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Separation of Projectile and Ejectile Spin-Orbit Distortions⁺
in an $\ell=0$ ($d, {}^3\text{He}$) Reaction

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Abstract: Analysing powers of the ${}^{31}\text{P}(\vec{d}, {}^3\text{He}){}^{30}\text{Si}, \ell_{\text{tr}}=0$, and its inverse reaction have been measured. Quantities which are proportional to the entrance and exit channel spin-orbit distortions have been constructed from these analysing powers. From these quantities the relative importance of the two spin-orbit distortions was ascertained. A DWBA analysis including D-state contributions in the ${}^3\text{He}$ wave function was conducted in order to fit the spin separated quantities. Optical model potential parameters used in the DWBA analysis were deduced from a study of the entrance and exit channel elastic scattering data.

Nuclear Reactions ${}^{30}\text{Si}({}^3\text{He}, d){}^{31}\text{P}$, ${}^{30}\text{Si}({}^3\text{He}, {}^3\text{He}){}^{30}\text{Si}$, ${}^{31}\text{P}(\vec{d}, {}^3\text{He}){}^{30}\text{Si}$, ${}^{31}\text{P}(\vec{d}, d){}^{31}\text{P}$; measured $d\sigma/d\Omega$ and A ; DWBA analysis; Natural ${}^{31}\text{P}$, enriched ${}^{30}\text{Si}$ targets.

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1. Introduction

The distorted wave Born approximation (DWBA) is used extensively in the analysis of single nucleon transfer reactions. Although experimental differential cross-section angular distributions are seldom irreproducible by the DWBA, it has been frequently reported that the DWBA predictions for polarisations are far from satisfactory.

Improvements to the "fitting" of the experimental data may occur by choosing different entrance and/or exit channel optical potentials. Therefore in the case of a poor reproduction of observable quantities it would be advantageous to differentiate between the inadequacies of a particular optical model potential set used in the DWBA calculation and the limitations of the DWBA theory. It is necessary to ascertain the shortcomings of the DWBA as it is widely used to extract spectroscopic factors in nuclear reactions and to assign spins and parities of nuclear states.

If it is possible to identify observables which are dependent of some terms in the optical potential, then the effectiveness of these particular terms in reproducing the data could be investigated. For polarisation observables the value of the orbital angular momentum transfer is the precursor for identifying terms in the optical potential which play the dominant role in producing the observable. For a reaction where the orbital angular momentum transfer, ℓ_{tr} , is non-zero, the polarisation effects originate primarily in the central potential^{1,2)}, whereas if the ℓ_{tr} is zero and D-state effects are neglected, the spin-orbit potentials are the only ones which contribute to the polarisation observables^{3,4)}.

Johnson^{5,6)} has produced a formalism that enables the separation of the spin dependent distortions in the entrance and exit channels when the ℓ_{tr} is zero. Combinations of the polarisation and analysing power in a single

nucleon transfer reaction yield two quantities which are dependent upon the spin-orbit potential in the entrance and exit channel. This theory can be applied to investigate the problems associated with the predictions of polarisation data in terms of the spin-orbit potential of one or the other channel. In addition the relative importance of the entrance and exit channel spin-orbit distortions in reproducing the data can be analysed.

By having observables that are dependent upon the spin-orbit potential in a particular channel it is possible to investigate the form of the spin-orbit potential in order to try to resolve any existing ambiguities. For example, if two radically different spin-orbit potentials used in a DWBA calculation reproduce the data equally well, then the existence of an observable which is directly related to the spin-orbit potential could be used to differentiate between the two.

In an $\ell_{tr}=0$ (d, ^3He) reaction initiated by polarised deuterons, the analysing power, A_y , in the absence of D-state considerations, is given by

$$A_y = (2/3)S_h + S_d \quad (1.1)$$

where S_h and S_d are terms proportional to the ^3He and deuteron spin-orbit potential, respectively. If the deuteron beam is unpolarised then the polarisation, p_y , of the outgoing ^3He particles is written as

$$p_y = S_h + S_d \quad (1.2)$$

Inspection of equations 1.1 and 1.2 yields the formalism for the construction of S_d and S_h from the analysing power and polarisation, namely

$$\begin{aligned} S_h &= 3p_y - 3A_y = 3p_y - 2/3 iT_{11} \\ S_d &= 3A_y - 2p_y = 2/3 iT_{11} - 2p_y \end{aligned} \quad (1.3)$$

where iT_{11} is the vector analysing power expressed in a spherical co-ordinate

system. In this way the ^3He and deuteron spin-orbit distortions are now separated, and experimental angular distributions can be obtained by measuring the analysing power and polarisation in an $\ell_{tr}=0$ ($d, ^3\text{He}$) reaction.

2. Experimental Method and Results

Analysing power data are best measured by initiating a ($d, ^3\text{He}$) reaction with polarised deuterons and measuring the asymmetry of the exiting ^3He . Polarisation results can be obtained by measuring the polarisation of the ^3He when the same reaction is initiated by unpolarised deuterons. Such measurements require the use of double scattering techniques which are difficult and subject to larger statistical errors than the analysing power data due to the low count rate. Since the spin separated quantities are constructed from a combination of the analysing power and polarisation the errors are therefore required to be as small as possible. If use is made of the "polarisation-asymmetry theorem"⁷⁾, then the polarisation in a ($d, ^3\text{He}$) reaction is equal to the analysing power in the inverse ($^3\text{He}, d$) reaction at the same centre of mass energy and angle. Thus experimentally the polarisation data are best obtained by measuring the analysing power of the exact inverse reaction.

In order to improve the choice of the optical potentials used in a DWBA analysis it is necessary to measure the elastic scattering differential cross-section and analysing power angular distributions for both the deuteron and ^3He channels. An optical model analysis of the elastic scattering data would serve to determine suitable optical potentials to be used in a DWBA calculation. In addition, the ($d, ^3\text{He}$) and ($^3\text{He}, d$) differential cross-section data would also be beneficial in a DWBA analysis.

The use of the exact inverse ($^3\text{He},d$) reaction to determine the $(d,^3\text{He})$ polarisation places two further constraints on the choice of the reaction in addition to the $\lambda_{tr}=0$ requirement. It is necessary for the target and residual nuclei in the $(d,^3\text{He})$ reaction to be stable so that a target may easily be manufactured for both the $(d,^3\text{He})$ and $(^3\text{He},d)$ reactions. In addition, the polarised ^3He beam is available only at Birmingham, where the cyclotron energy is fixed at 33 MeV. This factor places a constraint on the choice of deuteron energy.

Taking all this into consideration, the only two possible candidates are the $^{19}\text{F}(d,^3\text{He})^{18}\text{O}$ and $^{31}\text{P}(d,^3\text{He})^{30}\text{Si}$ reactions. Of these two, the latter reaction was chosen as the targets are available in a solid, high purity form and the possibility of compound effects in the scattering is expected to be less for the heavier nucleus.

Data were taken at Birmingham for the $^{30}\text{Si}(^3\text{He},^3\text{He})^{30}\text{Si}$ and $^{30}\text{Si}(^3\text{He},d)^{31}\text{P}$ reactions at 33 MeV using a self-supporting 0.39mg/cm^2 enriched ^{30}Si target. The beam polarisation was monitored by a downstream polarimeter based on the $^3\text{He} + d$ scattering⁸⁾. Spin reversal of the ^3He beam was implemented remotely and in such a way that the charge incident on the target for both spin states of the beam was equal. Reaction products were detected in six silicon $\Delta E \times E$ detector telescopes spaced 5° apart and mounted on two rotatable arms set at symmetric angles $\pm\theta^\circ$ with respect to the incident beam direction. Using this configuration, angular distributions for the differential cross-section and analysing power data were taken simultaneously for both the elastic and $(^3\text{He},d)$ reactions over the angular range 12.5° to 100° (lab.) in 2.5° steps up to 40° with 5° steps employed at larger angles. Details of the experimental arrangement and data reduction have been described previously⁹⁾.

Data for the $^{31}\text{P}(\vec{d}, ^3\text{He})^{30}\text{Si}$ reaction together with the deuteron elastic scattering were taken simultaneously at the Lawrence Berkeley Laboratory on the 88" cyclotron using a 35 MeV vector polarised deuteron beam. Four $\Delta E \times E$ detector telescopes, which were spaced 10° apart and mounted on two rotatable arms placed at $\pm\theta^\circ$ to the incident beam direction, were used to detect the reaction products. The beam polarisation was continuously monitored in a downstream polarimeter which utilized the $^4\text{He}(\vec{d}, d)^4\text{He}$ scattering, while the spin state of the beam was switched automatically ensuring equal charge on target for both spin states of the beam. The target used was a self supporting pure phosphorus foil made from red phosphorous with a thickness of about $10\text{mg}/\text{cm}^2$. High counting rates due to the thick target and high beam current ensured a good statistical accuracy of the data. However, due to the use of a thick target the energy resolution was such that background subtraction and peak fitting techniques had to be employed in the extraction of the data. Due to the inhomogeneity of the target and uncertainty of the thickness, coupled with the energy resolution, the elastic scattering differential cross-section data were considered unreliable and were not included in the analyses. The $(d, ^3\text{He})$ differential cross-section data were subject to the same normalisation problems but could be checked using the principle of detailed balance¹⁰⁾.

Elastic scattering angular distributions are shown in figure 1 with the reaction data shown in figure 2. Errors shown in these figures reflect the statistical uncertainties only. The ^3He elastic scattering analysing power distribution is similar to results on different target nuclei¹¹⁾ in that it is very small in magnitude at forward angles and only becomes appreciable in both magnitude and oscillatory patterns at large angles.

Reaction differential cross-sections and analysing powers are very similar in both shape and magnitude.

3. Analysis and Discussion

The $(d, {}^3\text{He})$ and $({}^3\text{He}, d)$ analysing powers measured at the same centre of mass angle were combined in the way prescribed by equation 1.3 producing the angular distribution of S_d and S_h , which are shown in figure 3. From this figure it can be seen that S_d and S_h are opposite in sign and are of equal magnitude. This observation implies that the deuteron and ${}^3\text{He}$ spin-orbit potentials play equally important roles in determining the polarisation observables.

Analysis of the ${}^3\text{He}$ elastic scattering data in the context of the optical model produced two different optical potentials. The first potential was based upon a search using the starting parameters of a ${}^3\text{He} + {}^{28}\text{Si}$ optical model analysis at the same ${}^3\text{He}$ energy¹²⁾, whilst the second potential resulted from a search with conventional starting parameters; this latter potential is given in Table 1 labelled X, with the resulting "fits" to the ${}^3\text{He}$ elastic scattering data shown in figure 1 as the solid lines. A significant aspect of these two potentials was the small spin-orbit diffusenesses, which have often been observed in polarised ${}^3\text{He}$ scattering¹¹⁾.

Deuteron optical potentials to be used in an optical model and DWBA analysis were taken from literature¹³⁻¹⁸⁾, and included global, adiabatic and specific $d + {}^{31}\text{P}$ potentials. In all, fifteen potentials were obtained in this way.

DWBA calculations, using the zero range DWBA code DWUCK4¹⁹⁾, were carried out using all possible permutations of the fifteen deuteron potentials and the two ${}^3\text{He}$ potentials found from the elastic scattering analysis plus one other

taken from literature¹⁸). The predictions for the $(\vec{d}, d)$, $(\vec{d}, {}^3\text{He})$, $({}^3\vec{\text{He}}, {}^3\text{He})$, and $({}^3\vec{\text{He}}, d)$ analysing powers, along with the $(\vec{d}, {}^3\text{He})$, $({}^3\vec{\text{He}}, d)$ and $({}^3\vec{\text{He}}, {}^3\text{He})$ differential cross-sections, were compared with the data in order to obtain the best pair of optical potential sets. It was found that the best ${}^3\text{He}$ potential was potential X coupled with a deuteron potential due to Childs¹⁵), which is given in Table 1. The fit to the elastic scattering analysing power due to this deuteron potential can be seen in figure 1. Reaction analysing powers and differential cross-sections predicted by the use of the above pair of potentials in the DWBA can be seen in figure 2 and are denoted by the solid line. Investigations into the effect of changing the parameters of the bound state potential, "finite range" effects in terms of a local energy approximation and radial cutoffs did little to enhance the "fit" to the data.

The predictions of the quantities S_d and S_h which are proportional to the deuteron and ${}^3\text{He}$ spin-orbit potentials, respectively, can be seen in figure 3, indicated by the solid line. These predictions were obtained using the computer code DTCODE²⁰), which employs the local energy approximation. Reproduction of S_d using the previously defined potentials is reasonable in that the phase of the data and prediction are in accord, and the magnitudes are similar, except at 65° , where the data indicate a sharp peak which is not reproduced by the calculation. This datum point originates from the difference between the iT_{11} and p_y data, which is very large. The quantity S_h is not reproduced at all by the calculation, with the prediction being very small in magnitude throughout the whole angular distribution.

The effect of setting the strength of the entrance and/or exit channel spin-orbit distortions to zero in the DWBA calculation can be seen in figures 4, 5 and 6. Figure 4 shows that the effect of the removal of the deuteron spin-orbit potential is to dramatically worsen the fits to iT_{11} and p_y , whilst

the effect upon S_d and S_h is as predicted by theory; which is that S_d should be zero whilst S_h is hardly affected. In contrast, figure 5 depicts the situation when the ^3He spin-orbit strength is set to zero and shows that the effect on iT_{11} and p_y is minimal and S_h is zero with S_d unaffected. This apparent insensitivity of iT_{11} and p_y to the ^3He spin-orbit potential is in disagreement with the experimental magnitudes of S_d and S_h . Removal of both spin-orbit potentials as in figure 6 produces zero iT_{11} , p_y , S_h and S_d as expected.

Calculations which include the D-state component in the ^3He wave function are shown in figures 3 to 6 as the dashed line. Differences between the S+D and S-state only calculations are reflected by the dashed-dotted line and for a parameter J are given by

$$J(D) = J(S+D) - J(S), \quad (1.4)$$

where the bracketed terms reveal the states included in the calculation.

It can be seen from figure 3 that the effect of the inclusion of the ^3He D-state upon iT_{11} and p_y is very small with the most pronounced feature being the reduction in the predicted peak for p_y at 40° providing better agreement with the experimental data. The D-state effects on S_d and S_h are more pronounced especially in the S_h distribution which is more oscillatory, larger in magnitude and in better agreement with the data than the S-state only predictions for angles forward of 60° . Upon removal of one or both of the spin-orbit potentials, the predictions for $S_d(D)$ and $S_h(D)$ are only slightly affected, as shown in figures 4, 5 and 6. Cadmus and Haeberli^{2†}), in their study of the (d,p) reaction, showed that the D-state contribution to S_d and S_p (where S_p is proportional to the proton spin-orbit potential) can be in both a linear and a quadratic form. The linear term is proportional to one or the

other spin-orbit potentials whereas the quadratic term is independent of both⁴). In the (d,p) case it was found that the linear D-state terms were negligible in comparison to the quadratic terms. This result was fortuitous as it was discovered that when the D-state terms were considered the complete separation of the proton and deuteron spin-orbit distortions was broken by the appearance of a linear D-state term proportional to the proton spin-orbit potential in the equation for S_d . Therefore the almost negligible effect of the linear terms meant that the separation was restored even with the effects of the D-state included. In the (d,³He) case, as shown in figures 4, 5 and 6, it appears that the linear D-state terms are once again negligible as the effect of the removal of one or both of the spin-orbit potentials has very little effect on $S_d(D)$ and $S_h(D)$; which are the contributions to S_d and S_h due to the introduction of the ³He D-state. Further confirmation of the dominance of the quadratic D-state terms over the linear terms can be seen in figure 7. By plotting the averaged values of $S_d(D)$ and $S_h(D)$ against the square of the D-state parameter D_2 , which is proportional to the quadratic D-state term, an almost straight line is observed. This straight line indicates that the linear D-state terms are smaller than the quadratic ones and that the ratio of the gradients of $\langle S_d(D) \rangle$ and $\langle S_h(D) \rangle$ vs. D_2^2 reveals the relative contribution of the quadratic D-state term to S_d and S_h . In this case the gradients are in the ratio

$$S_d(D)/S_h(D) = -0.75$$

indicating that the contribution to S_d and S_h from the quadratic D-state terms are in the ratio -3:4, which is to be confirmed by theory. This observation also implies that the D-state contribution to A_y and p_y depend on the square of D_2 .

Following the unsuccessful attempts to reproduce S_h by the ^3He spin-orbit potential used, characterised by a small spin-orbit diffuseness, an extensive optical model search to was carried out to find a potential which had a "conventional" larger diffuseness. Such a potential was difficult to find, and the one that produced the lowest chi-squared per point is given as potential W in Table 1. This potential had a chi-squared per point for the polarisation data that was over twice as large as for potential X, which had a small spin-orbit diffuseness. The corresponding fits to the ^3He elastic scattering and $(^3\text{He}, d)$ and $(d, ^3\text{He})$ observables are shown in figures 1 and 2 as the dashed lines. From these figures it can be seen that the ^3He elastic scattering analysing power prediction is worsened as is the $(^3\text{He}, d)$ differential cross-section, whilst there is little to choose between the potentials for the $(^3\text{He}, d)$ and $(d, ^3\text{He})$ analysing powers. Predictions for S_d and S_h resulting from DWBA calculations with the ^3He potential W are shown in figure 8. From this figure it can be seen that there appears to be no pronounced improvement to the S_h fit and that the S+D state calculation is again of better quality at forward angles. The predicted angular distribution of S_d is similar to the previous DWBA prediction with ^3He potential X. Therefore there appears to be no indication as to whether the ^3He potential should be characterised by a large or small spin-orbit diffuseness.

4. Discussion and Conclusions

An optical model study of the ^3He elastic scattering data revealed that the spin-orbit potential with a radial variation that is sharply peaked at the nuclear surface is preferred. A "forced fit" with a large spin-orbit diffuseness could not reproduce the elastic scattering analysing power data as well as a potential with a small diffuseness.

The method for choosing deuteron optical potentials was to perform "one-shot" optical model and DWBA calculations and to compare the predictions with the data. This was justified by the satisfactory quality of the fits to the experimental observables including S_d . The reaction differential cross-section and analysing power data were described by DWBA calculation, which assumed a single step direct reaction mechanism which reproduced the phase and magnitude of the data.

Experimental angular distributions of the quantities S_d and S_h indicate that there is no predominance of the entrance or exit channel spin-orbit distortion over the other. However, DWBA predictions reproduce the trend of S_d reasonably well, whereas predictions for S_h are only appreciable when the D-state component of the ^3He wave function is included in the calculation. The result of the removal of one or the other of the spin-orbit potentials in the calculation is in agreement with theoretical expectations for S-state only calculations.

As in the case of (d,p) work the linear D-state terms seem negligible in comparison to the quadratic terms. More information on the D-state effects described by the D_2 parameter could be attained via measurements of the $(\vec{d}, ^3\text{He})$ tensor analysing powers. It has been shown²²⁾ that the effect of the variation of the D_2 parameter upon the vector analysing power is not as pronounced as in tensor analysing power predictions.

Investigation of the role of the ^3He spin-orbit potential by removing it from DWBA calculations or use of a large or small diffuseness parameter had shown that it has little effect upon the prediction of iT_{11} and p_y . However, it is to be noted that since the DWBA predictions for S_h were small in magnitude then theoretically this effect is to be expected. Should a potential be found for which DWBA predictions for S_h were large in magnitude,

then the effect of its removal from the calculation might be as marked as in the deuteron case.

It appears that by using the "conventional" derivative Woods-Saxon potential form factor a satisfactory fit to S_h is very difficult to find, indicating perhaps that a different potential form factor may prove to be required in order to reproduce the data for S_h . Calculations with different form factors have not been attempted in detail. In spite of the difficulties encountered with the description of the spin separated quantities S_d and S_h , the present work has clearly proven the usefulness of this approach in the study of the role of nuclear distortion in the mechanism of the $(d, {}^3\text{He})$ one-nucleon transfer reaction.

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Table I.

CHANNEL	Name	$V_R(r_R, a_R)$	$W_V(r_V, a_V)$	$W_D(r_D, a_D)$	$V_S(r_S, a_S)$
$^3\text{He}+^{30}\text{Si}$	X	171.2(1.205, .698)		31.722(1.031, .882)	2.799(1.302, .203)
$^3\text{He}+^{30}\text{Si}$	W	99.152(1.349, .697)	12.757(1.7, .284)	7.31(1.45, .913)	1.207(.969, .673)
$d+^{31}\text{P}$	-	85.8(1.15, .78)	1.13(1.33, .705)	12.6(1.33, .729)	5.7(1.1, .55)

Figure Captions

Figure 1. Elastic scattering observables for the $^{30}\text{Si}(^3\vec{\text{He}}, ^3\text{He})^{30}\text{Si}$ and $^{31}\text{P}(\vec{\text{d}}, \text{d})^{31}\text{P}$ reactions with the solid and dashed lines for the former reaction denoting prediction using optical potentials X and W respectively. The curve in the $^{31}\text{P}(\vec{\text{d}}, \text{d})^{31}\text{P}$ analysing power is the result of an optical model calculation using the potential given in Table 1.

Figure 2. Differential cross-sections and analysing power data for the $^{30}\text{Si}(^3\vec{\text{He}}, \text{d})^{31}\text{P}$ and $^{31}\text{P}(\vec{\text{d}}, ^3\text{He})$ reaction. The solid and dashed lines denote DWBA predictions using the ^3He potential X and W respectively.

Figure 3. Experimental angular distribution of iT_{11} , p_y , S_d and S_h and associated DWBA predictions for S-state only (solid line), S and D-state (dashed line) and D-state-only (dashed/dotted line) calculations.

Figure 4. The effect of the removal of the deuteron spin-orbit distortion in the DWBA calculations with the curves as defined in figure 3.

Figure 5. The effect of the removal of the ^3He spin-orbit distortion in the DWBA calculations with the curves as defined in figure 3.

Figure 6. The effect of the removal of both entrance and exit channel spin-orbit distortions in the DWBA calculations with the curves as defined in figure 3.

Figure 7. Dependence of D_2^2 on the D-state contributions to S_h and S_d .

Figure 8. DWBA predictions for iT_{11} , p_y , S_d and S_h when using ^3He potential W with the curves as defined in figure 3.

Fig 1.

Fig. 2.

Fig. 3.

Fig. 4

Fig 5.

Fig. 6

Fig 7

Fig. 8

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