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FEW-BODY EXPERIMENTS WITH POLARIZED BEAMS AND POLARIZED TARGETS

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A survey is presented concerning recent polarization experiments in the elastic p-d, p-^{3}He, and p-^{4}He systems. Mention is made of selected neutron experiments. The nominal energy range is 10 to 1000 MeV. Recent results and interpretations of the p-d system near 10 MeV are discussed. New experiments on the energy dependence of back angle p-d tensor polarization are discussed with respect to resolution of discrepancies and difficulty of theoretical interpretation. Progress is noted concerning multiple scattering interpretation of forward p-d deuteron polarization. Some new results are presented concerning the p-^{3}He system and higher energy p-^{4}He polarization experiments.

1. INTRODUCTION

It is my object here to make a broad survey of few body polarization phenomena that have been reported in the past few years. Energies will be in the range of about 10 to 1000 MeV. Requirements of time and space will limit my subject matter to the elastic channels in nucleon interactions with deuterium, helium-3, and helium-4. Excellent reviews cover prior elements of my subject: At the Few Body Conference in Eugene, Grüebler[1] discussed three- and four-body systems at lower energies ($\simeq$ 10 MeV); at the Santa Fe Polarization Conference, Igo[2] discussed polarization experiments at intermediate energies ($\simeq$ 1000 MeV); at Graz, Ohlsen[3] reviewed polarization effects in the three-body system, with emphasis on break-up phenomena. At the Santa Fe conference Kloet[4] compared theory with experiment.

2. LOW ENERGY NUCLEON-DEUTERON SCATTERING

I turn first to a very recent experiment concerning the literal subject of my talk. Schmelzer et al.[5] have submitted a contribution to this conference on the measurement of the spin correlation parameter C_{yy} in d-p scattering at incident deuteron energy T_d = 10 MeV. This is a difficult measurement in which a vector polarized deuteron beam was scattered from a thin (70μm) LMN-type polarized proton target. The experimental results for C_{yy} are shown in Fig. 1. The five data cover the angular range of $\theta_{c.m.}$ (proton) from 75 to 135°. These values represent slight changes from the published values. Three curves are also shown; two of these are Faddeev calculations with Coulomb corrections. The solid curve was from Stolk and Tjon[6] using a local N-N interaction; it gives a good qualitative prediction for the data. The dashed curve is from Fayard et al.[7] with separable interaction; it is not so good. The dot-dash curve is a prediction from the phase shift analysis of Schmelzbach et al.[8] in 1972; it lies between the other two. It is expected that refinement of such data will help to define the nature of the off-shell N-N interaction. Comparison to prior work at Grenoble in Birmingham is noted in Ref. 5.

The Zurich group (ETHZ) has made a significant contribution to understanding proton-deuteron scattering for equivalent proton energies in the range 8.5 to 22.7 MeV. A detailed account of their analyzing power measurements with polarized proton and deuteron beams was published this year by Grüebler et al.[9] Sawada et al.[10] at Tsukuba have also made a series of accurate analyzing power measurements near T_d = 20 MeV (published this year). These efforts have cleared up certain discrepancies, produced complementary information, and brought greater confidence to the experimental situation.

Comparison of such p-d data to theory is based on the Faddeev equations.[11] To the extent that the N-N interactions are known, with correct inclusion of the Coulomb force, the Faddeev equations may be integrated to give exact values of the p-d wave functions. On the whole, the method provides remarkable predictions for N-d scattering below 50 MeV. In the following paragraphs we illustrate the comparison between theory and experiment at T_p = 10 MeV equivalent energy. Figure 2 shows the proton analyzing power A_y^p at T_p = 10 MeV as given by Doleschall et al.[12] For this and the following figure the Faddeev predictions are given by four curves labelled in a common fashion. All curves are calculated for n-d scattering using separable potentials. The S-wave interactions include a repulsive core. All curves include a two-term singlet S-wave (2^1S_0R) and P-waves. The four curves are summarized as follows: Dashed, with two term tensor (2T2R); dot-dash, with four term tensor (4T4); continuous, same as preceding but with all D-waves; dotted, same as preceding but with approximate Coulomb corrections. In principle, the dotted curve should give the best representation of the data; the continuous curve is next best. In Fig. 2 we see a good prediction for A_y^p from the full n-d calculation (solid curve); inclusion of Coulomb corrections (dotted curve) is somewhat better at small angles, but a little less

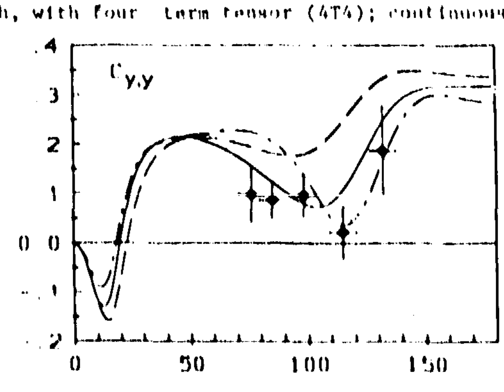

Fig. 1. Spin correlation parameter C_{yy} for p(d,p)d at T_d = 10 MeV. Data from Ref. 5. For curves see text.

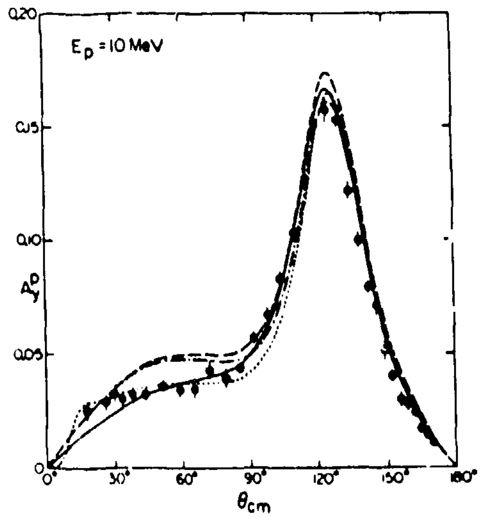

Fig. 2. Proton analyzing power for d(p,p)d at T_p = 10 MeV. Data from Ref. 12. The dotted curve is the full Faddeev calculation.

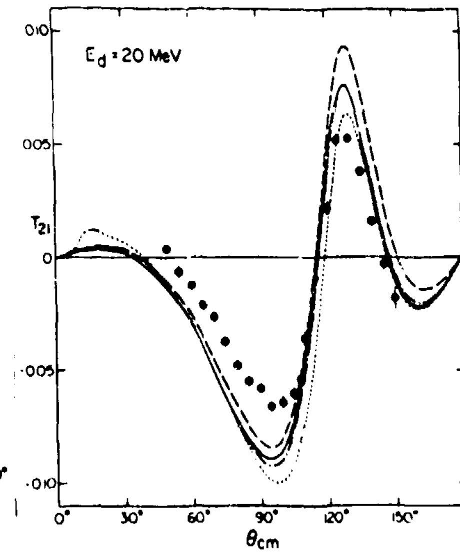

Fig. 3. Tensor analyzing power T_{21} for p(d,p)d at T_d = 20 MeV. Data from Ref. 10. Dotted curve is the full Faddeev calculation.

good at larger angles. The four-term tensor interaction definitely improves the fit for angles less than 90°; this is related to superior representation of the ϵ_1 $^3S_1 - {}^3D_1$ mixing parameter.

As another example, Fig. 3 shows T_{21}, a deuteron tensor analyzing power at T_d = 20 MeV. This parameter is determined by XZ components of beam polarization, and the data are from Tsukuba[10] where the necessary control of spin quantization direction is available. The Faddeev predictions are from Ref. 12 with the same definitions as above. There seem to be relatively serious discrepancies between the Faddeev predictions and the data, and it is not obvious which curve does best. Doleschall et al. note that the way the Coulomb corrections are treated could have a significant effect on T_{21} and some of the other parameters. Kloet[4] has also emphasized the importance of Coulomb effects.

Further work on the Coulomb questions appeared this year by Zankel and Hale,[13] who made calculations for the n-d and p-d $A(\theta)$, parameter including Coulomb distortion effects. Comparison was made to precision n-d data of Tornow et al.[14] and p-d data of Ref. 9. The conclusion was that 5% differences occur at the back angle peak of $A(\theta)$ that are not obtained from simpler correction procedures.

Space does not permit further examples of the low energy p-d analyzing powers. Suffice it to say that the 4T4R predictions of Ref. 12 provide good predictions for the tensor analyzing powers T_{20} and T_{22} near T_d = 20 MeV;

comparison was not as good for the vector analyzing power iT_{11}.

Sperisen et al.[,16] at ETHZ have recently published two papers on a series of measurements of polarization transfer observables in p-d scattering at T_p = 10 MeV. In the second paper measurements were made for the $d(\vec{p},\vec{d})p$ process; three vector-vector and seven vector-tensor parameters were obtained. The Faddeev predictions for these observables showed little sensitivity to the form of the tensor force or to additional D-waves or the Coulomb force. There were indications of sensitivity to P-waves in the vector to tensor observables. Figure 4 shows three of these. The curves showing Faddeev predictions are not the same as for Figs. 2 and 3. The dashed curves contain no P-waves; they do not agree with the data. The other two curves include P-waves and variants of the tensor force; they have a qualitative resemblance to the data, but deviations are still observed. The P-wave sensitivity of these parameters was a very interesting finding and encouraged the expectation that further analysis of these results would lead to better understanding of the N-N interaction in the Faddeev context.

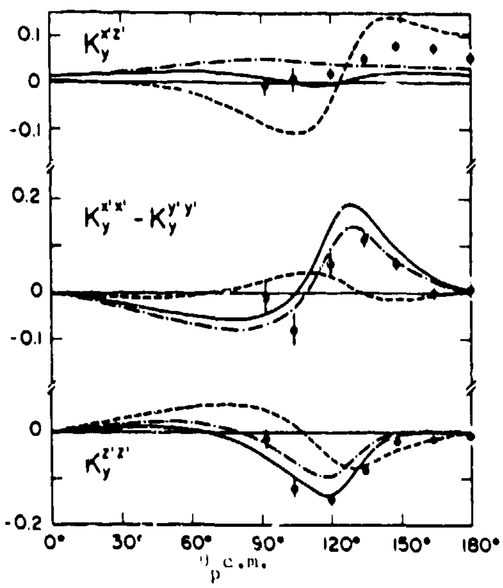

Fig. 4. V-T polarization transfer parameters in $d(\vec{p},\vec{d})p$ at T_p = 10 MeV. Data from Ref. 16. Dashed curves have no P-waves; others do.

Much effort has been put into low energy N-d scattering experiments (of which I have mentioned but a small part here). Such experiments were done at Lawrence Berkeley Laboratory (LBL) as described by Conzett.[17] Work at Los Alamos was described in Ref. 3. Shimizu et al.[18] have made $\vec{p}$-d analyzing power measurements at Kyoto at 65 MeV. Further work from that laboratory is being reported to this conference by Hatanaka et al.[18] on d-p tensor measurements; rather good agreement is reported with theory employing the Graz interactions. Brock et al.,[29] Romero et al.,[20] and Watson et al.,[21] at Davis have reported n-d analyzing power measurements giving partial reference to recent neutron work.

At Karlsruhe a significant neutron-deuteron scattering program has been underway at the cyclotron accelerator for energies up to 50 MeV. Quite recently Schwarz et al.[22] published results for precision n-d differential cross sections from 2.5 to 30 MeV. New results from this group will be reported to the conference by Brady et al.[22] on the n-d analyzing power from 14 to 50 MeV. Such data will be important for understanding the basic interaction and the role of Coulomb effects.

The exploitation of the Faddeev method for the explanation of low energy elastic scattering has been a major success of the past decade. The general qualitative agreement between theory and experiment is most impressive. We hope that additional knowledge might be gained about the on-shell N-N interaction in this way, owing partly to the enhanced effects that occur in some observables of the N-d system. From my viewpoint, it is not obvious that this has happened. Nor does it appear that new insights have been gained with respect to the off-shell N-N interaction from the elastic system. In this connection, R. Brown[23] has called my attention to the importance of breakup studies to off-shell effects and to new experiments of this kind currently underway at Indiana. The calculational complexity of the Faddeev method is partly to blame for these circumstances. For significant improvement to occur from this state it appears that the calculations must be made more accurate with respect to current understanding of the N-N interaction.

I have not found any recent publications on the phase shift analysis of the low energy p-d system. Reference 8 (1972) was one of the most complete. This undoubtedly derives from the complexity of the problem and the relative success of the Faddeev approach. At T_p = 10 MeV alone, almost 400 data on 21 independent observables over a broad range of angles exist. Perhaps this is the time to reconsider this question. Would it be possible to calculate higher partial waves or some of the inelasticity parameters from the Faddeev method? This might make phase-shift analyses more feasible while keeping the theoretical input reasonably small. If by this means the mass of data on N-d scattering from 5 to 50 MeV could be compactly described, this would be a significant accomplishment.

3. INTERMEDIATE ENERGY p-d POLARIZATION

Nucleon deuteron scattering may be considered as dividing into two regions: the forward direction where the incoming particle scatters individually from the two constituents of the deuteron, and backward angles where the incoming particle exchanges with one of the particles picking up the other to form an outgoing deuteron. Nucleon exchange was identified thirty years ago by Christian and Gammel[24] as the significant physical process for low energy N-d backward scattering. Its importance continues into the intermediate energy range. At energies near 600 MeV, however, another process becomes important and enhances backward scattering -- delta(1232) formation in the intermediate state. It is the same process that drives the pp → πd reaction to a peak at that energy, as described by Barry[25] and others.

Berthet et al.[26] have measured backward p-d scattering from 0.6 up to 2.7 GeV. Their data overlaps the enhancement in the scattering at 600 MeV. Beyond 600 MeV an experimental decline was observed to 2.2 GeV where a new change of slope was seen. They compared existing data on the backward scattering from 200 to 2000 MeV using nucleon exchange (ONE) and pion exchange (OPE) models. They found that neither model was adequate by itself. In unpublished work Laget and Lecolley[27] have formulated a model that employs a coherent sum of ONE and OPE, which apparently does give good predictions for p-d backward scattering at intermediate energies.

Measurements of the back angle tensor analyzing power $T_{20}(180)$ have generated much interest in the past few years. Earlier this year Arvieux et al.[28] reported such measurements using the polarized deuteron beam at Saturne-2 over the energy range $T_d = 0.3$ to 3.0 GeV. Their experimental arrangement had good signal to background for detection of protons over the full energy range and deuterons over a part of it. Their results are shown in Fig. 5. There is a good deal of information on this figure of which I can discuss but a part. Their experimental data are seen in the lower part of the figure as solid dots (proton detection) or open squares (deuteron detection).

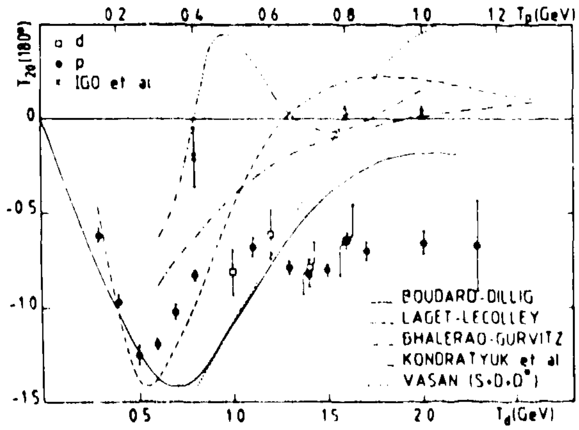

Fig. 5. Back angle tensor analyzing power T_{20} vs T_d for p(d,p)d at intermediate energies. Dots and squares Ref. 28; crosses Ref. 31.

A prominent feature of the data of Fig. 5 is the dip in T_{20} near $T_d = 0.5$ GeV. The nature of this dip was predicted by Vasan[29] some time ago on the basis of ONE. This calculation is indicated by the dotted curve in Fig. 5, but the position comes too high in energy. Keister and Tjon[30] have investigated relativistic effects in the ONE model; their pseudovector calculation is comparable to that of Vasan; their pseudoscalar calculation is not consistent with the data. A second feature of the data is a dip of lesser magnitude near $T_d = 1.4$ GeV, which has not been seen or predicted heretofore. The model of Ref. 27 included nucleon and pion exchange in a coherent fashion. This prediction is shown as the dashed curve and describes well the dip at $T_d = 0.5$ GeV; however, by 1.2 GeV it has climbed far above the data.

Significant on Fig. 5 are the data points from Argonne of Igo et al.[31] shown as crosses at T_p = 0.4, 0.8, and 1.0 GeV. These points are consistent with zero and are in complete disagreement with those of the Saturne group. Something went wrong at Argonne, which was probably related to the difficult problem of detecting low energy deuterons from back angle scattering. It must be noted that these problems pertain only to back angle scattering. Argonne and Saturne are in excellent agreement on forward-scattering measurements. We see that this very interesting experiment from Saturne has resolved an experimental discrepancy and provided new data for theoretical comparison.

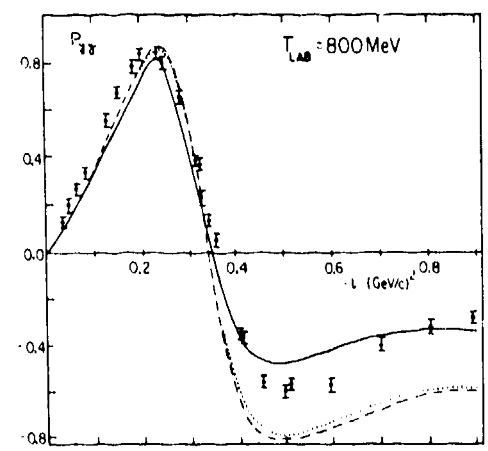

Fig. 6. Tensor analyzing power P_{yy} in p(d,d)p at T_p(equiv.) = 800 MeV. Data and M.S. curves Ref. 33.

In the forward scattering of nucleons from deuterium at intermediate energies two regions are identified At small angles the scattering occurs singly from the constituent nucleons. At momentum transfers near $-t$ = 0.3 $(GeV/c)^2$ double scattering becomes important, and the scattering decreases less rapidly. The deuteron D-state must be involved[32] to obtain a quantitative explanation of the process. Measurement of the polarization parameters is essential to the verification of the validity of multiple scattering theory.

Figure 6 shows one example of the many polarization measurements of the UCLA group and their collaborators, as reported by Bleszynski et al.[33] Shown is the tensor analyzing power P_{yy} at T_p (equiv.) = 800 MeV, where y is parallel to the normal scattering plane. The experiments were done at the Argonne ZGS machine with a polarized deuteron beam incident on a liquid hydrogen target. The data show a rise to a substantial peak near $-t$ = 0.25 $(GeV/c)^2$, at the onset of double scattering, then a sharp decline and a broad minimum.

There are two significant theoretical predictions in Fig. 6, which were described in Ref. 33, and in greater detail in Alberi et al.[34] The dashed curve represents a Glauber model calculation including the deuteron D-states and current N-N amplitudes. It represents well the forward peak but undershoots the data at larger values of $-t$. The solid curve gives results of a complete systematic multiple scattering calculation[33,34] of which the most significant new elements are corrections to the eikonal approximation. These corrections allow additional diffraction effects and phase changes for the nucleon wave as it propagates from the first to the second scattering. The solid curve gives a significantly improved representation of the data in the region of larger momentum transfer. Note that the experiments at Argonne[33] also yield values for P_y and P_{xx} at 800 MeV and other energies.

It may be noted that the Saturne group[28] has obtained A_{yy} ($=P_{yy}$) data at T_p (equiv.) = 600 MeV over the whole angular range, with good agreement to the Argonne data at forward angles. At the moment, however, there is no theoretical model that can give a qualitative explanation of a growing mass of N-d data at both forward and backward angles.

In closing this section, I would like to mention some very recent results from the UCLA collaboration in $d(\vec{p},\vec{p})d$ polarization transfer at 500 and 800 MeV. In a contribution to this conference Sun et al.[35] describe the measurements that were done at LAMPF in the polarized external proton beam. The preliminary results for two parameters, D_{LL} and D_{SL}, are shown in Fig. 7 at T_p = 800 MeV. The nomenclature is such that L means longitudinal and S means perpendicular to L in the plane of scattering. The dashed curves are preliminary multiple scattering calculations of the type mentioned above.[33] The interesting point is that these curves do not represent the data well. New effects may be showing up here. Dr. Igo informs me that the p-d program is, on this very date, being pursued at LAMPF at 800 MeV in a HRS experiment with polarized proton beam, polarized deuteron target, and final state proton polarization measurement. The long range objective is determination of the elastic amplitudes at 800 MeV.

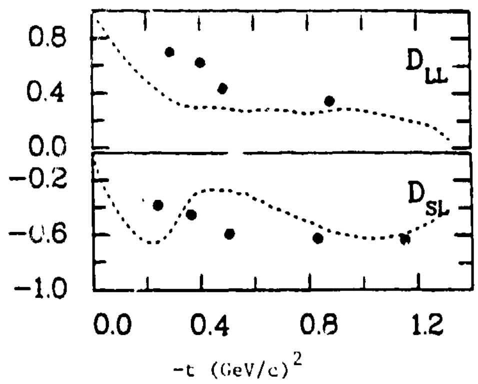

Fig. 7. Polarization transfer in d(p,p)d at T_p = 800 MeV. Preliminary data from Ref. 35.

4. UPDATE ON N- ^{3}He SCATTERING

In a contribution to this conference by Verheijen et al.,[36] the Manitoba group have continued low energy p- ^{3}He analyzing power studies with a polarized ^{3}He gas target. By optical pumping, polarizations of about 16% were achieved. New data at 30 and 35 MeV were obtained. In addition, a phase-shift analysis was performed on all available data at seven energies between 19.5 and 35 MeV. A good representation of the existing data was obtained but with no claim to uniqueness. Reference to prior work is given in Müller et al.[37] I note also that Brady et al.[38] of the Karlsruhe group have submitted a contribution to the conference on preliminary results on the n- ^{3}He analyzing power at eleven energies between 16 and 50 MeV.

At higher energy very recent results are becoming available on p- ^{3}He scattering from Hasell et al.[39] in a collaboration of Manitoba and others at TRIUMF. Differential cross sections and analyzing powers were measured with the polarized proton beam at four energies between 200 and 515 MeV. Evidence for interference between double and triple scattering was seen in the cross sections. An example of the analyzing power data at T_p = 200 MeV is shown in Fig. 8. The curve represents a Glauber-theory prediction with up to three scatterings. At this stage in the development of the model, agreement is reasonable out to about 40° c.m.

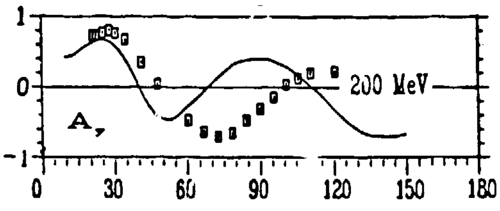

Fig. 8. Analyzing power in $^3He(\vec{p},p)^3He$ at T_p = 200 MeV. Data and M.S. curve from Ref. 39.

In terminating this section, I note the p- ^{3}He back angle differential cross section measurements of Berthet et al.[40] at Saturne-2 for T_p between 700 and 1700 MeV. They observed two structures associated with delta and possibly heavy baryon excitation.

5. SOME RESULTS IN N- ^{4}He SCATTERING

I have not found many recent publications in low energy N- ^{4}He polarization work. Most recent is a measurement by York et al.[41] at TAMU on neutron-^{4}He analyzing power at 50 MeV. The $d(\vec{d},\vec{n})^3He$ reaction at 0° was used as the polarized neutron source. Their data show a clear minimum in A(θ) at 110° c.m. and a strong maximum at 135°. In a report to the conference, Doll et al.[42] of the Karlsruhe group describe their measurements for n- ^{4}He A(θ) at eleven energies up to 50 MeV. Shown in Fig. 9 is an example of their data at T_n = 40 MeV. The solid points are their work, the open ones are proton data of Plattner et al.[43] The dashed curve is for n- ^{4}He phase shift prediction and the other is for n- ^{4}He. At back angles there is excellent agreement between the two data sets. Near 90° a very interesting charge-dependent difference develops that

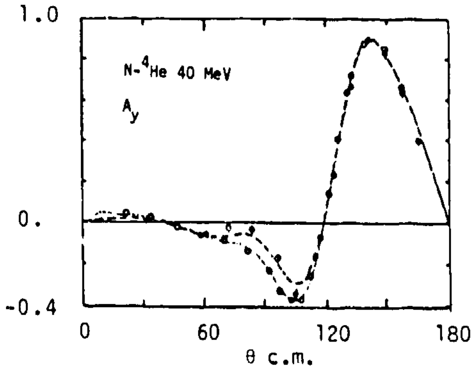

Fig. 9. N-^{4}He analyzing power at T_N = 40 MeV. Dots preliminary neutron data Ref. 42; open circles proton data Ref. 43. Dashed curve is n-^{4}He PSA.

will be important in clarifying the way in which Coulomb corrections are employed. In this connection, I note the recent paper of Fröhlich et al.[44] who treat such Coulomb differences explicitly for the N- ^{4}He system; references are also given to prior phase-shift analyses.

At intermediate energy the most timely results in p- ^{4}He scattering come from TRIUMF. Most recently Moss et al.[45] reported measurement of the rotation parameter (R) at 500 MeV. In a somewhat earlier work the same group[46] published measurements for the differential cross section and analyzing power for p- ^{4}He scattering at 200, 350, and 500 MeV over the full angular range.

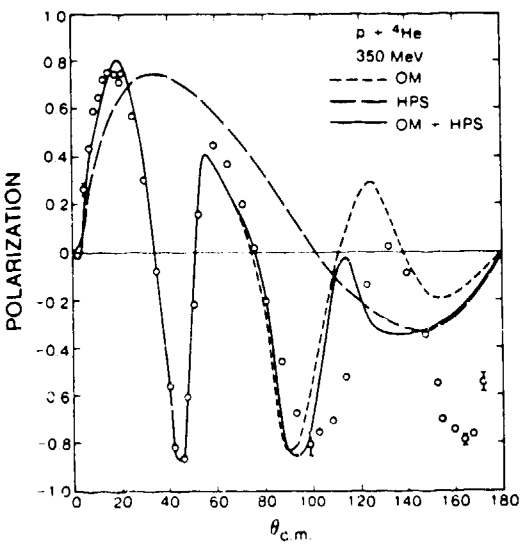

Fig. 10. p-^{4}He analyzing power at T_p = 350 MeV. Data from Ref. 46. Optical model predictions from Ref. 47.

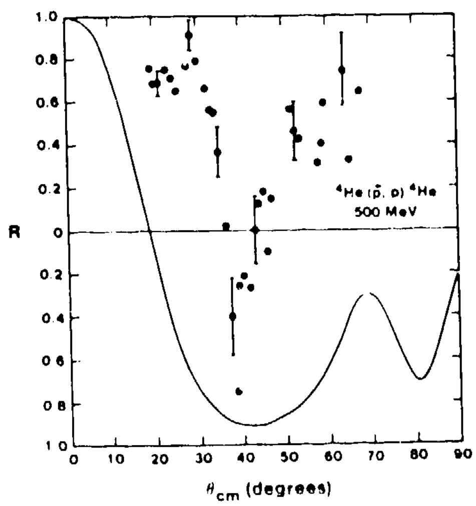

Fig. 11. p-^{4}He rotation parameter at T_p = 500 MeV. Data and optical predictions from Ref. 45.

In a very recent paper, Sherif[47] has discussed these results (not R) in an optical model (OM) with exchange effects. The ^{4}He target nucleus may be thought to consist of a proton plus triton cluster, and the associated heavy particle stripping (HPS) mechanism is calculated by the distorted wave Born approximation. Thus the total interaction is OM + HPS. The chief focus is on the exchange effects, manifested through HPS, with the object of reproducing the back angle cross section and analyzing power.

At 350 MeV, the differential cross section data are reproduced rather well. The case for the p- ^{4}He analyzing power at T_p = 350 MeV is shown in Fig. 10; the data are from Ref. 46. The short dashed curve is the optical model alone; it does well out to 90° c.m. The long dashed curve re·resents exchange through heavy particle stripping. The solid curve gives the complete interaction. Unfortunately HPS does not help very much; agreement in the large angle region is lacking.

Data for the p- ^{4}He spin rotation parameter from Ref. 45 are shown in Fig. 11 at T_p = 500 MeV. Carbon scattering was employed in the polarimeter. To the best of my knowledge this is the first such measurement for p + ^{4}He above ~50 MeV. The parameter has definite structure with a negative minimum near 40° c.m., rising to large positive values to either side. Also shown on the figure is a prediction for R from results of a standard optical model fit to the differential cross section and analyzing power in the forward hemisphere. The prediction is poor.

In a current preprint Greben and Gourishankar[48] have carefully examined p- ^{4}He scattering at 500 MeV in the optical model context. Their considerations of the data set led them to a model with a more pronounced attractive tail in the real central potential and to reduced spin orbit potentials than some prior models. In this manner they achieved excellent fits in the forward hemisphere for $d\sigma/d\Omega$, A and R. They emphasize the value of R data in arriving at good optical model parameters.

A substantial amount of theoretical activity has occurred in the past few years concerning intermediate energy p- ^{4}He scattering. Brief mention of some of this follows. Auger et al.[49] investigated intermediate isobaric states in the multiple scattering model. Wallace and Alexander[50] studied correlation effects with inclusion of isobar states in the context of multiple scattering. Alexander and Landau[51] described a microscopic optical model for energies near 200 MeV. Arnold et al.[52] presented a relativistic optical model for energies in the range 0.5 to 1.5 GeV.

Knowledge of the p- ^{4}He system at intermediate energies is in a state of development. Experimentally the system is fairly simple, both to measure and with respect to the number of observables (3). With the theoretical interest now evident we may expect significant increase in our understanding in the next few years.

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