# Effect of Breakup on the Spin Dependence of the Deuteron-Nucleus Interaction

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Realistic breakup states with spin, based on Reid's nucleon-nucleon potential, are used to calculate the correction to elastic deuteron-nucleus scattering matrix elements $S$, to second order in the distorted-wave Born approximation. There are no free parameters. The breakup corrections move the values of $S$ obtained with a simple folding model towards those obtained by Goddard and Haeberli in optical-model fit to observed elastic cross-section and polarization data.

The deuteron-nucleus tensor polarizations have been an interesting as well as vexing source of information on the deuteron-nucleus optical potential. At incident energies below the Coulomb barrier the simple folding or Watanabe optical potential is able to give a good account of the data.[1] However, above the Coulomb barrier a simultaneous fit to the elastic cross section, the vector polarization, and the three tensor polarizations is difficult to achieve, particularly if $T_{21}$ is included.[2] Recently Goddard and Haeberli[3] were able to obtain much improved fits by adding to the spin-orbit part of the deuteron optical potential, which normally is real, a large and narrowly peaked imaginary part, all other potential components also being different from the Watanabe potential. In the Watanabe model, the deuteron is assumed to be in the ground state, and the nucleon-nucleus optical-model potentials are folded over the deuteron internal wave function. Thus, the deuteron internal degrees of freedom such as breakup and stripping channels are ignored.

It has been recognized for many years that deuteron breakup has a sizable influence on the deuteron-nucleus interaction,[4] but no good theoretical guidance was available up to now on how breakup is expected to modify the spin-dependent part of the deuteron-nucleus interaction. The main reason is that up to now only the spherically symmetric breakup states have been included in the calculations.[5-7] In these states the relative neutron-proton orbital angular momentum $\hbar l$ is predominantly zero. However, in recent studies[8,9] it was shown that spherically asymmetric breakup states (in which mainly $l=2$ is present) are also strongly excited and it was then suspected that the effect of these states on the tensor part of the deuteron-nucleus interaction should be large.

The purpose of the present Letter is to show that our calculation of breakup, which includes spin and which for the first time uses the realistic spin-dependent nucleon-nucleon potential of Reid[10] to construct the breakup states, indeed confirms that the tensor and spin-dependent parts of the deuteron-nucleus interaction are strongly affected by breakup, further that the asymmetric breakup states give a substantial contribution, particularly to the tensor part of the deuteron-nucleus interaction, and that our elastic scattering matrix elements turn out to be reasonably close to those based on the phenomenological optical potential.[3] Hence the possibility now arises that the breakup calculations are making contact with reality.

Apart from the added complication due to angular momentum algebra required to incorporate the spin-orbit components of the nucleon-nucleus optical potential and which will be described in future publications, the calculation proceeds along very similar lines as the previous spinless "$k$-by-$k$" method.[8] This method, also being used by Austern and co-workers,[7] differs from the adiabatic procedure of Johnson and Soper[5] in that the breakup energies are not neglected and the continuum breakup states may contain quantum numbers such as the neutron-proton relative angular momentum ($\vec{j}=\vec{l}+\vec{s}$) which are different from those of the bound deuteron state ($j=1$). The $n$-$p$ relative-motion states provide a basis set into which the bound and continuum parts of the incident deuteron wave function is expanded. These states are averaged into sets of momentum bins and the coefficients of each set which are functions of the displacement $\vec{R}$ of the center of mass of the neutron-proton system relative to the nucleus are obtained from the solution of a set of coupled equations which they obey. From these equations the correction to the elastic deuteron scattering matrix is obtained in the second-order distorted-wave Born approximation. The $j$ values of the $n$-$p$ system used are 1, 2, and 3; two momentum bins are included (one in which the $n$-$p$ relative energy $\epsilon_k$ varies from 0 to 10 MeV, and another from 10 to 40 MeV); and two eigen-

 

phase quantum numbers are present for the $j=1$ and 3 states for which the $l=j-1$ and $l=j+1$ components obey coupled equations. The sets for which the $l=2$ components have the largest amplitude are denoted as the "the quadrupole deformation states."

These are no free parameters in the calculations and the present formalism is applied to $d$-$^{64}$Ni collisions at 13 and 21.6 MeV incident deuteron energies. The nucleon-nucleus optical potentials required for obtaining the diagonal and coupling potentials are taken from the work of Bechetti and Greenlees[11] at nucleon energies half the deuteron energy. The deuteron-nucleus scattering elements $S_{L,L'}{}^{J}$ corrected for breakup are obtained numerically (to second order) and are discussed in what follows: For the second momentum bin the energy of the motion of the center of mass system of the $n$-$p$ pair relative to the nucleus is negative, both for the 13- and for the 21.6-MeV cases, and it is found that this bin produces only a small contribution to the $S_{L,L'}{}^{J}$'s.

Since the tensor part of the deuteron-nucleus interaction causes transitions between different values of $L$, its effects can be seen most unequivocally in the off-diagonal parts ($L \neq L'$) of the $S_{L,L'}{}^{J}$'s. Here $\vec{J}$ is the total angular momentum, $\vec{J}=\vec{L}+\vec{j}$, and $\vec{L}$ is the orbital angular momentum of the motion of the center of mass of the $n$-$p$ system relative to the nucleus. The numerical calculations show that breakup increases the absolute value of $S_{J-1,J+1}{}^{J}$ in the surface region of the $J$'s by about 40% and 70% for the incident deuteron energies of 21.6 and 13 MeV, respectively ($J$ from 7 to 11 and from 5 to 8, respectively). For the interior range of $J$'s breakup slightly decreases the $|S^J|$'s for 21.6 MeV and substantially enhances the values for 13 MeV. In the surface region, almost the complete contribution due to breakup comes from the quadrupole breakup states, thus showing the inadequacy of previous breakup calculations for the tensor interaction, which leave out such states.[6]

The tensor and spin-orbit deuteron-nucleus interactions also affect the diagonal parts of $S_{L,L}{}^{J}$ in that they give rise to a $J$ dependence of $S$. This $J$ dependence can be decomposed into the form

$$S_{L,L}{}^{J}=S_C(L)+\langle(SL)J|\vec{L}\cdot\vec{S}|(SL)J\rangle S_{LS}(L)+\langle(SL)J|T|(SL)J\rangle S_T(L). \quad (1)$$

Here $T$ is the usual tensor operator $(\vec{S}\cdot\hat{R})^2-\frac{2}{3}$ and the states $|(SL)J\rangle$ are the eigenstates of $S^2$, $L^2$, $J^2$, and $J_Z$. The $J$-independent coefficients $S_C$, $S_{LS}$, and $S_T$ provide a measure for the strength for the central, spin-orbit, and tensor parts of the deuteron-nucleus interaction, even if the spin-dependent forces are not weak. The results for $S_C$, $S_{LS}$, and $S_T$ for 13-MeV $d$-Ni scattering are shown in Fig. 1. The dashed lines connect the Watanabe results with breakup to those with breakup for a given value of $L$, and the solid (heavy) arrows connect the optical-model (OM) results, obtained[3] from best fits to $\sigma$, $iT_{11}$, $T_{20}$, $T_{21}$, $T_{22}$ with an imaginary $\vec{L}\cdot\vec{S}$ potential to those without it. The figure shows that the correction to the optical-model points, due to the addition of the imaginary part of the $\vec{L}\cdot\vec{S}$ potential plus a related readjustment of the central and tensor components of the potential, is present not

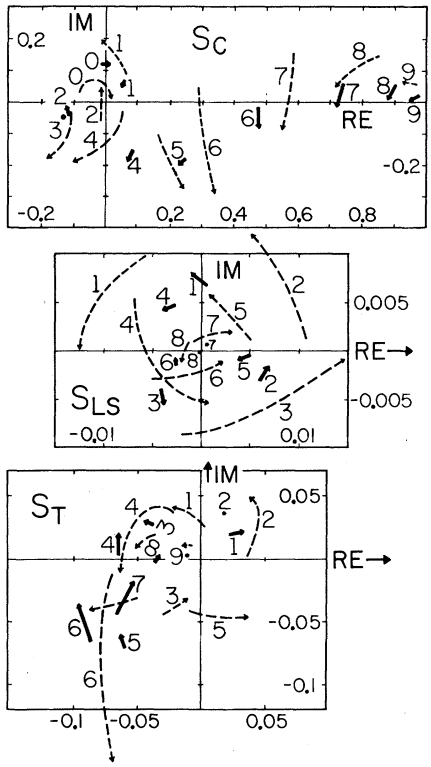


FIG. 1. Argand diagram of the central, spin-orbit, and tensor components, $S_C$, $S_{LS}$ and $S_T$, respectively, of the elastic $d$-$^{64}$Ni scattering matrix elements for a 13-MeV incident deuteron energy. Note the scale change from one panel to another. The solid lines are based on the optical model of Ref. 3, obtained without and with an imaginary spin-orbit potential (start of arrow and end of arrow, respectively) for the same value of the orbital angular momentum $L$, which is written next to the arrows. The dashed lines start at the Watanabe $d$-$^{64}$Ni potential without breakup and end at the result which includes breakup to second order in the breakup potential, for the same value of $L$.

only for $S_{LS}$ but for $S_C$ and $S_T$ as well. Furthermore, the correction on $S_C$ is of the same type as the correction due to breakup on the Watanabe points for the surface partial waves $4 < L < 8$. The $S_C$ points move towards the origin (i.e., absorption is enhanced) and also downward. In the interior of the nucleus the neutron-proton interaction should be much different from that on the surface due to effect of the Pauli exclusion principle,[12] not included here, and hence a good correspondence between the OM and (Watanabe +breakup) results should not be expected for the small values of $L$.

The lack of inclusion of Pauli effect may also explain why the Watanabe points of a given surface $L$ correspond to an optical-model point of one lower $L$, as is particularly clear for the surface partial waves for $S_C$ and $S_T$.[13] The reason is that the Pauli effect tends to reduce the central part of the Watanabe potential,[14] giving the nucleus the appearance of being smaller.

The breakup effects give rise to corrections to the Watanabe optical potential, which are complex and $L$ as well as energy dependent.[15] The $\vec{L}\cdot\vec{S}$ component of these so-called trivally equivalent potentials is found to have a real part which makes the corresponding Watanabe potential of shorter range in agreement with experiment, but the imaginary part is a factor of roughly 6 times smaller than the phenomenological one,[3] and of opposite sign. What is the explanation for this discrepancy? The imaginary part of the $(\vec{L}\cdot\vec{S})$ optical potential[3] is very peaked and narrow (its full width at half-maximum is 0.7 fm; the peak has a value of $-1.9$ MeV). Since $\delta$-function additions to a potential give $L$-dependent corrections to the scattering matrix elements,[16] it is very likely that the $\mathrm{Im}(\vec{L}\cdot\vec{S})$ potential[3] is trying to simulate a central $L$-dependent breakup or rearrangement effect, rather than to give rise to an $L$ dependence usually associated with a smooth, long-range $(\vec{L}\cdot\vec{S})$ potential. The $L$ dependence in the breakup calculation comes from the nonlocality of the Green's function in the breakup channel. By making suitable approximations to the Green's function,[17] it might be possible in the future to arrive at a physical prescription for a $L$-dependent correction to phenomenological potentials. Thus, breakup—insofar as it describes the distortion of the projectile during the collision—may serve as a guide for the introduction of $L$-dependent corrections applicable to a wide range of other situations, such as heavy-ion collisions,[18] or proton nucleus collisions.[19] In summary, it is shown here that breakup makes significant contributions to the spin-dependent part of the deuteron-nucleus interaction, of the order of (50–100)% of the breakup-independent results.

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[13]Careful inspection of the $S_T$ panel of the figure shows that breakup moves the Watanabe points W($L$) relative to the optical-model points OM($L$) as follows: W(9) remains nearly fixed; W(8) moves to a region in between

OM(8) and OM(7); W(7) moves towards OM(6); W(6) moves toward OM(5) but overshoots it, probably because of the excessively large second-order breakup correction for this particular $L$ value; W(5) moves in a wrong direction; W(4) moves towards OM(4) and OM(3) but overshoots both. Even if the location of the corrected W points is not in perfect correspondence with the OM points for the surface partial waves, the magnitudes of the $S_T$(W) scattering elements are remarkably close to the corresponding OM values.

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# Enhancement of the Excitation Function for the $0^+$, 6.049-MeV State of $^{16}O$ in the Reaction $^{12}C(^{16}O,^{12}C)^{16}O$

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Excitation functions for the $0^+$, 6.049-MeV and $3^-$, 6.130-MeV states were measured separately at $\theta_{c.m.} \sim 15.0°$, in steps of 86 keV from $E_{c.m.} = 22.7$–$33.0$ MeV. Enhancement of the cross section by a factor of 2–5 above the constant cross section is clearly observed at 23.60, 24.60, 28.40, and 32.20 MeV, for the lowest three of which the most probable total spins, $J^\pi$, are found to be $14^+$, $14^+$, and $15^-$, respectively. These resonance energies are quite different from those for the $3^-$, 6.130-MeV state observed at 25.2 and 29.8 MeV.

Recently, there has been a great deal of interest in alpha-particle exchange during heavy-ion reactions. In particular, it is predicted that alpha particles are easily formed in $p$- and $sd$-shell nuclei having rather low excitation eneries,[1] resulting in enhancement of the cross section for the production of such alpha-cluster states in alpha-transfer reactions. Another way to confirm the occurrence of alpha-particle exchange during such collisions is to search for intermediate resonances which selectively decay to good alpha-cluster states. Michaud and Vogt have proposed the alpha-particle doorway-state model for the $^{12}C + ^{12}C$ system.[2] However, no strong experimental evidence to support their model has been observed in the $^{12}C + ^{12}C$ system.[3]

For the $^{12}C + ^{16}O$ system, several intermediate resonances have also been found above the Coulomb barrier in various exit channels[4] and in fusion.[5] Precise measurements have mainly concentrated on the $E_{c.m.} = 19.7$ MeV resonance, for which the transition to the $3^-$, 6.130-MeV state dominates, thus explaining the failure to identify any alpha-particle doorway state in $^{28}Si$.[6] Recently, the $^{12}C + ^{16}O$ inelastic scattering excitation functions were measured by Malmin and Paul over a wider energy range between 14 and 23 MeV (c.m.).[7] Striking features are found for inelastic scattering to the $0^+$ and $3^-$ states in $^{16}O$ for which resonance doublets appear to occur both at 20 and 22.5 MeV with widths of ~ 300 keV. In their measurement,[7] the lack of separation of the decay to the $0^+$, 6.049-MeV state from that to the $3^-$, 6.130-MeV state prevents confirmation of the alpha-particle doorway states in the $^{12}C + ^{16}O$ system.

In the present work, the excitation functions for the alpha-transfer reaction, $^{12}C(^{16}O,^{12}C)^{16}O^*$, were investigated at the forward angle, first, by separately measuring the $^{12}C$ ions to the $0^+$, 6.049-MeV and the $3^-$, 6.130-MeV states. Four other transitions to the ($2^+$, 6.919-MeV), ($1^-$, 7.117-MeV), ($4^+$, 10.353-MeV), and ($4^+$, 11.095-MeV) states of $^{16}O$ were measured at the same

 