Measurement of the Spin-Rotation Parameter β in Proton-He[4] Scattering at 48 MeV

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The spin-rotation parameter β has been measured at nine scattering angles between 11° and 90° (lab) in proton-He[4] elastic scattering at 48 MeV, using the polarized proton beam from the Proton Linear Accelerator at the Rutherford High Energy Laboratory, Chilton, England. The results are in good agreement with the predictions of the 40-MeV phase shift analysis of Giamati, Madsen, and Thaler.

1. INTRODUCTION

THE scattering of nucleons by He[4] has been extensively studied at energies below 30 MeV[1] since it is one of the simplest interactions in which the spin dependence of the scattering amplitude can be studied. Until recently, however, very few data have been available between 30 and 50 MeV. An understanding of the interaction in this energy region is particularly important since the polarization in nucleon-He[4] elastic scattering is large over a wide range of scattering angles and varies only slowly with energy; it is therefore an important process for preparing and analyzing polarized nucleon beams.

Prior to the measurement of the polarization in p-He[4] scattering at 38 MeV,[2] Cammel and Thaler[3] had derived a set of phase shifts to describe the p-He[4] interaction near 40 MeV. Their S and P phase shifts were obtained from a graphical extrapolation of the existing low-energy phase shifts and also from an optical-model potential, while the D and F phase-shifts were fitted to the differential cross-section values of Brussel and Williams.[4] The disagreement between the polarization predicted by Cammel and Thaler and the subsequent measurement prompted further phase shift analyses of the data.[5–7] The first of these, by Giamati, Madsen, and Thaler[5] (GMT) considered real phase shifts for states with $l\leqslant 4$ and used the Cammel-Thaler values as the starting points in the search. In theory, complex phase shifts should be employed to allow for the inelastic p-He[4] reactions which amount to 40% of the scattering at 50 MeV.[8] Using complex phases for $l\leqslant 3$, Suwa and Yokosawa[6] obtained a slightly better fit to the data (SY-A), their χ^2 being 176 for 71 experimental points. They, too, used the Gammel-Thaler phases as starting points in the search, together with a set calculated by Kanada *et al.*,[9] from a nonlocal proton-He[4] potential which was derived from the nucleon-nucleon interaction. Giamati and Thaler,[7] using complex phases for $l\leqslant 3$ together with entirely real parameters for $l=4$ and $l=5$, have recently obtained a further set of phase shifts (GMT-B) which also appear to fit the data.

It is clear, therefore, that the available data do not lead to a unique set of phase shifts for p-He[4] elastic scattering near 40 MeV, and that further experimental measurements are required. Wolfenstein[10] has shown that for the interaction of nucleons with a spin-zero nucleus such as He[4] the scattering matrix at a given energy is uniquely determined, apart from an arbitrary phase factor, by the measurement of the angular distribution of just one parameter β, in addition to the differential cross-section and polarization. If the scattering matrix M is assumed to be invariant under parity and time-reversal transformations, it may be written as

$$M=g(\theta)+h(\theta)\boldsymbol{\sigma}\cdot\mathbf{n}_1 \tag{1}$$

where $\boldsymbol{\sigma}$ is the Pauli spin matrix and $\mathbf{n}_1$ is a unit vector normal to the scattering plane in the direction defined by the Basle convention. The complex functions $g(\theta)$ and $h(\theta)$, which are respectively the spin-independent and spin-dependent scattering amplitudes, may be directly related to the phase shifts for the interaction. As there is some ambiguity in the literature the expressions used for $g(\theta)$ and $h(\theta)$ in the present work are given explicitly below

$$g(\theta)=\frac{1}{k}\Big\{-\tfrac{1}{2}\eta\csc^2(\theta/2)\exp\{i\eta\ln[\csc^2(\theta/2)]\}+\sum_{l=0}^{\infty}[(l+1)\exp(i\delta_l^+)\sin\delta_l^+ + l\exp(i\delta_l^-)\sin\delta_l^-]\times\exp(2i\omega_l)P_l(\cos\theta)\Big\}$$

$$h(\theta)=\frac{i}{k}\Big\{\sum_{l=1}^{\infty}[\exp(i\delta_l^+)\sin\delta_l^+ - \exp(i\delta_l^-)]\times\exp(2i\omega_l)\sin\theta\frac{dP_l(\cos\theta)}{d\cos\theta}\Big\}. \tag{2}$$

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The first term in $g(\theta)$ is the amplitude for pure Coulomb scattering; ω_l are Coulomb phase shifts and δ_l^+, δ_l^- the nuclear phase shifts for states of total-angular-momentum quantum number $(l+\frac{1}{2})$ and $(l-\frac{1}{2})$, respectively. The quantity β is then defined by

$$\tan\beta = 2\,\mathrm{Im}gh^*/(|g|^2-|h|^2). \quad (3)$$

Physically, β is the angle in the scattering plane through which the polarization vector is rotated in the p-He^4 interaction (Fig. 1) and clearly a triple-scattering experiment is required for its measurement.

The solutions SY-A and GMT-B predict widely different values for β at forward scattering angles, and a determination of this spin-rotation parameter should enable a more reliable phase shift analysis to be performed. The present work describes a measurement of β at nine scattering angles between 11° and 90° (lab), employing the 50-MeV polarized proton beam of the Proton Linear Accelerator at the Rutherford High Energy Laboratory of the Science Research Council, Chilton, England.

2. METHOD

Wolfenstein[10] has defined five triple-scattering parameters, D, A, A', R, and R' which relate the components of polarization of a particle before and after scattering, and has shown that, for the p-He^4 interaction, the depolarization parameter D is necessarily unity, while A, A', R, and R' may all be expressed as simple functions of the angle β

$$R=(1-P^2)^{1/2}\cos(\beta-\theta_L)=A', \qquad A=(1-P^2)^{1/2}\sin(\beta-\theta_L)=-R', \quad (4)$$

where θ_L is the laboratory scattering angle and P is the p-He^4 polarization at this angle. Thus, if both R and A are measured, the spin-rotation angle β may be directly determined from the ratio

$$A/R=\tan(\beta-\theta_L). \quad (5)$$

In experiments to measure A and R the polarization vector of the incident beam lies in the plane of the p-He^4 scatter which is horizontal in the present work. After the interaction the component of polarization perpendicular to the outgoing momenta is measured by a further scatter in the vertical plane from a target of known analyzing power. If the initial polarization is parallel to the direction of the incident beam, the observed asymmetry in the final scatter is given by

$$\epsilon_A = AP_1P_3, \quad (6)$$

where P_1 is the magnitude of the beam polarization, and P_3 the analyzing power of the final scatter. Similarly, if the polarization vector of the incident beam lies in the plane of the scatter and transverse to the beam direction then the asymmetry will be

$$\epsilon_R = RP_1P_3. \quad (7)$$

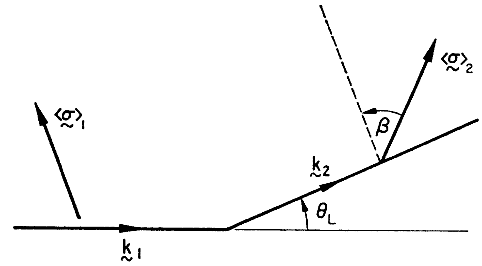

FIG. 1. The spin-rotation parameter β. ($\mathbf{k}_1$ and $\mathbf{k}_2$ are the incident and outgoing momenta; $\langle\boldsymbol{\sigma}\rangle_1$ and $\langle\boldsymbol{\sigma}\rangle_2$ the corresponding polarizations.)

Combining Eqs. (6) and (7) gives

$$\epsilon_A/\epsilon_R=\tan(\beta-\theta_L). \quad (8)$$

This ratio does not depend directly upon either P_1 or P_3 and, provided that they do not change between measurements of ϵ_A and ϵ_R, precise knowledge of these parameters is not required for the evaluation of β.

Bird *et al.*[11] have shown that by combining the asymmetries measured with the polarization vector of the incident beam in a given direction and reversed, ϵ_A and ϵ_R can be expressed in a form which is independent of the efficiencies of the analyzer counters and also of the exact equality of the beam monitoring for the two states of polarization. It is, however, necessary to ensure that reversal of the polarization does not result in either a movement of the beam on the target or a change in the profile of the beam.

These procedures are obviously possible only if longitudinally and transversely polarized beams, with reversible polarization, can be readily obtained. The polarization direction of the beam emerging from the Rutherford Laboratory Proton Linear Accelerator is defined by the direction of a weak magnetic field in the ionizer region of the polarized ion source.[12] The magnetic field is produced by a system of three mutually orthogonal Helmholtz coils,[13] whose axes are respectively along the axis of the beam, transverse vertical and transverse horizontal. By passing suitable currents through these coils, any polarization direction can be selected. Tests have established that controlling the proton polarization in this way produces neither a change in position nor an alteration in profile of the beam emerging from the accelerator.

3. APPARATUS

The experimental arrangement is shown in Fig. 2. The 50 MeV polarized proton beam, having an intensity of 10^8 protons per sec and a polarization of 0.36, was deflected by a bending magnet and focused by two

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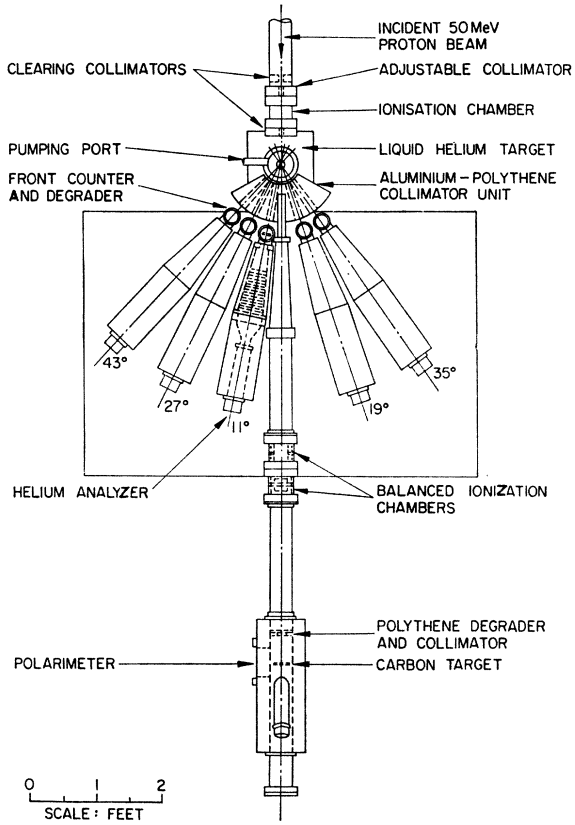

FIG. 2. Apparatus layout (showing Queen Mary College analyzers in position around helium target).

pairs of quadrupole lenses to form a spot approximately 1 cm in diameter on the scattering volume of a liquid helium target.[14] This target was mounted directly above a 17-liter storage Dewar, the liquid helium being driven up the central tube and into the scattering volume which was enclosed by a seamless nylon tube, 1.2 cm in diameter with 0.05 mm walls. The helium level was maintained by an excess pressure inside the Dewar, the pressure being controlled by a silicone oil manometer. Protons elastically scattered from the helium were degraded in polythene to an energy of approximately 22 MeV before entering polarization analyzers[15,16] containing helium gas at a pressure of 31 atm. Inside the analyzers, scattering angles of $60°\pm15°$ in the vertical plane were defined by a system of copper vanes, and protons scattered from the helium gas were detected in strips of NE 102A plastic scintillator, 0.75 mm thick, placed along the edges of the vane system. A Perspex light guide, 6 mm thick, which was viewed from one end by a 56 AVP photomultiplier, was bonded to the back of each scintillator. Protons entering an analyzer traversed a thin counter between target and analyzer, and fast coincidences between this counter and each of the side counters were recorded. Since the 1% duty cycle of the linear accelerator led to appreciable random coincidence rates, two identical fast-coincidence units, with resolving times of 15 nsec were used in parallel; one measured genuine-plus-random coincidences and the other, having one input delayed by 30 nsec, recorded only random coincidences. The functions of the two coincidence units were interchanged regularly to avoid systematic errors due to their different characteristics. The spectra of both genuine-plus-random and random coincidences in the analyzer counters were continuously recorded with two Laben multichannel pulse-height analyzers. Both pulse-height analyzers were operated in the 16×32-channel mode and were gated by the outputs of the coincidence units through 16-way selective storage units.

The incident-beam intensity was measured with a thin ionization chamber situated just upstream of the helium target. In order to minimize false asymmetries produced by movement of the beam spot on the target due to energy variations in the incident beam, the beam position at the target was continuously monitored and stabilized by two balanced ionization chambers[17] with their control foils at right angles. These chambers were located immediately behind the target and their output signals controlled the currents in a pair of steering magnets.

The polarization of the beam incident on the helium target was also monitored continuously by two similar carbon polarimeters. The component of polarization in the scattering plane and transverse to the beam direction was measured directly by degrading the beam traversing the target to an energy of 16 MeV and scattering up and down at an angle of 45° (lab) from a thin carbon target (0.1063 g cm^{-2}) of analyzing power P_c. This quantity, which did not have to be known accurately, could be estimated from the data of Brockman,[18] Yanabe *et al.*,[19] Boschitz,[20] Craig *et al.*,[21] and Rosen *et al.*[22,23] A second polarimeter[24] of polarization P_m, was situated at the end of the accelerator, before the bending magnet; two carbon targets, together with their degraders, were mounted on a wheel rotating at a speed such that they intercepted one beam pulse in ten. The sampled protons, degraded to an energy of 15

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MeV, were scattered through 45° (lab) in both the horizontal and vertical planes. The two asymmetries obtained enabled the two components of polarization in the plane perpendicular to the beam axis before the bending magnet to be calculated.

The energy of the beam was measured to be 49.7 MeV with the monitor of Hanna and Hodges.[25] Using this result, the mean energy at the center of the target was calculated to be 48.0 MeV from the data of Rich and Madey[26] for the energy losses of protons in aluminium, helium, and CH_2.

4. DATA COLLECTION

The measurements were made in three separate periods of machine time, approximately 250 h being spent in the collection of data. The values of β at 20°, 30°, 50°, and 90° (lab) were measured with four helium analyzers, designed at University College London,[15] on a beam line at 77° to the axis of the accelerator; the data at 11°, 19°, 27°, 35°, and 43° (lab) were obtained with five similar analyzers[16] constructed by the Queen Mary College London group at the Rutherford Laboratory. These analyzers, which were used on a beam line at 47° 40′ to the machine axis, had the advantage that they could be arranged very compactly around a target to measure asymmetries in the vertical plane.

With the 77° beam line, a preliminary run was necessary to determine the currents required in the Helmholz coils to give longitudinal or transverse polarization at the target. The selection of these currents was greatly simplified for the 47° 40′ beam line since for a proton beam of energy 49.7 MeV the angle of precession of the proton spin in the field of the bending magnet is exactly 90°; a longitudinally polarized beam emerging from the machine therefore became transversely polarized at the target, and vice versa.

Calibration runs were required to measure the quantities P_1P_m and P_1P_c for the two carbon polarimeters. The polarization vector was set transverse at the end of the accelerator, when the observed asymmetry in the vertical plane was equal to P_1P_m for the machine polarimeter. Having measured the energy of the beam entering the bending magnet, the angle of precession of the polarization vector θ_P was calculated from the relation

$$\theta_P=(\mu-1)\gamma\theta_0, \tag{9}$$

where μ is the magnetic moment of the proton in nuclear magnetons, γ is the ratio of the total proton energy to its rest energy, and θ_0 is the angle through which the proton orbit is deflected. Knowing θ_P, the orientation of the polarization vector at the target, δ, was calculated and hence P_1P_c determined from the asymmetry at the target polarimeter, ϵ_2

$$\epsilon_2=P_1P_c\cos\delta. \tag{10}$$

The collection of data was divided into cycles, each lasting between four and five hours and consisting of four runs to measure ϵ_A and four to measure ϵ_R. In each case, two of the four runs were for positive polarization and two for negative polarization, the functions of the coincidence units recording genuine-plus-randoms and randoms being interchanged for each setting of the polarized proton source.

Protons scattered in the nylon wall of the helium target or in the copper vanes inside the analyzer constitute a further source of background and thus complete cycles were also performed under the following conditions of target and analyzers:

(1) Target full, analyzers filled to 1 atm (FE)

(2) Target empty, analyzers filled to 31 atm (EF)

(3) Target empty, analyzers filled to 1 atm (EE).

By suitably combining counts obtained in this way, the contribution from this background has been eliminated. The FE runs were performed after every third FF run, while EF and EE runs followed every sixth FF run. For those cycles in which the helium target was empty, an additional degrader was placed behind the target and in front of the carbon polarimeter to compensate for the reduced energy loss of protons traversing the empty target.

5. DATA REDUCTION

The genuine coincidences were first calculated, by subtracting randoms from genuine-plus-randoms as recorded by the same coincidence unit in consecutive runs. This was permissible since the short-term fluctuations in the beam intensity were observed to be small. To correct for the background of genuine coincidences arising from protons scattered in the target walls and analyzer vanes, the counts obtained in all the FE, EF, and EE cycles during one period of machine time were combined to evaluate quantities C_i per cycle for each of the analyzer counters, for positive and negative states of both longitudinal and transverse polarization at the target. These quantities, calculated from

$$C_i=\mathrm{FE}+\mathrm{EF}-\mathrm{EE} \tag{11}$$

were subtracted from the appropriate counts obtained for each cycle with both target and analyzers full. This background of genuine coincidences was approximately 20% of the FF counting rate at all scattering angles. Equation (11) is slightly in error, since no allowance has been made for the difference in energy loss of protons traversing a full or empty target, and an analyzer containing helium gas at a pressure of 1 atm or 31 atms. However, since the energy losses in both target and analyzer are small compared with the mean energy of

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the protons traversing them, the error introduced by this approximation is much smaller than the statistical error.

The asymmetries ϵ_A, and ϵ_R, and their ratio ϵ were then determined for every cycle at each scattering angle. In practice it was not possible to calculate β from Eq. (8), as the currents in the Helmholtz coils could not be set with sufficient accuracy to give precisely longitudinal or transverse polarization at the target. Since an angle in the scattering plane was being measured, any small angular error in the alignment of the incident polarization vector was reflected in the observed value of β. It was therefore necessary to define correction angles α_1 and α_2 which represent the angular misalignment for nominally longitudinal and transverse polarization, respectively. The observed asymmetries are now given by

$$\epsilon_A'=P_1P_3(A\cos\alpha_1+R\sin\alpha_1), \quad (12)$$

$$\epsilon_R'=P_1P_3(A\sin\alpha_2+R\cos\alpha_2), \quad (13)$$

and hence

$$\tan(\beta-\theta_L)=(\sin\alpha_1-\epsilon'\cos\alpha_2)/(\epsilon'\sin\alpha_2-\cos\alpha_1), \quad (14)$$

where ϵ' is the ratio of the observed asymmetries, ϵ_A'/ϵ_R'.

The correction angles were determined for each cycle, and their values were always less than 5°. In the case of longitudinal polarization at the target, the angle α_1 could be measured independently by the two carbon polarimeters; thus, for the polarimeter located behind the target

$$\alpha_1=\arccos(\epsilon_2/P_1P_c). \quad (15)$$

From the machine polarimeter the orientation of the polarization vector before the bending magnet was determined and hence, knowing the angle of precession, the angle at the target calculated. For transverse polarization at the apparatus, the target polarimeter could not be used since the asymmetry ϵ_2 varied only slightly with angle α_2 and so a single measurement was made with the machine polarimeter. A useful check on the values of the correction angles was provided by retaining the coil currents used for either longitudinal or transverse polarization at the end of one cycle for the beginning of the following cycle. By interleaving the settings in this way, four values were obtained for each α_1 and two for each α_2; these were all found to agree within their statistical errors.

The angle β was then calculated from Eq. (14) for every cycle at each scattering angle.

In estimating the errors on the asymmetries, the usual assumptions were made concerning the propagation of errors; that is, the variables were taken to be independent and the errors themselves to be normally distributed. The error on $\tan(\beta-\theta_L)$, denoted by $\Delta\epsilon$, was calculated in this way but, since the second differential of the tangent function is not necessarily small compared with the first, the error on $(\beta-\theta_L)$ was asymmetric. However, for the purposes of providing a weighting factor for each value of β, a symmetric quantity, which was essentially proportional to the number of counts used in calculating $(\beta-\theta_L)$, was employed. The expression used was

$$\Delta(\beta-\theta_L)=\Delta\epsilon/(1+\epsilon^2). \quad (16)$$

This was taken as the error on β itself, as the error on the mean laboratory scattering angle θ_L was negligible compared with the statistical error on $(\beta-\theta_L)$.

The assumption that the sample of values of β at each scattering angle belonged to a normal parent distribution was tested. Although the samples were small, each containing between 15 and 26 measurements, this assumption was found to be justified in every case. The weighted mean of each sample, $\bar{\beta}$, was therefore taken as the best estimate of the mean of the parent distribution, the error in $\bar{\beta}$ being the most probable error on the weighted mean. These are the figures quoted in Table I, with the exception of the value at 90° (lab), where the number of counts obtained was too small to evaluate β for each cycle; a single result was therefore calculated from all the counts accumulated during the run.

During the measurement using the 47° 40′ beam line it was not possible to determine the correction angles due to faults in the carbon polarimeters. However, the precession angle for this line is exactly 90°, which considerably simplifies the setting of the currents in the Helmholtz coils since a beam polarized longitudinally before the bending magnet is transversely polarized at the target, and vice versa. The angular misalignment of the polarization vector can arise either from errors in setting the currents through the coils or from the stray magnetic field in the ionizer of the polarized proton source. Tests have shown that the stray field, which is due to the sextupole magnet of the source, is transverse to the beam direction in the horizontal plane and can be compensated by a current of (17.5±0.5) A through one pair of coils. Transverse polarization at the accelerator is therefore obtained by supplementing the sextupole stray field with the appropriate pair of Helmholtz coils to produce an overall field equivalent to a coil current of approximately 50 A, and is reversed

TABLE I. Experimental results for β at 48.0 MeV.

θ_L (lab. angle, deg)	$\theta_{c.m.}$ (c.m. angle, deg)	β (deg)
11.0	13.8	+2.3± 5.9
19.0	24.0	−14.0± 2.7
20.0	25.1	−16.1± 3.8
27.0	33.8	−17.7± 3.4
30.0	37.5	−24.6± 2.8
35.0	43.6	−39.3± 6.0
43.0	53.2	−44.7± 4.6
50.0	61.5	−62 ±18
90.0	105.0	−173 ±46

by reversing both sextupole magnet and Helmholtz coil currents. Longitudinal polarization is obtained by compensating the stray field and passing a sufficiently large current (50 A) through the pair of coils which produces a longitudinal magnetic field. Once again, reversing the polarization is accomplished by reversing all coil and magnet currents. It is estimated that by orienting the polarization in this way the correction angles for any cycle should both be less than 0.6°, while the mean values for all the cycles performed should be close to zero. The systematic error introduced into the measurements at 11°, 19°, 27°, 35° and 43° (lab) by not correcting for possible misalignment of the polarization vector at the target should therefore not be greater than ±0.6°. When using the 77° beam line it was necessary both to compensate for the stray field and also to set the currents in the two pairs of coils to values determined during calibration runs. For the 32 cycles performed on this line, both correction angles were found to be approximately normally distributed about a mean of 3°, the standard deviation of 2° about this mean arising from the precision with which the currents through the Helmholtz coils could be reset. The correction angles were therefore considerably larger than for the 47° 40′ beam line, and since these angles were calculated from measured values of P_1P_m and P_1P_c the errors on these two quantities resulted in a systematic error on β. There is thus a possible scale error, calculated to be ±0.8°, on the measurements at 20°, 30°, and 50° (lab) in addition to the statistical errors quoted in Table I.

No correction was made for the finite angular resolution of the polarization analyzers, since this was calculated to be negligible compared with the statistical error on each point.

6. DISCUSSION

The experimental values for β are compared with the predictions of the 40-MeV phase shift analyses in Fig. 3. The results appear to favor solutions of the GMT type, but since the measurement was made at an energy close to 48 MeV a direct comparison is probably not realistic. In fact, the results of Boschitz *et al.*,[27] who have recently measured the proton polarization in p-He^4 scattering at 37.8 MeV for six angles between 8° and 20° (lab), are, with the exception of the smallest angle point, in good agreement with the predictions of the SY-A solution. The authors point out, however, that the SY-A solution contains partial waves only for $l \leqslant 3$, and that the phase-shifts for $l=3$ are not small. The behavior of the proton polarization in the angular region between 50° and 90° (c.m.), where the SY-A solution predicts an angular variation which is too smooth, while the GMT-B solution, having $l \leqslant 5$, oscillates too violently, would also appear to indicate that partial waves up to at least $l=4$ are required to perform a meaningful phase-shift analysis at 40 MeV. An intermediate solution might therefore provide a better fit to the existing data.

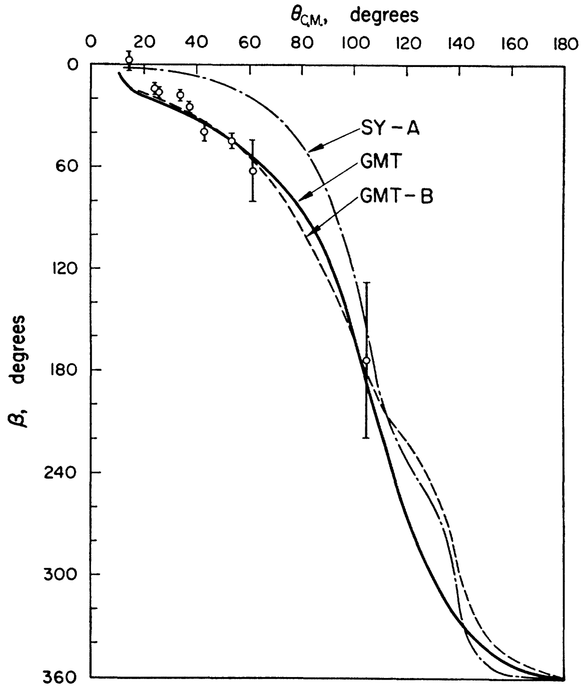

FIG. 3. Experimental results for β as a function of c.m. scattering angle at 48.0 MeV, compared with theoretical predictions of β at 40.0 MeV.

These conclusions are borne out by the recent analyses of Davies *et al.*[28] at 40 and 48 MeV. At 40 MeV they find that if the fit is restricted to partial waves up to $l=3$ the SY-A solution is frequently found, even if the GMT-B phase-shifts for *SPD* and *F* waves are used as the starting point. If the analysis is extended to include *G* waves, a solution is found which is very similar to GMT-B, even when the SY-A phase shifts are used as the starting point for the search. It seems therefore that the occurrence of the SY-A solution may be associated with the use of too few partial waves in the analysis.

At 40 MeV Davies *et al.* have analyzed the differential cross-section measurement of Brussel and Williams[4] and the Rutherford Laboratory polarization data[29] in terms of *S*, *P*, *D*, *F*, and *G* partial waves. They obtained a final fit with a χ^2 of 104 compared with the expected value of 50. At 48 MeV the data used in the analysis were the Rutherford Laboratory polarization[29] and cross-section[28] results, together with preliminary data from the present experiment. Starting with the 40 MeV

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solution they obtained a set of phase-shifts having a χ^2 of 136. This was later reduced to 44, compared with an expected value of 38, by omitting six differential cross-section points lying more than three standard deviations away from a smooth curve drawn through the data. At the present time a faster minimization routine is being tested, and it is hoped to investigate the uniqueness of the 48-MeV solution and perform a more comprehensive analysis of the p-He^4 phase-shifts between 10 and 50 MeV in the near future.[30]

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Neutron-Deuteron Polarization at 22.7 MeV*

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A measurement of the neutron-deuteron polarization function has been made at $E_N=22.7$ MeV over the angular range 44.5° to 158.8° c.m. Neutrons with polarization approximately 0.5 were obtained from the $T(d,n)^4He$ reaction at a deuteron energy of 6.6 MeV and a lab angle of 30°. Comparison is made to existing neutron data at 23.7 MeV and to proton data at 22 MeV. Agreement with the latter is good except near 130° c.m. where the value given here falls low. Theoretical comparisons do not exist in the energy range of this experiment.

I. INTRODUCTION

THE existing data at 22 MeV on p-d polarization measured by Conzett, Igo, and Knox[1] display considerable structure. These data show a positive hump in the forward hemisphere, a negative region in the range $70° \leq \theta_{c.m.} \leq 120°$, where the polarization attains the value -0.16, and a positive peak at angles between 128° and 136° c.m. where $P \approx +0.26$. Charge symmetry of nuclear forces would imply that the polarization in n-d and p-d scattering should be similar, especially at back angles. The neutron data of Walter and Kelsey,[2] at the energy, $E_N=23.7$ MeV, gave appreciably lower values than the p-d data of Ref. 1 at back angles. The motivation for the present experiment resides in the attempt to improve the back-angle neutron data and to extend the angular range of the measurements.

It may be noted that heretofore the work of Walter and Kelsey[2] provided the only existing neutron-polarization data above 6 MeV. Measurements of n-d differential cross sections in this energy range exist at 14 MeV,[3,4] while p-d cross sections[5,6,7] have been measured at 20, 32, and 40 MeV. The measurements on n-d polarization at low energy have been discussed by Elwyn, Lane, and Langsdorf,[8] with particular emphasis on energies below 2 MeV.

Recently the p-d polarization has been measured at 40 MeV by Conzett *et al.*[9] and at 30 MeV by Hall *et al.*[10] and Johnston *et al.*[10] The shape of the polarization function at the higher energies remains similar to that at 22 MeV. The magnitude of the negative peak near 115° c.m. shows a monotonic increase as a function of energy, reaching the value of -0.39 at 40 MeV.[9] The recent p-d data[10] at 30 MeV indicates that the maximum polarization in the positive peak at 140° c.m. has decreased to the value of $+0.21$, relative to the data[1] at 22 MeV. At 40 MeV, however, one datum point at 141.5° c.m. gives a value of $+0.49\pm0.20$ for the

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