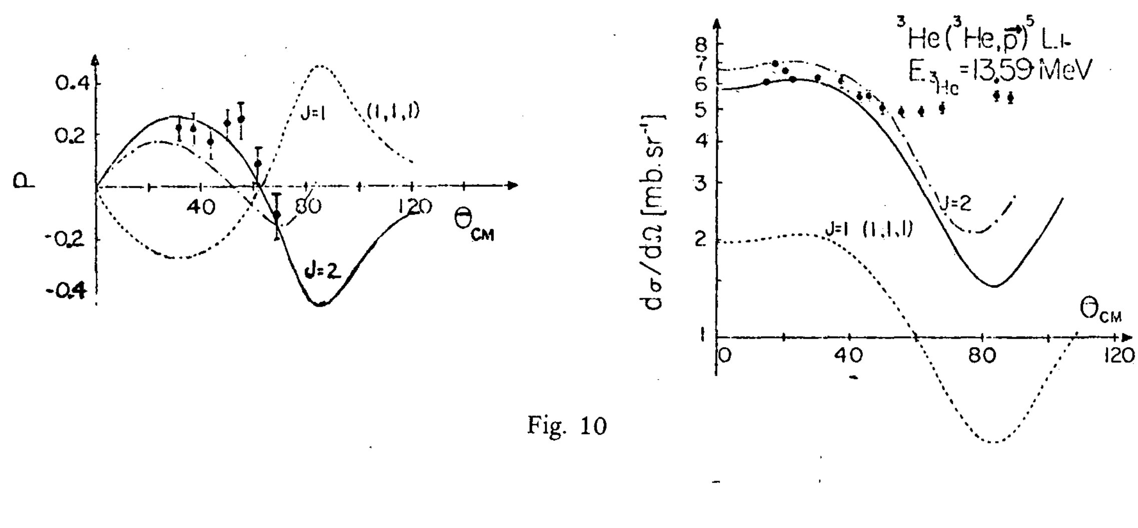

Fig. 10

Elastic scattering from ^{4}He has emerged as the principal means for determinations of the absolute polarizations of beams of polarized particles. Proof was given several years ago of the existence of points at which the analyzing power $A_y = 1.0$ in $\vec{p}$ - ^{4}He elastic scattering [26]. The establishment of $A_y = -1.0$ points in $\vec{t}$ - ^{4}He scattering was reported at Zürich [27]. Recent work has also been devoted to the search for similar points of maximum analyzing power in $\vec{d}$ - ^{4}He scattering. The more complicated spin-1 structure, as compared with spin-½, has led to some interesting developments. Analogous to the spin-½ case, the necessary and sufficient condition for the deuteron tensor analyzing-power component A_{yy} to be exactly unity has been established [28]. It is that $M_{11} + M_{1-1} = 0$, where M_{11} is a non-spin-flip element and M_{1-1} is a spin-flip element of the (3 × 3) d - ^{4}He M-matrix. From a phase-shift analysis of d - ^{4}He data, Grüebler et al. [29] showed that the equation $M_{11} + M_{1-1} = 0$ was satisfied at three points (E,θ). Fig. 11 illustrates the method for determination of one such point. Plotted are trajectories of the (complex) values of $M_{11} + M_{1-1}$ at several energies for different θ_{cm}. These were calculated from the known phase shifts. Because of continuity of these amplitudes in energy and angle, it is seen that at some point near E = 12.0 MeV, $\theta_{cm} = 55°$ $M_{11} + M_{1-1} = 0$, so that $A_{yy} = 1$. The experimental task was to find the point of relative maximum

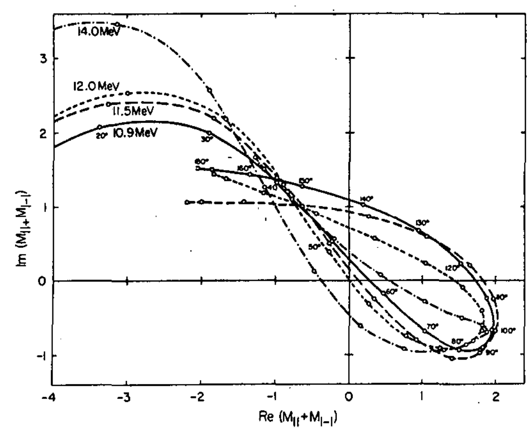

Fig. 11

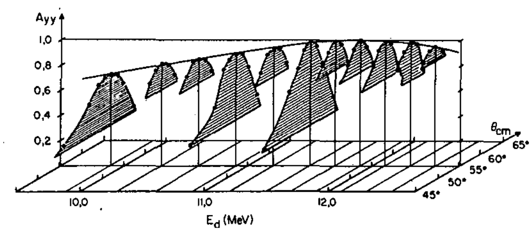

Fig. 12

A_{yy} in the region, to which one could then assign the value 1.0. Fig. 12 displays the data from that search in both E and θ_{cm}. The final determination was A_{yy}(11.88 MeV, 55°) = 1.0 Grüebler et al. also examined the conditions imposed on the d - ^{4}He M-matrix in order that the vector analyzing power A_y reach the value ±1.0. The conditions are so restrictive, requiring three equations among the M-matrix elements to be satisfied simultaneously, that at such a point all the analyzing-power components would be determined. Seiler et al. [30] then showed that this result followed from the basic condition that the density matrix is positive semi-definite, so that it is valid in reactions with the general spin structure 1 + a → b + c, where a, b, and c are arbitrary spins. The spin-1 analyzing power components are constrained to points within the cone shone in Fig. 13. It is easily seen that the points $A_y = \pm 1$ (points B or C) are quite unique, and at those points the other components are determined to be $A_{yy} = 1.0$, $A_{xx} = A_{zz} = -½$ (since $A_{xx} + A_{yy} + A_{zz} = 0$), and $A_{xz} = 0$. The a priori likelihood for an $A_y = \pm 1$ point in d - ^{4}He scattering is vanishingly small because of the requirement that three equations be satisfied simultaneously for a single (E, θ) point. In spite of that probability, an A_y value close to 1.0 in d - ^{4}He scattering was reported at Zürich by the Berkeley group [31]. Their measurements in the region of maximum A_y are shown in Fig. 14. Unlike the case of A_{yy}, it is not possible to prove that a point A_y = 1.0 has been reached. It is clear, however, that an $A_y \simeq 1.0$ point exists, so it follows that the three equations among the M-matrix amplitudes are approximately satisfied. The particular importance of an A_y = 1.0 point is that here all of the analyzing-power components and, with a cross section measurement, all of the M-matrix amplitudes are determined.

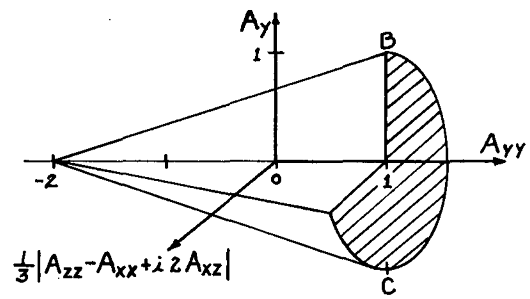

Fig. 13

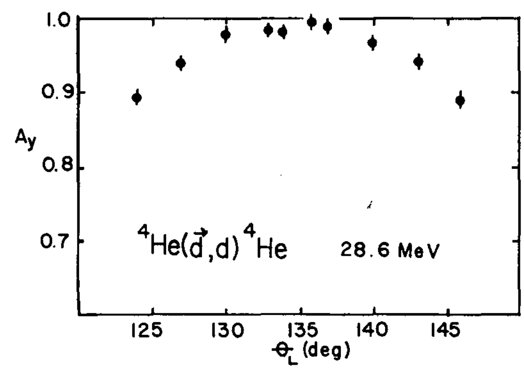

Fig. 14

5. POLARIZATION SYMMETRIES

There have been two rather recent developments that show the consequent effects on polarizations that follow from particular symmetries of the nuclear interaction. The first of these involves charge-symmetry or isospin conservation. Experiments on the ^{3}H(p,n)^{3}He and ^{7}Li(p,n)^{7}Be reactions [32] had shown that the neutron polarizations P_y and the proton analyzing powers A_y were essentially equal, with limited exceptions. This equality was seen to result from charge-symmetry [33], and it is an approximate equality because of the presence of the Coulomb interaction. However, it is in just those regions of significant difference between P_y and A_y that useful information can be derived on the structure of the nuclei studied [34]. Recent studies of $P_y = A_y$ in (p,n) reactions on other nuclei were reported at Zürich. Fig. 15 shows the data of Lisowski et al. [35] on ^{9}Be. At 8.1 MeV the older P_y values (crosses) are quite different from those reported here (dots), and the latter are close to the measured A_y values (triangles). Final corrections to the A_y values from background subtractions are expected to improve the agreement. As is suggested by the comparison at 9.1 MeV, new measurements will be made there of P_y as a check on the old values (crosses).

The second development shows that for reactions with identical or charge-symmetric particles in the initial state, the angular-distribution symmetry of the analyzing powers can provide a clear signature of the reaction mechanism [36]. Consider, for example the ^{2}H($\vec{d}$, p)^{3}H reaction. There is, in general, no angular-distribution symmetry imposed on $A_y(\theta)$ by virtue of the identical initial-state deuterons, and indeed no symmetry was seen in such data below 20 MeV. However, if the reaction mechanism is a purely direct nucleon-transfer process it was seen that $A_y(\theta) = -A_y(\pi-\theta)$. Fig. 16 shows the two nucleon-transfer amplitudes which contribute. Since a and a′ are deuterons the amplitudes for the transfers of

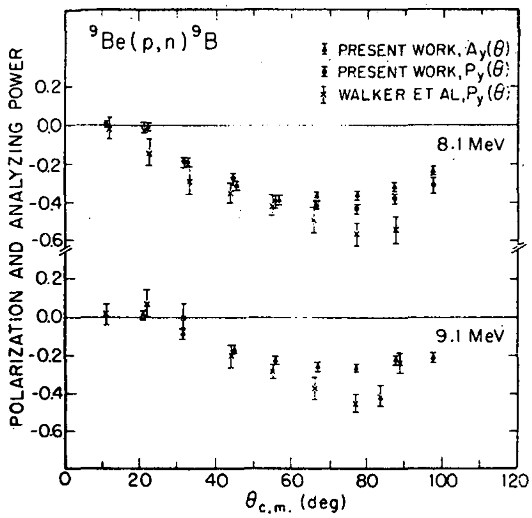

Fig. 15

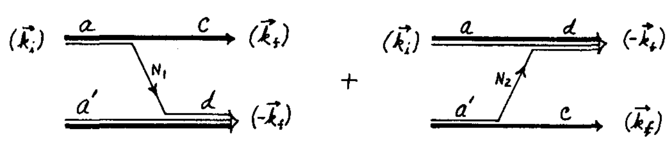

Fig. 16

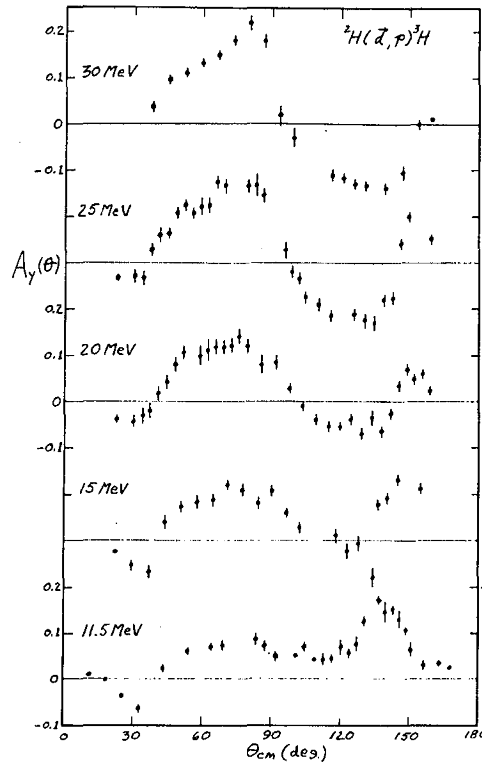

Fig. 17

neutrons N, and N_2 must be equal, and this equality imposes the symmetry on $A_y(\theta)$. Again, it is the deviations from the symmetry that provides the significant information. Fig. 17 shows $A_y(\theta)$ data for this reaction. The lower energy data show no symmetry, so it is clear that analysis in terms of ^{4}He intermediate states is required there. At the higher energies there is clear trend toward antisymmetry with respect to $\theta = \pi/2$, as is required of the direct nucleon-transfer process. Even there the antisymmetry is not exact, so this is evidence for contributions from the compound-nucleus mechanism at energies considerably above those for which excited states of ^{4}He are known to exist.

6. SUMMARY

Recent polarization studies in N-N scattering at and below 50 MeV have provided specific and significant improvements in the phase-shift parameters. High energy investigations with both polarized proton beams and targets have shown unexpectedly large spin effects, and this provides a challenge for theoretical effort to explain these results. Experimental and theoretical work on the three-nucleon problem continues to yield new and interesting results, with the emphasis now shifting to polarization studies in the breakup reaction. On-going work on several-nucleon systems continues to provide polarization data for general analyses, nuclear structure information, or specific resonance effects. Finally, the basic interaction symmetries continue to have unique and important consequences for polarization observables.

FOOTNOTE AND REFERENCES

*Work performed under the auspices of the U. S. Energy Research and Development Administration.

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