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SPIN DEPENDENCE OF THE DEUTERON-NUCLEUS INTERACTION AS AFFECTED BY BREAKUP[+,*]

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Abstract

The effect of breakup on the elastic deuteron-nucleus scattering elements $S^J_{L,L'}$ is calculated numerically for deuterons incident on ^{64}Ni for the energies of 13, 21.6 and 45 MeV. The S's are decomposed into central, spin orbit and tensor components. All three are affected strongly by breakup, and so are the various polarization angular distributions.

The calculation proceeds in second order distorted wave Born approximation and includes breakup energies up to 40 MeV divided into two bins. Three values of the neutron-proton relative angular momenta $j = 1$, 2 and 3 are included. The n-p potential is that of Reid, and the nucleon-nucleus optical potential is that of Becchetti and Greenlees.

Comparison with experiment at 45 MeV for $d\sigma/d\Omega$ and $i\,T_{11}$ is presented.

1. The Physical Background

It is easy to see that the deuteron should "stretch" as it passes by the

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vicinity of the nucleus. The stretching is due to the fact that the attraction which the nucleus exerts on one of the nucleons is different from that on the other nucleon if the two nucleons are not at the same distance from the nucleus. Since the deuteron is a "large" object, such attraction differentials are quite likely, and stretching takes place with a probability which depends on whether the nucleons in the deuteron have or not the time to adjust their orbits during the collision process. It is also quite plausible from the geometry of the collision that the stretching should be into an oblong shape rather than into a spherically symmetric "breathing" deformation.

The usual way to describe stretching is to expand the deuteron internal wave function into a complete set of states, and then solve equations for the coefficients of the expansion. In our case we choose the wave functions to be eigenstates of the neutron-proton hamiltonian H_{np}. Since the deuteron has only one bound state, stretching implies that breakup states with positive continuous n-p relative energies are involved in the expansion, and spherically asymmetric stretching implies that n-p relative orbital angular momenta ℓ different from zero also occur. Such angular momenta are already present as a result of the n-p tensor interaction, but in our case their presence is mainly due to the fact that the sum of the neutron-nucleus plus proton nucleus optical potentials, V_N, when expressed in the coordinates $\vec{R} = (\vec{r}_n + \vec{r}_p)/2$ and $\vec{r} = \vec{r}_n - \vec{r}_p$, is a function of the direction of $\vec{r}$,

$$V_N(\vec{r},\vec{R}) = V_{n-A}(r_n) + V_{p-A}(r_p) \quad . \tag{1}$$

The $\vec{r}$ dependence of V_N for fixed $\vec{R}$ then causes transitions between bound and continuum states of the n-p system, $\varphi_b(r)$ and $\varphi_k(r)$, respectively as well as transitions between $\varphi_{k'}$ and φ_k. The R dependent matrix elements

$$\int \varphi_k(\vec{r})\, V_N(\vec{r},\vec{R})\, \varphi_b(\vec{r})\, d^3r = V_{kb}(R) \qquad (2)$$

then serve as coupling potentials for the system of equations which describe the breakup probability amplitude $F(k,\vec{R})$ in each momentum bin of size Δk.

After averaging of the various coupling and distorting potentials is carried out, the coupled equations in the F's are not much different from conventional coupled equations in which the deuteron breakup states are replaced by discrete "excited" states of certain energies and internal angular momentum values $\vec{j}$.

Various theoretical calculations along these lines have been carried out in the past. That of Johnson and Soper[1] stands out because it is very successful in including the effect of breakup on stripping or pick up cross sections. Keaton et al.[2] we[3] and also Norman Austern[4,5], among others, have spent a good deal of effort on this problem. The main difficulty is in how to do a realistic three body calculation and yet not to stray too far from DWBA procedures which are numerically well understood and not as complicated as the Faddeev based methods. The continuum nature of the excitations leads to complications having to do with the averaging procedure, particularly at large values of R. The difference between Austern's group and ours is the care with which the averaging of these wave functions is performed, and also how realistically the nucleon-nucleus input potentials are chosen. We are very simplistic in our averaging method, we use large bin sizes and we do not yet couple one continuum bin to the other. But we use experimental Woods Saxon shaped nucleon-nucleus optical potentials, we allow neutron-proton relative angular momentum values $\hbar\ell$ of 0, 2h and 4h, and lately in the calculations with spin we use Reid's realistic nucleon-nucleon potentials with tensor inter-

action. As already mentioned, the Pittsburgh group uses more and smaller momentum bins, a careful asymptotic averaging procedure, but unrealistic gaussian nucleon optical potentials and $\ell = 0$ only. They have as their main goal the purpose of examining the viability of the method. They did demonstrate the adequacy of the method, and they also showed that the coupling between bins is important since the continuum to continuum coupling matrix elements are very large. Our two calculations complement each other but none is yet good enough to be compared with experiment. As will be said later on, apart from computational inadequacies probably the major defect is the lack of allowance for the Pauli exclusion effects.

Sometime in the future it would be desirable to do a model three body calculation using exact Faddeev methods, or other methods[6], and compare the results with a careful calculation of the type we do. All the calculations mentioned up to now do not include the spins of the nucleons, and ours was the only one which included the $\ell \neq 0$ excitations. When we found that the latter are excited as strongly as the $\ell = 0$ states, we realized that breakup should play an important role in the tensor part of the deuteron nucleus interaction. Since at the time the experimental tensor polarizations were very hard to fit by the phenomenological optical models, we were motivated to include spins into our calculation so as to be able to make predictions about the tensor interaction and the resulting tensor polarizations. As we shall see the tensor interaction is indeed strongly affected by deuteron breakup, but we are not as yet able to fit the data.

2. Inclusion of Spin

In order to understand the effect of spin, it is convenient to review the

spinless case first. There the internal spin angular momenta $\hbar j$ of the "excited" deuteron states are equal to the relative n-p orbital angular momentum $\hbar \ell$, and the total angular momentum $\hbar J$ of the (n-p) system relative to the nucleus is equal to the orbital angular momentum $\hbar L_D$ brought in by the deuteron. In the excited states the "deuteron" can have various orbital angular momenta L_i ranging from $J + j$ to $|J - j|$ (from $L_D + \ell$ to $|L_D - \ell|$ in the spinless case) and they get coupled to the incident L_D by the various multipole components λ of the transition matrix element (2) described above. Thus if for example $\ell = 2$ and $\lambda = 2$ then L_i can differ from L_D by two units. However the excited channels all couple back to the same L_D in the elastic channel since J cannot be changed by the interaction. No tensor potentials are thus produced.

Not so in the case with spin. There for a given J, because the spin of the deuteron is unity, the elastic channel has three values of L_D and each can be coupled by a $\lambda \neq 0$ transition potential to a L_i in the excited state which is different from L_D and then return to a L_D' in the elastic channel which now need <u>not</u> be equal to L_D. For example, if $J = 10$ and $L_D = 9$, L_i can be 9 or 11 (not 8 for parity reasons if the neutron-nucleus and proton-nucleus optical potentials are assumed to be equal) and the return step from $L_i = 9$ can proceed to the elastic values of L_D of 9 or 11. The excitation of the $L_D' = 11$ wave, even though initially only $L_D = 9$ was assumed present, is equivalent to the effect of a deuteron nucleus tensor interaction, i.e., the off diagonal elements $S^J_{L,L'}$ of the elastic scattering matrix are indicative of tensor forces. The diagonal components of the scattering matrix elements can also be affected by breakup, and these corrections can be due to the combined effect of added central, spin orbit or tensor potentials. The extent to which each contributes can be found out from the J dependence of the diagonal scattering

matrix element. For example a $\vec{L}\cdot\vec{S}$ interaction leads to a characteristic J dependence, while the central interaction has no J dependence. Thus the $L_D = 9$ wave is present in the J = 8, 9, and 10 angular momentum cases, and the effect of breakup for each J may be different, in part because the Green's functions are J dependent, in part because different intermediate states can be reached according to the value of J. Formally the separation of S^J_{LL} into central spin orbit and tensor parts $S_C(L)$, $S_{LS}(L)$ and $S_T(L)$ respectively can be accomplished by writing

$$S^J_{LL} = S_C(L) + \langle (SL)J | (\vec{L}\cdot\vec{S}) | (SL)J \rangle S_{L\cdot S}(L) + \langle (SL)J | T | (SL)J \rangle S_T(L) \qquad (3)$$

This equation can be solved for S_C, $S_{L\cdot S}$, and S_T in terms of S^J_{LL} by using the orthogonality of the 3j symbols implicit in the matrix elements of the operator $\vec{L}\vec{S}$ and T in Eq. (2).

3. Numerical Results

In order to obtain an idea of the size of the breakup correction on the central, spin orbit and tensor parts of the deuteron nucleus interaction we did a numerical calculation of deuterons incident on the nucleus of Nickel at the energies of 13, 21.6 and 45 MeV[7]. The effect of breakup on the elastic scattering matrix elements $S^J_{L_D L_D''}$ is calculated in second order distorted wave Born approximation[7] with two breakup momentum bins present (bin 1 and 2) and three values of n-p relative angular momentum states j = 1, 2 and 3. The breakup energies in the two momentum bins range from 0 - 10 MeV and 10 MeV - 40 MeV, respectively. The values of ℓ involved for the three j values are ℓ = 0 and 2 for j = 1; 2 for j = 2; and 2 and 4 for j = 4. The n-p breakup states for which the ℓ = 2 component has the largest amplitude

are collected into set 1, also denoted as the "quadrupole" set, while the others are collected into set 2. The nucleon-nucleus optical potential parameters are taken from Greenlees and Bechetti[8] and the n-p relative wave functions are calculated[9] by means of Reid soft core potentials one for each j = 1, 2, and 3. The breakup matrix elements (2) involve a great deal of angular momentum algebra, as is described in Ref. 9.

The results for the off diagonal values of S^J are shown in Fig. 1. Only the absolute values are shown. The points labeled "Watanabe" indi-

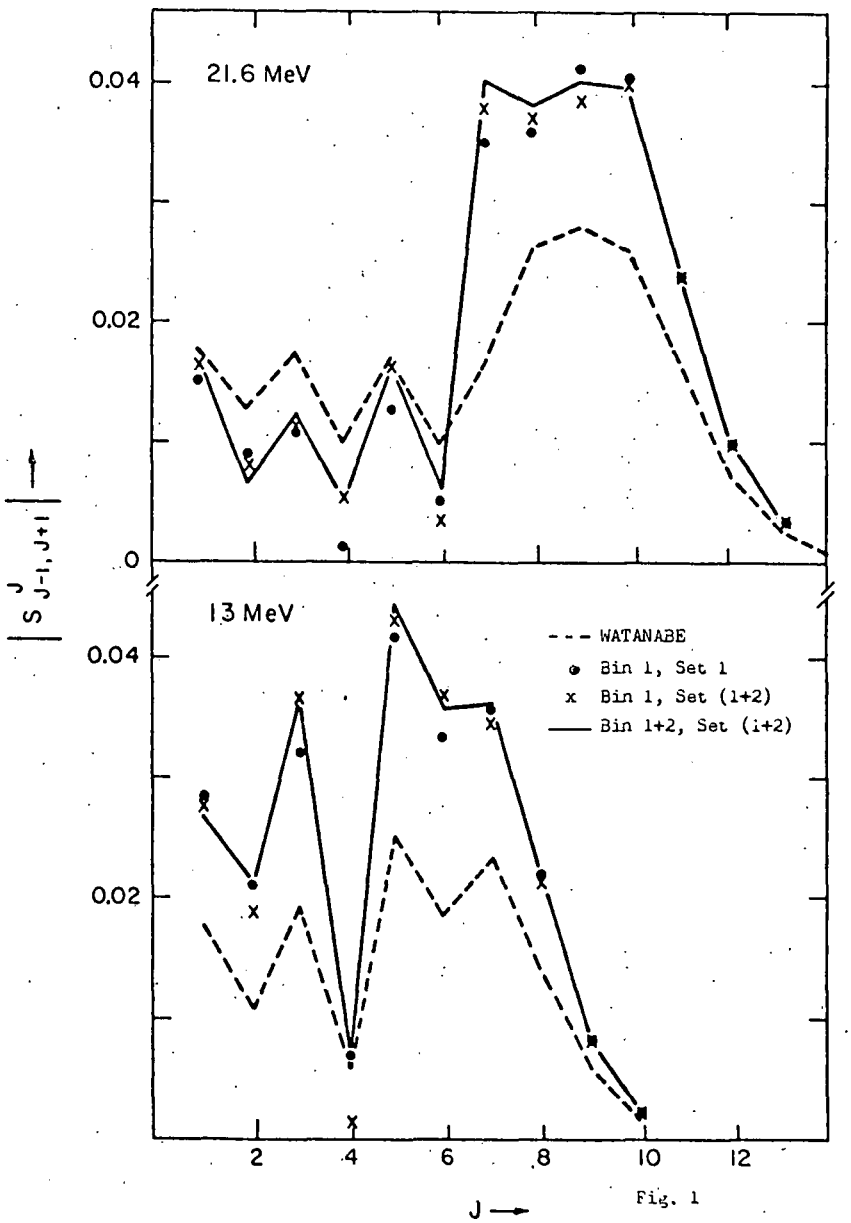

Fig. 1

cate the result in the absence of breakup. The word is quite suitable because the deuteron optical potentials are the "static" folding potentials first suggested by Watanabe[10]. One sees that breakup approximately doubles the magnitude of the off diagonal matrix elements in the surface region and also that set 1 has a larger effect than set 2. Which of the values of L belong to the surface region can be seen from the graph of the absolute value of the diagonal scattering matrix elements, usually denoted as reflection coefficients. These are shown in Figs. 2 and 3. One notices that breakup decreases

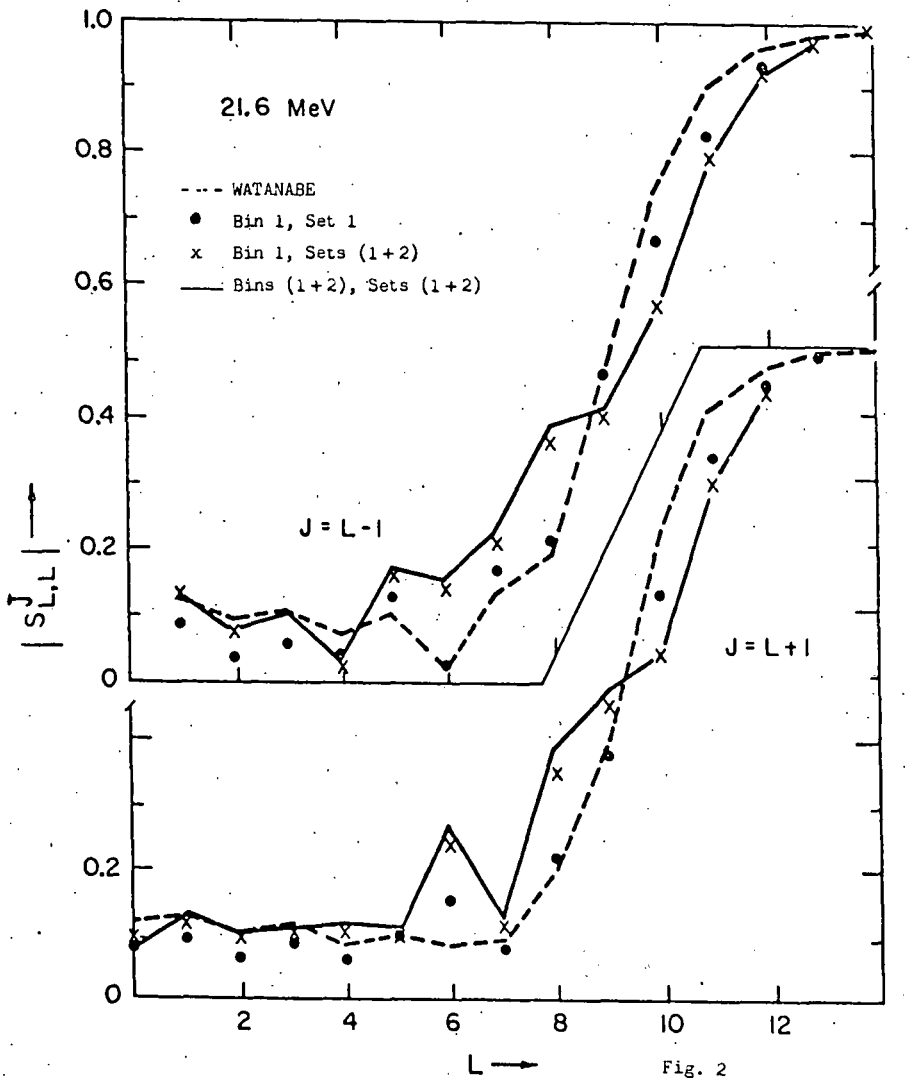

Fig. 2

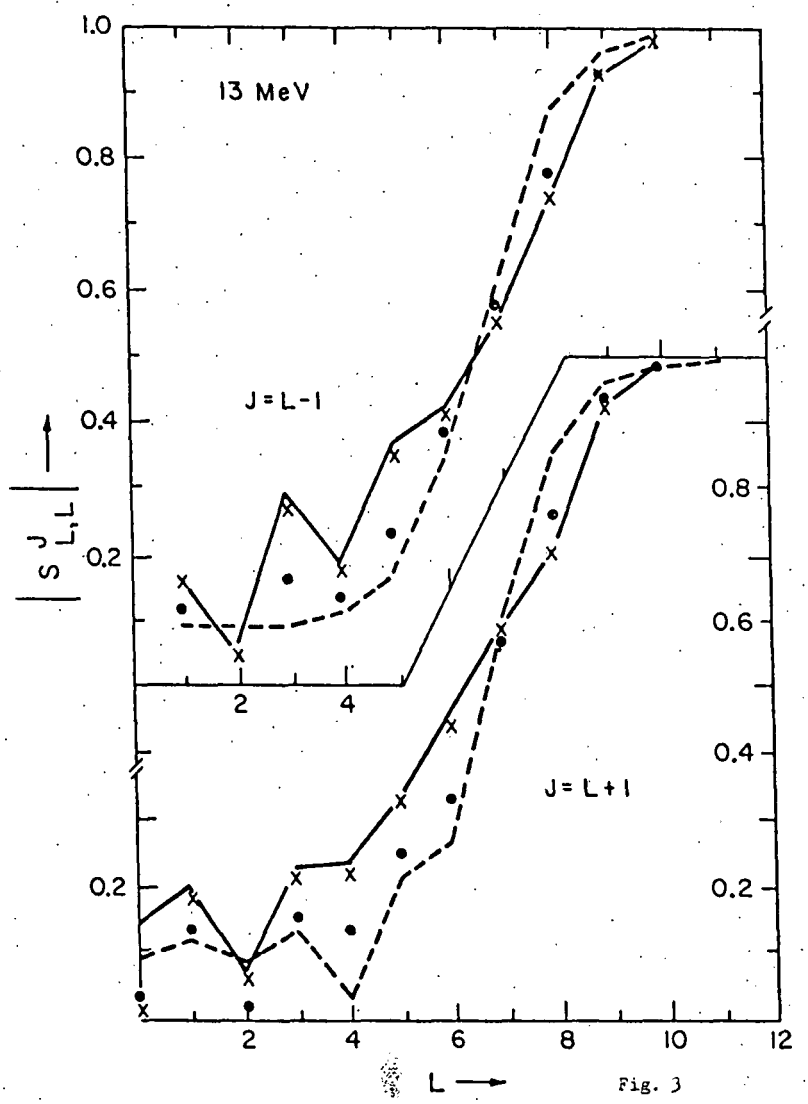

Fig. 3

the reflection coefficients for the large L values, i.e., absorption is enhanced. This is quite reasonable since breakup provides additional absorption channels and its effect should extend to large distances. However it may be surprising that absorption is decreased at small distances. This may be understood as the propagation of the broken up deuteron through the nucleus and subsequent recombination into the elastic channel at the surface. Indeed, as the Pittsburgh group has pointed out[5], breakup plays a large role in the nuclear interior. (This conclusion was arrived at by comparing two calculations with different imaginary optical potentials in the elastic channel). These results and also the discussion made below show that it is important to understand the propagation of a correlated neutron proton system through nuclear matter, in particular the effect which the presence of the other nucleons have on such a propagation.

The effects of breakup on the central, spin orbit and tensor parts of the diagonal S matrix elements are shown in Fig. 4 for the 13 MeV case, in

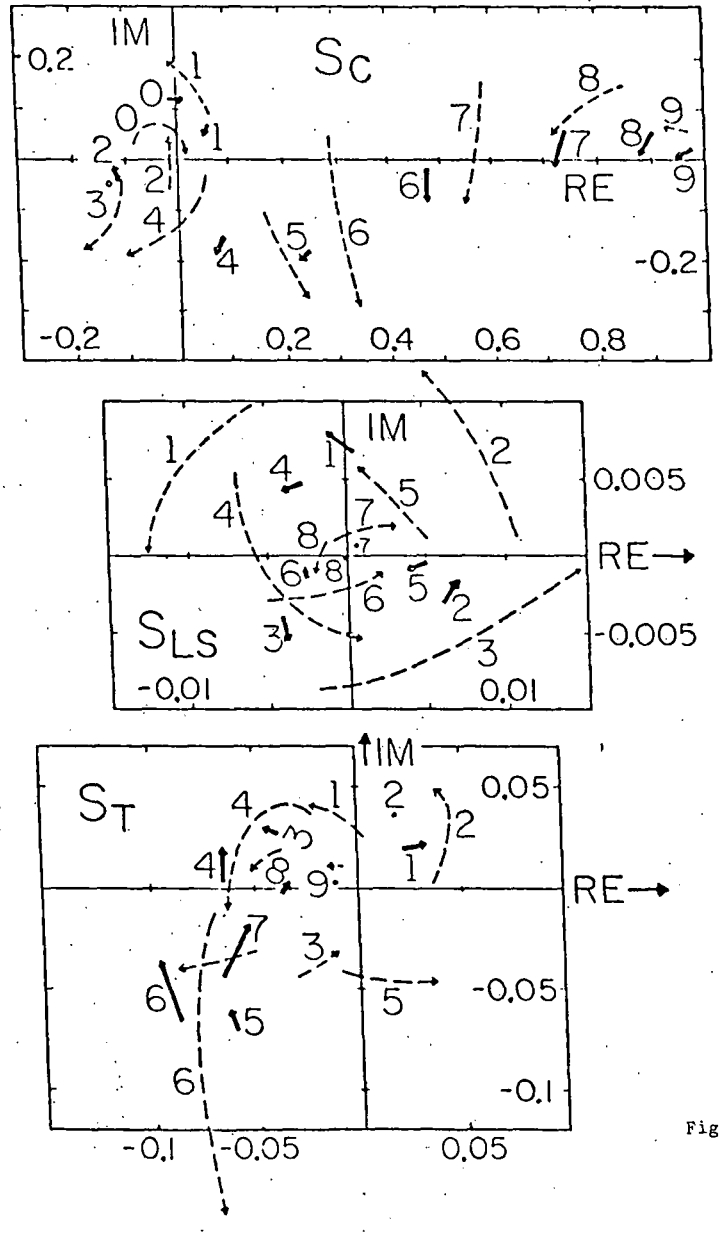
IM
0.2
S_C
RE
-0.2
-0.2
0.2
0.4
0.6
0.8
IM
0.005
RE
-0.005
S_{LS}
-0.01
0.01
IM
0.05
S_T
RE
-0.05
-0.1
-0.1
-0.05
0.05

Fig. 4

the form of Argand diagrams[7]. The tip of the dashed arrows represent the values of S corrected for breakup, and the tail of the arrow is located at the uncorrected, i.e., Watanabe results. The numbers next to the arrows represent the values of L. For comparison optical model values are also shown by the solid arrows. The optical model parameters are the ones obtained by Goddard and Haeberli[11] in a successful fit to the 5 quantities $d\sigma/d\Omega$, T_{11}, T_{20}, T_{21}, T_{22} for 15 MeV deuterons scattering on Ni 64. They[11] give two sets of parameters, one in which the deuteron-nucleus L·S potential is purely real, the other in which a imaginary part is added. The former gives rise to points located at the start of the solid arrow, the latter to the tip of the arrow. Looking again at the S_C portion of Fig. 4, the comparison between the theoretical and phenomenological values of S_C is gratifying for the surface region of L in particular if one considers that there are no free parameters in the theoretical calculation. One sees that breakup moves the Watanabe values into the optical model region, and for some L's, notably L=6 the correction overshoots that region. The large size of the L=6 dashed arrow shows that the iteration of the effect of coupling is not converging for this L, i.e., the second order DWBA correction is very likely still quite different from the result given by a rigorous solution of the coupled equations. Another feature of interest is the displacement in L value between the theoretical and the phenomenological points. The theoretical point for a given L is comparable with a optical model point of a smaller L value, which indicates that the theoretical nucleus appears to have a larger radial size than the phenomenological one. This is borne out by comparing the central parts of the Watanabe and of the phenomenological optical potentials[11]. The former is more diffuse and deeper than the latter, but between 3 and 5 fm the latter is deeper. The above comment suggests that inclusion of antisymmetrization

effects is very likely needed here, since these effects reduce the size of the deuteron-nucleus potential. The comparison shown in Fig. 4 between the optical model and the theoretical values of the LS and T components of the elastic scattering elements is not as satisfying as the comparison between the central parts. Nevertheless, the magnitudes of the respective values are approximately of the same order, and one sees that breakup has a large effect on both $S_{L\cdot S}$ and S_T.

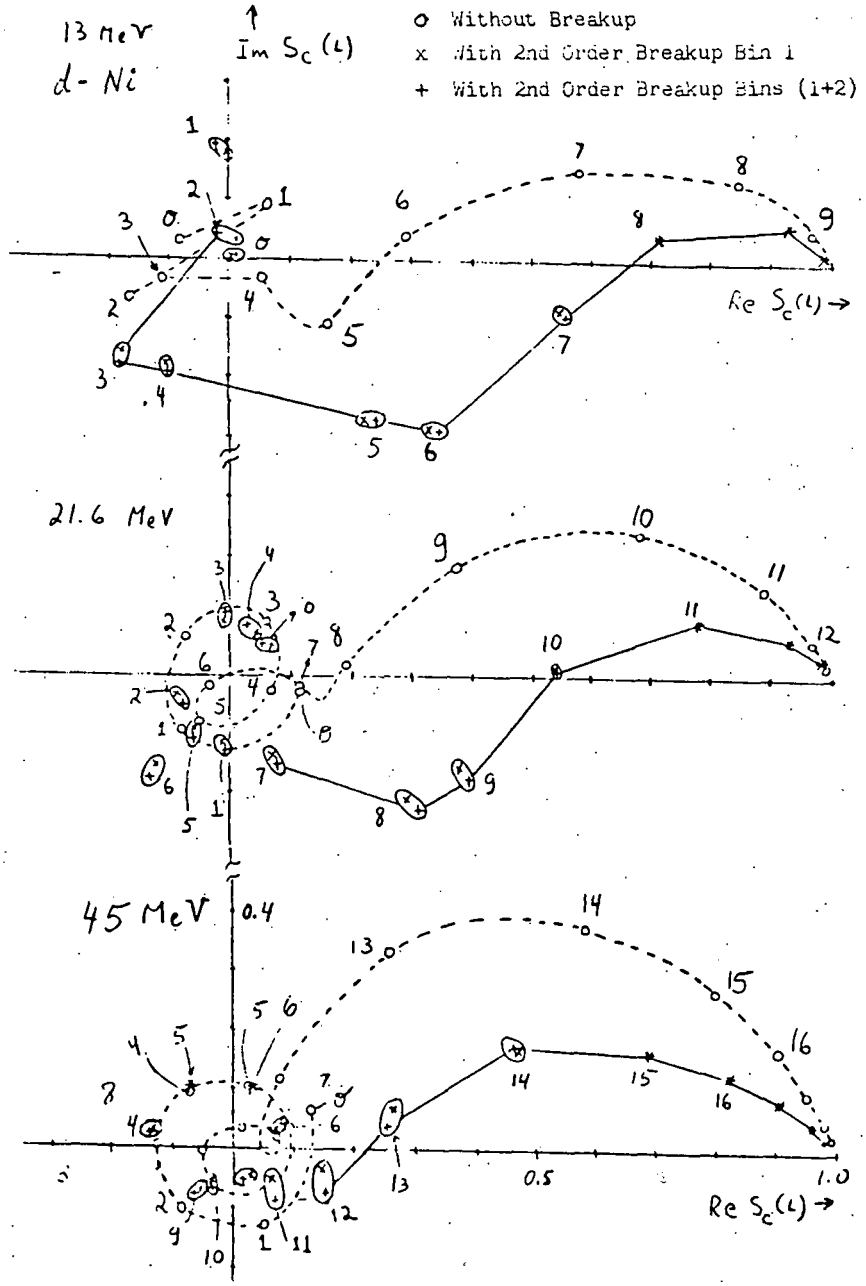

Fig. 5

In Fig. 5 the values of $S_C(L)$ are shown by means of Argand diagrams for the three incident deuteron energies. The figure shows that the corrections to the Watanabe scattering matrix elements (open circles) due to our second order breakup calculation is about as large for the 13 MeV case as it is for the 21.6 and the 45 MeV cases. The corrected values of $S^J_{LL'}$ however vary more smoothly with L the larger the energy. Also the effect of the second momentum bin is very much smaller than that of the first bin, at most 10 to 20% for the interior partial waves. The relative importance of the first and second breakup bins may be related to the large difference between the Q values for the two bins. The larger the average Q value of the bin the larger is the difference between the wave number of the motion of the c. of m. of the n-p pair in this bin compared to the wave number in the elastic channel and hence the smaller is the coupling interaction between these two channels. For the second momentum bin the Q value is taken to be approximately 28 MeV, while in the first bin it is about 7 MeV. The kinetic energy of the c.m. of the broken up pair in the second momentum bin is negative for E_D = 13 and 21.6 MeV, and it is positive for E_D = 45 MeV.

We have also calculated the angular distributions for $d\sigma/d\Omega$, iT_{11}, T_{20}, T_{21} and T_{22}. The comparison with experiment at the two lower energies is not very good, but improves at the higher energies. The reason is, at least in part, to be attributed to the large effect which breakup makes on the scattering elements, and hence our second order treatment is likely to be inadequate. A complete solution of the coupled equations is required before comparison with experiment is justified. The angular distribution for $d\sigma/d\Omega$ (divided by the Rutherford cross section) and iT_{11} is shown in Figs. 6 and 7.

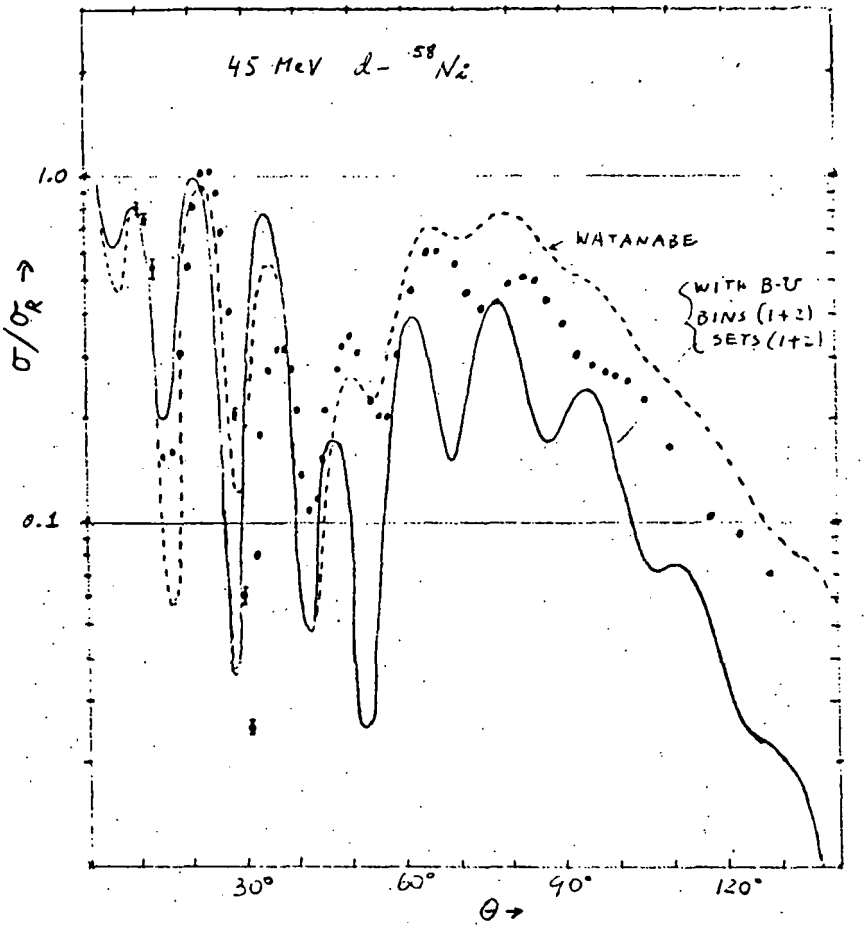
45 MeV d- ^{58}Ni
1.0
0.1
σ/σ_R →
WATANABE
WITH B-U
BINS (1+2)
SETS (1+2)
30°
60°
90°
120°
θ →

Fig. 6

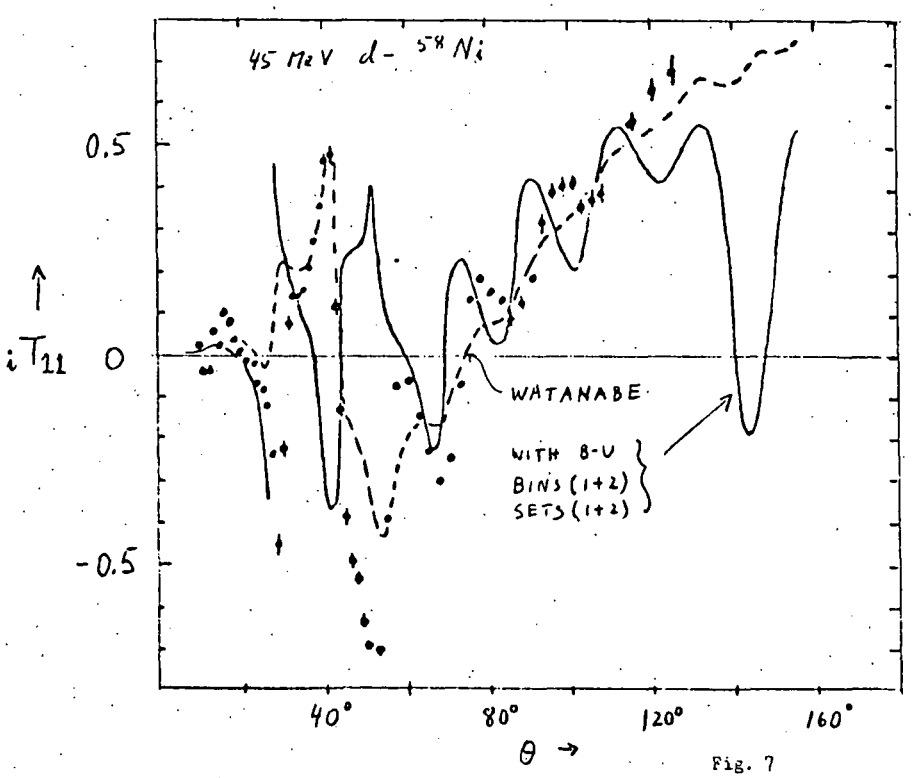
45 MeV d- ^{58}Ni
0.5
↑
iT_{11} 0
-0.5
WATANABE
WITH B-U
BINS (1+2)
SETS (1+2)
40°
80°
120°
160°
θ →

Fig. 7

The data are for 45 MeV deuterons incident on ^{58}Ni, obtained by Stephenson et al[12].

The figures illustrate that the breakup modifies the curves so as to reduce the disagreement with experiment compared with the Watanabe curves. However, the final theoretical angular distributions are shifted forewards relative to experiment, again indicating that the theoretical nucleus is too large in size. A Argand plot of the scattering matrix elements for the optical model calculation based on parameters given by Stephenson et al[12], when compared with the Argand plot of the theoretical values of $S_C(L)$, again shows that the theoretical S's are displaced up in L relative to the phenomenological S's. The displacement is by about one unit of L; for example, $S_C(L=13)$ corresponds to $S_{OPT.MOD}$ $(L=14)$.

4. Summary and Conclusions

First of all, our calculations support the conclusions already reached previously that breakup gives a large effect to the folding or Watanabe model of the deuteron nucleus interaction. The corrections are large not only for the central parts of the deuteron nucleus interaction, but we show that the $L\cdot S$ and tensor parts are also strongly affected, particularly the latter. The spherically asymmetric breakup states play a large role here. It is thus possible that effects involving spin will be very useful in identifying the role of breakup on the deuteron nucleus interaction. They might even enable one to distinguish between the various processes which affect the deuteron nucleus interaction, such as inelastic nuclear excitation, rearrangement processes and breakup. This is pure speculation at this point, but each of these effects has an energy and angular momentum dependence which may be peculiar to its physical nature.

The present calculations are still quite primitive and a good deal of additional effort appears needed. Apart from the obvious need of using more finely divided bins and of rigorously including the coupling between bins, probably the two most important effects required to be included simultaneously are 1. antisymmetrization with the nucleons in the nucleus, 2. energy dependence of the nucleon-nucleus interaction.

The need for antisymmetrization is shown by the fact that for the small values of L the absorption coefficients are not less than about 0.1. This means that the propagation of the deuteron through the nuclear interior, where antisymmetrization is important gives substantial contributions to the elastic deuteron nucleus interaction. Furthermore, the Pauli exclusion principle also gives rise to breakup[13] and to additional tensor interactions[13]. It is thus possible that one may learn a good deal about the corrolations of nucleons in the nuclear interior from the study of deuteron-nucleus interactions[14].

The energy dependence of the nucleon-nucleus interaction comes into play in several places. For situations in which one of the nucleons has negative energies one obtains the stripping portion of the wave function of the A+2 system, left out from the present type of breakup calculation. For these energies the imaginary part of the optical potential becomes zero. As this conference for example shows, such effects are very important for the reaction mechanisms.

Another case in point occurs for the high momentum bins for large incident deuteron energies. The energy of each nucleon relative to the nucleus will then vary over a large range depending on the direction of internal motion of the broken up pair relative to the motion of its center of mass, and the nucleon optical potential should vary accordingly.

In conclusion, the deuteron nucleus interaction involves essentially the propagation of a correlated nucleon pair through a region of nuclear matter, and may, in the long run, provide a rich source of information about the corrolations of the nucleons in the nucleus.

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