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Dynamic polarization potential due to pickup coupling for proton scattering from ^{6}He

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We present dynamic polarization potentials (DPPs) arising from neutron pickup coupled reaction channels, contributing to the proton-nucleus interaction for 71 MeV/nucleon protons scattering from ^{6}He. The DPPs do not represent a uniform renormalization of the potential and result in a change in the rms radius of the real part. The inclusion of breakup of the deuteron somewhat reduces the repulsive effect of the coupling and enhances the absorption. The linearity of the coupling effect suggests a method of incorporating it into a computationally feasible phenomenological scheme.

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I. INTRODUCTION

Recently it has become possible to measure, in inverse kinematics, the analyzing power (AP) of protons scattered elastically from the unstable nucleus ^{6}He. The elastic scattering data for 71 MeV/nucleon protons cannot be fitted by global phenomenology or current theory [1]. One process not included in the theory is the coupling to deuteron pickup channels. It is now well established that such coupling makes a significant contribution to the nucleon optical potential, see, for example, Refs. [2,3] and work cited therein. It is natural to ask whether such coupling improves the fit to the analyzing power in the case cited, and this was the initial motivation for the present work in which such coupling is included through coupled reaction channel (CRC) calculations. These are implemented here using the code FRESCO [4].

The elastic channel S-matrix elements that are output by FRESCO make it possible to determine the local and l-independent representation of the dynamic polarization potential (DPP) generated by whatever channels are coupled to the elastic channel. The "coupled-channels plus inversion" procedure for determining the DPP due to specific processes is fully described and compared with other methods in Ref. [3]. In brief, the elastic scattering S matrix from the CRC calculations is subjected to $S_{lj} \rightarrow V(r) + \mathbf{l}\cdot\mathbf{s}\, V_{\rm SO}(r)$ inversion, and the difference between this inverted $V(r) + \mathbf{l}\cdot\mathbf{s}\, V_{\rm SO}(r)$ and the bare potential (defined below) is identified as the DPP. It is the result of such DPP determinations that is the main focus here, going beyond the original motivation. In this way, we are led to new generic features of DPPs including a significant amendment to previous work [3].

We report here, for 71 MeV/nucleon protons, the DPPs generated by the coupling of the pickup channels leading to the $3/2^-$ and $1/2^-$ resonance states of ^{5}He. The Q value of the $3/2^-$ resonance is reasonably well defined, but the $1/2^-$ level is very broad, and we did some test cases to examine the sensitivity of our results to the energy of this level, as we shall discuss below. DPPs are presented for the three cases: pickup to the $3/2^-$ state alone, to the $1/2^-$ state alone, and to both states. When both pickup channels are coupled to the elastic channel (the "full" calculation), we do not consider any coupling between them. In the absence of such mutual coupling, the sum of the formal DPPs, that correspond to coupling to the $3/2^-$ and $1/2^-$ channels alone, is just the DPP arising from coupling when both states are included. The extent to which this additivity fails for the local DPPs determined by inversion, provides a measure of the nonlocality of the underlying nonlocal DPP. This is discussed in Ref. [3]. In that reference it was shown that breakup of the outgoing deuteron can strongly modify the effect on the elastic scattering, and we have extended the pickup calculations to include that process. Our final results include the effect of deuteron breakup using the continuum discretized coupled channel (CDCC) procedure. As in Ref. [3] we refer to CRC and CDCC calculations simply as CC (coupled channel) calculations.

II. DETAILS OF THE CC CALCULATIONS

A key ingredient in these calculations is the interaction potential in the proton-^{6}He entrance channel, the "bare potential." We did not attempt a detailed fit to the elastic scattering data by the full CC calculations, since single-shot pickup calculations with fully converged breakup contributions are at the limit of our computing resources. Instead, we adopted the Koning and Delaroche (KD) [6] global potential, although it is outside its stated range of applicability. We acknowledge that the KD potential, like all potentials fitted to empirical data, implicitly includes the pickup processes under study. We are thus exploiting the approximately linear response of the DPP to the addition of such channels; previous experience [3] suggests that the DPPs that will emerge are not very sensitive to changes in the bare potential that are of the order of the DPPs themselves. At the end of this paper, we describe a calculation that reflects directly on this linearity. We note that the KD interaction contains an imaginary spin-orbit term with

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a negative sign, and our results will have a bearing on why the global potential might have this property.

The interaction potentials in the outgoing deuteron channels were of Watanabe single-folding type, employing the central parts of the KD potential for the necessary n and $p + {}^5$He optical potentials. The deuteron wave function, with the D state included, was calculated using the Reid soft-core interaction [7] as the neutron-proton binding potential. Full finite range transfer couplings were implemented and nonorthogonality corrections were included.

Prior to the full calculations, including breakup of the exit channel deuterons, we carried out test calculations of pickup coupling effects without deuteron breakup (i) both with and without a spin-orbit term in the bare potential, and (ii) both with and without the reorientation that is possible as a result of the inclusion of the D state of the exit channel deuteron. The results will throw light on the extent to which the contribution of coupling to the spin-orbit term is independent of the bare spin-orbit potential, and also provide evidence for the general consistency of the CC-plus-inversion procedure. The subsequent calculations, that do include deuteron breakup, lead us to reexamine the conclusions in Ref. [3], concerning proton-^{8}He scattering.

To quantify the DPPs, we calculate the difference, ΔJ in the volume integrals (defined as in [5]) of the specific components (real central, ..., imaginary spin-orbit): $\Delta J = J_{\rm inverted} - J_{\rm bare}$, where $J_{\rm inverted}$ represents the volume integral of various specific components of a potential found by the inversion of the elastic channel S matrix from the CC calculation. The local, l-independent DPPs are never proportional, as a function of r, to the bare potentials, exhibiting some degree of "waviness" which can be associated with the l dependence and nonlocality of the underlying DPP. Thus, the DPPs are nonuniform in the sense that the inverted potentials cannot be represented as a renormalization of the bare potential and we quantify this in some cases with the change, $\Delta R_{\rm rms}$, in the rms radius of the real central component. The volume integrals J that we present are stable against the influence of any further, spurious, waviness of the kind that can occur when extremely precise fits to S_{lj} for all active l and j are found by inversion.

III. RESULTS OF INVERSIONS

We first studied the contribution of pickup coupling without breakup in the exit channels. Table I presents ΔJ values for DPPs generated by coupling to deuteron channels for three combinations of ^{5}He final states: the $1/2^-$ state, the $3/2^-$ (ground) state and both these states. The last column presents the numerical sum of the DPPs for the first two cases. The scale of these ΔJ values may be compared with the volume integrals of the KD bare potential: for the four components, real and imaginary central, real and imaginary spin-orbit, these were, respectively: 415.80 MeV fm^3, 195.41 MeV fm^3, 27.76 MeV fm^3, and -3.92 MeV fm^3. It will be seen that the combined effect of the two coupled states is repulsive and absorptive: J for the real part is reduced by 12.5% and the imaginary part is increased by about 15%. The real spin-orbit interaction is increased in each case by about 11% of the KD value. The KD imaginary spin-orbit potential has a negative

TABLE I. For 71 MeV/nucleon, characteristics of the DPPs generated by coupling to pickup channels for the four cases: the $1/2^-$ state alone, the $3/2^-$ state alone, both $1/2^-$ and $3/2^-$ states coupled, and, for comparison, Σ, the sum of the separate $1/2^-$ and $3/2^-$ DPPs. All ΔJs have units MeV fm^3.

Component	$1/2^-$ state	$3/2^-$ state	Both states	Σ $1/2^-, 3/2^-$
ΔJs for no bare SO potentials and no reorientation				
Real central	−16.47	−34.35	−51.0	−50.82
Imaginary central	9.85	16.93	30.4	26.78
Real SO	1.25	1.039	2.403	2.289
Imaginary SO	−0.94	0.320	−0.924	−0.62
ΔJs for no bare SO potentials but reorientation included				
Real central	−16.48	−34.34	−51.00	−50.82
Imaginary central	9.82	16.95	30.44	26.77
Real SO	1.25	1.06	2.42	2.31
Imaginary SO	−0.98	0.34	−0.96	−0.64
ΔJs with SO in bare potential and no reorientation included				
Real central	−16.80	−34.52	−51.71	−51.32
Imaginary central	9.57	16.71	29.96	26.28
Real SO	1.43	1.30	2.96	2.73
Imaginary SO	−0.79	0.51	−0.63	−0.28
ΔJs with SO in bare potential and reorientation included				
Real central	−16.54	−34.10	−50.92	−50.64
Imaginary central	9.60	16.90	30.20	26.50
Real SO	1.50	1.33	3.09	2.83
Imaginary SO	−0.86	0.54	−0.72	−0.32

volume integral, and the corresponding DPP component is negative in each case, having a magnitude about 20% of that for the KD potential, not greatly depending on whether the spin-orbit term was included in the bare potential.

As expected, the central DPPs arising from coupling to the $3/2^-$ state are about double those from coupling to the $1/2^-$ state. D-state reorientation has almost no effect on DPPs, but the spin-orbit DPPs are somewhat modified by the presence of a spin-orbit term in the bare potential. The coupling to the $1/2^-$ state consistently generates an imaginary SO term that is (perhaps surprisingly) larger in magnitude than that due to the $3/2^-$ coupling; we discuss the possible significance of the signs below.

Comparing the four sets of results, it is evident that the CC-plus-inversion method yields a consistent account of the DPP generated by pickup coupling, at least when breakup of the deuteron is not included. Comparing the last two columns of Table I, we see that the local DPPs generated by the $1/2^-$ and $3/2^-$ channels, that are not mutually coupled, do not add exactly. As discussed in [3], this must be related to the nonlocality of the underlying DPP. Nevertheless, although there is a consistent departure from additivity for the imaginary terms, the additivity holds remarkably well for the real terms. We find that the increase in reaction cross section when both states are included is 9% greater than the sum of the increases due to each state coupled separately. We do not know of a direct link to nonlocality, but note that it lies between the almost zero nonlocality effect on the real ΔJ and the 14% effect on the imaginary ΔJ.

One interesting and possibly suggestive result is the consistently negative volume integral of the "both states" imaginary spin-orbit DPP. A negative imaginary spin-orbit DPP was found in Ref. [3] for scattering from ^{8}He. This suggests an explanation for the purely empirical KD global potential having an imaginary spin-orbit potential with a negative volume integral. The imaginary spin-orbit ΔJ has a different sign for the $3/2^-$ and $1/2^-$ states, and, unlike for the central potentials, the $1/2^-$ state appears to dominate, leading to a net negative value when both states are coupled. We remark, however, that pickup from ^{10}Be [2] at much lower energies led to a positive imaginary spin-orbit DPP (this was not reported in [2]). For all cases, the $1/2^-$ state generates *larger* real spin-orbit ΔJs than the $3/2^-$ state, and although the net ΔJ of the real spin-orbit term is always positive for the $3/2^-$ state, examination of the radial dependence suggests a cancellation between opposing processes. The extent to which these pickup contributions to the nucleon-nucleus potential are generic deserves exploration, possibly leading to systematic variations in the spin-orbit potential along an isotopic sequence in accord with the varying occupancy of the bound nucleon orbitals.

A. Influence of deuteron breakup

Reference [3] demonstrated, for protons scattering from ^{8}He at the much lower energy of ≈ 16 MeV, that the breakup of the outgoing deuteron had a major effect on the scattering in the entrance channel and on the DPP. We have therefore extended the pickup calculations for 71 MeV/nucleon protons on a ^{6}He target to include deuteron breakup. For comparison, we have carried out similar calculations for 71 MeV/nucleon protons on ^{8}He, using the same description of the target as in [3], but with the bare incident channel OM potential calculated in the same way as for the ^{6}He target.

TABLE II. The effect of including deuteron breakup on characteristics of the DPP arising from pickup. The case for a ^{8}He target at 71.0 MeV/nucleon is compared with that for the ^{6}He target. The final column gives the change in the rms radius of the real, central term. BU and NoBU signify cases with and without breakup of the deuteron; "SO" indicates that the spin-orbit interaction was included in the bare nucleon potential.

Target	Case	$\Delta J_{\rm R}$	$\Delta J_{\rm IM}$	$\Delta J_{\rm RSO}$	$\Delta J_{\rm IMSO}$	$\Delta R_{\rm rms}$
^{6}He	NoBU, SO	−51.23	32.98	3.119	−0.853	−0.120
^{6}He	BU, SO	−26.01	118.27	−1.90	−4.131	−0.204
^{8}He	NoBU, SO	−49.99	23.97	1.303	0.790	−0.101
^{8}He	BU, SO	−34.11	105.35	0.18	−1.69	−0.170

Deuteron breakup was modeled using the CDCC technique, as implemented in FRESCO [4]. Couplings to breakup states with neutron-proton relative angular momentum $L = 0, 2$ were included, along with all allowed continuum-continuum couplings up to multipolarity $\lambda = 2$. The neutron-proton continuum was discretized into a series of bins in momentum (k) space, of constant width $\Delta k = 0.125$ fm^{-1}, except that the highest-momentum bin was of width 0.053 fm^{-1} to avoid numerical problems. The breakup space was truncated at a maximum value of $k_{\rm max} = 1.178$ fm^{-1}, corresponding to a deuteron "excitation energy" of 60 MeV. Our initial calculations had a much smaller maximum value, but this was progressively increased until convergence was reached.

Table II quantifies the extent to which the breakup of the deuteron modifies the DPP induced by pickup coupling. The overall effect on the real central potential, as measured by $\Delta J_{\rm R}$, is still repulsion, but the magnitude of the repulsive effect is considerably reduced. Figure 1 presents the radial dependence of the DPP for the case without breakup and the "Full" case with breakup included. Without breakup, the real central DPP is repulsive at most radii, but with breakup, the repulsion is reversed at smaller radii, the DPP becoming attractive for $r \leqslant 3$.

Such behavior accounts for the greater reduction $\Delta R_{\rm rms}$ in the rms radius when breakup is included. The main effect of increasing the breakup space, i.e. increasing $k_{\rm max}$, was to reduce the magnitude of $\Delta J_{\rm R}$ until a convergence was reached around $k_{\rm max} = 1.178$ fm^{-1}. The "Full" central DPPs in Fig. 1 exhibit oscillations in the surface region. These are required by the inversion for a close fit to S_{lj} and reflect the fact that the local and l-independent representation of an intrinsically l-dependent process often requires such oscillations.

Coupling to the deuteron breakup channels greatly increases the absorption in the central component, as shown in Fig. 1 and quantified in Table II. This effect is much less sensitive to $k_{\rm max}$. The numbers given in the first line (no breakup) do not exactly match those in the last panel of Table I because for all the calculations in which the effects of breakup were examined, a more suitable set of parameters

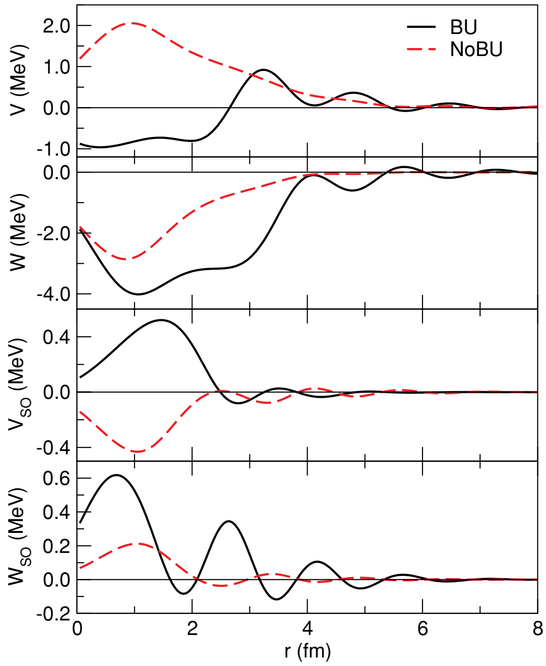

FIG. 1. (Color online) For 71 MeV protons on ^{6}He, the radial dependence of the DPPs without deuteron breakup (dashed lines) and including breakup (solid lines). From the top, real central, imaginary central, real spin-orbit, and imaginary spin-orbit components.

for the deuteron-nucleus interaction were chosen. This did not result in significantly different conclusions.

A comparison of lines 3 and 4 of Table II reveals that breakup also reduces the repulsion due to pickup in proton scattering from ^{8}He at 71.0 MeV/nucleon. For ^{8}He, when breakup is included, the DPP is repulsive in the surface ($3 < r < 4$) and it is near zero further in.

For both target nuclei, pickup coupling with breakup of the deuteron generates a negative spin-orbit interaction. We shall discuss elsewhere how the results of Ref. [3] at 61.3 MeV/nucleon require modification in view of the requirement for a large value of $k_{\rm max}$.

The final column of Table II presents evidence of a further effect common to both ^{6}He and ^{8}He: the coupling decreases the rms radius of the real central potential, an effect increased by deuteron breakup. This correlates with the fact that the real central DPP is uniformly repulsive when breakup is omitted, but less so, or even attractive toward the nuclear center when breakup is included, so decreasing the magnitude of $\Delta J_{\rm R}$. This is significant since: (i) if it proves to be generic, it affects the use of elastic scattering for determining nuclei sizes, and, (ii) it shows once more that a uniform renormalization is an unsatisfactory means of correcting a folding model for channel coupling effects.

We see that coupling contributions are broadly the same for both target nuclei. The most consistent effect on the spin-orbit term is the production of a negative imaginary contribution, but we note that $1/2^-$ and $3/2^-$ pickup states are included in the ^{6}He case, but only a $3/2^-$ state is relevant for ^{8}He.

For the ^{6}He case, we have studied the additivity of the DPPs corresponding to coupling to the $1/2^-$ and $3/2^-$ states, see Table III. Quite unlike the case in Table I, the real-central DPP contributions do not add at all, and in fact the total is less than the contribution from the $3/2^-$ state alone. We stress that there is no coupling between the continuum states associated with the $1/2^-$ and $3/2^-$ states of ^{5}He. The failure of the local DPPs to add must be attributed to strong nonlocal effects of the underlying nonlocal DPP; it may eventually yield understanding of how the continuum reduces the repulsion due to the breakup.

From Fig. 2, we see that the coupling does have a considerable effect on the angular distribution and analyzing power, but does not provide a fit to the data. This fit is limited by our choice of bare potential, and a full search on the parameters

TABLE III. For 71 MeV/nucleon, characteristics of the DPPs generated by coupling to pickup channels with fully converged breakup: the $1/2^-$ state alone, the $3/2^-$ state alone, both $1/2^-$ and $3/2^-$ states coupled, and, for comparison, Σ, the sum of the separate $1/2^-$ and $3/2^-$ DPPs. All ΔJs have units MeV fm^3. The bottom line gives the change in rms radius of the real central term.

Component	$1/2^-$ state	$3/2^-$ state	Both states	Σ $1/2^-, 3/2^-$
Real central	−20.67	−36.87	−26.01	−57.54
Imaginary central	36.82	80.10	118.27	116.92
Real SO	1.021	1.869	−1.899	2.89
Imaginary SO	−2.3982	−1.7907	−4.1306	−4.1889
$\Delta R_{\rm rms}$	−0.0202	−0.1231	−0.2040	−0.1433

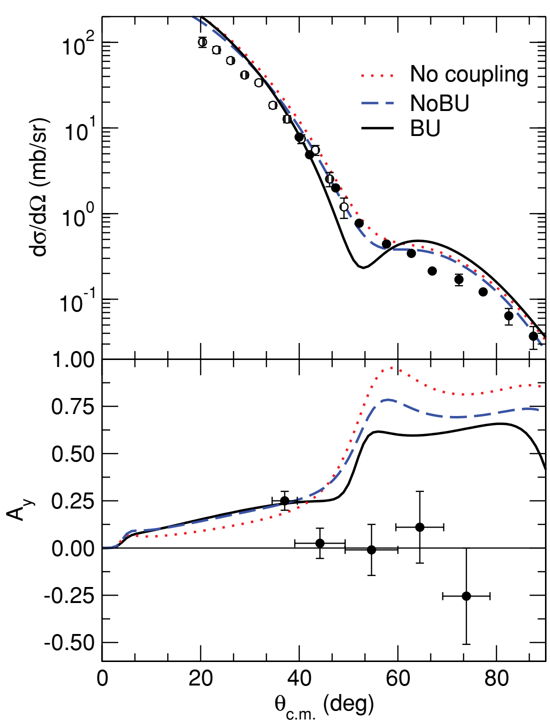

FIG. 2. (Color online) For 71 MeV protons on ^{6}He, the fit to the angular distribution data (above) and analyzing power data (below) of Ref. [1]. The unfilled circles represent the earlier angular distribution data of Ref. [8]. The dotted lines represent the fit with the bare potential, the dashed lines with pickup but no breakup and the solid lines represent the full calculation.

of the bare potential with all coupling included is far beyond our computational means. However, we do present a possible way out of this problem below. The effect of the full coupling on the angular distribution becomes much larger beyond the angular range for which there is data for this target. The coupling increases the differential cross section at 180° by two orders of magnitude, suggesting the importance of these effects for targets for which wide angular range data can be measured.

The width of the $1/2^-$ resonance in ^{5}He prompted us to test the sensitivity of the DPPs to the placement of this state. Accordingly, the full DPP calculation was repeated with the energy of the $1/2^-$ state in the deuteron partition increased by 1 MeV. The resulting changes in the inverted potential were small, the most significant being a 0.65% fall in the volume integral of the real central component. This corresponds to a decrease in the magnitude of the repulsive real central DPP by about 2.5 MeV fm^3, leaving our general conclusions unchanged. The change to the analyzing power was barely perceptible, and the change to the angular distribution was imperceptible.

B. Sensitivity to the bare potential

How does the DPP depend upon the bare potential? Since we were not able to optimize the bare potential to fit the data with the complete CC calculation, it is conceivable that a different bare potential would lead to quite a different DPP. To test this we (i) repeated the full CC calculation but using as bare potential the original bare potential minus the DPP, and (ii), inverted the resulting S_{lj}. If the DPP is completely independent of the bare potential, the result of (i) and (ii) should be to regain the original bare potential.

We follow these steps for both cases: with and without breakup of the deuteron. Table IV presents the no-breakup results in terms of volume integrals and rms radii of the potentials involved. The agreement between row 1 and row 4 is remarkable.

Table V presents the results when breakup is included.

The angular distribution (AD) and AP for the final inverted potential were close to those for the original bare potential out

TABLE IV. For 71 MeV/nucleon protons, with pickup but no breakup in the deuteron channels. Volume integrals J and rms radii $R_{\rm rms}$ of, in order, the original bare potential, the inverted potential, the new bare potential (twice the original bare potential minus the inverted potential) and the potential found by inverting S_{lj} from calculations involving pickup to $1/2^-$ and $3/2^-$ states in which the bare potential was that quantified in the third row. In each case, the signs are such that attractive is positive and repulsive is negative; J is in units of MeV fm^3 and $R_{\rm rms}$ in fm.

Case	Real central		Imag. central		Real S-O	Imag S-O
	J	$R_{\rm rms}$	J	$R_{\rm rms}$	J	J
Bare 1	415.80	2.9471	195.41	3.0676	27.763	−3.9203
CC−inv 1	364.57	2.8270	228.39	3.0325	30.882	−4.7723
Bare 2	467.03	3.0376	162.43	3.1163	24.644	−3.0683
CC−inv 2	416.66	2.9486	194.10	3.0764	27.806	−4.0034

TABLE V. As for Table IV but with breakup in the deuteron channels. Volume integrals J and rms radii $R_{\rm rms}$ of, in order, the original bare potential, the inverted potential, the new bare potential (twice the original bare potential minus the inverted potential) and inverted S_{lj} from full CC calculation in which the bare potential was the potential labeled "Bare 2."

Case	Real central		Imag. central		Real S-O	Imag S-O
	J	$R_{\rm rms}$	J	$R_{\rm rms}$	J	J
Bare 1	415.80	2.9471	195.41	3.0676	27.763	−3.9203
CC−inv 1	389.79	2.7427	313.68	3.2141	25.864	−8.0509
Bare 2	441.81	3.1163	77.14	2.3810	29.662	0.2103
CC−inv 2	405.88	2.9555	195.78	3.0436	28.820	−4.6376

to about 110° beyond which the AD, in particular, departed substantially. The properties given in line 4 are remarkably close to those in line 1, particularly the rms radii. Evidently, the DPP is close to the same with both bare potentials, in spite of the fact that "Bare 2" had an imaginary part with only about 40% of the depth of "Bare 1." In particular, the CC effects on the spin-orbit potential appear to be robustly determined. Only the real central DPP seems to depend significantly upon the bare potential.

Three things follow when we include breakup of the outgoing deuterons: (i) the repulsive effect of the deuteron coupling is greatly reduced in a way that is sensitive to the truncation of the breakup space; (ii) the contributions of the $1/2^-$ and $3/2^-$ states to the real DPP do not sum to the total as they do when there is no breakup; and, (iii) the linearity test (regaining the bare potential) works less perfectly when breakup is included. These effects appear to suggest that, when breakup is included, the underlying DPP, that we have represented by a local potential, is more strongly nonlocal. As yet, we do not have a satisfactory qualitative account of these results.

IV. SUMMARY AND OUTLOOK

We have not made a case for the omission of pickup channel coupling being the origin of the apparent discrepancy in the 71 MeV/nucleon AP [1], but we have presented further evidence that the generation of substantial repulsion is a generic property of coupled pickup channels. A new finding is the extent to which this repulsion is reduced when breakup of the deuteron is included. Moreover, the breakup appears to have markedly increased the nonlocal effect that we have identified through the nonadditivity of DPPs of reaction channels that are not mutually coupled. We have also found some possibly generic effects of transfer processes on the spin-orbit potential. The generic nature of these effects will require a program of similar calculations applied to more "normal" target nuclei.

This work is not a comprehensive account of all the contributions by reaction processes to the $p+{}^6$He interaction. A clear omission is the breakup of ^{6}He, previously studied in Ref. [9], and deserving reinvestigation. Nevertheless, some representation of these pickup coupling effects is required for any complete description of nucleon scattering from nuclei. We have noted that a full parameter search involving the complete CC calculation as described here is beyond our computing resources. Our choice of the KD global parameters for the bare potential has limited our ability to fit the experimental data. Nevertheless, the results presented in Table V and the related discussion show that the DPPs that emerge are in large degree independent of the bare potential. This suggests the following means of including the CC effects within a semiphenomenological framework: (i) carry out a precise OM fit to the AD and AP data, (ii) carry out full CC-plus-inversion calculation of the DPP arising from whatever processes are included in the CC calculation, using the OM fitted potential as bare potential, (iii) subtract that DPP from the bare potential to generate a new bare potential, (iv) carry out a full CC calculation with the new bare interaction. This should get a close fit to the AD and AP data, except at far backward angles, and the purely phenomenological improvement to the fit should require just minor adjustments. In that case, *the bare potential would represent that part of the interaction that should be the result of any theory that does not include a representation of pickup processes.* Unfortunately, as noted in [3] it is currently difficult to know what representation of such processes is included implicitly in other approaches. However, local density models cannot fully represent the nonlocality and l dependence of the full DPP of which we present the local equivalent.

A comprehensive search on the parameters of the bare potential, to fit elastic scattering data, would be impractical when breakup of the coupled deuteron is included. Nevertheless, it might be practical in cases where breakup can be shown to be unimportant, such as (^{3}He, ^{4}He) coupling. CC calculations of pickup are many times faster when breakup is excluded. We plan to investigate the importance of pickup coupling for heavier and less unusual nuclei, where, indeed the effects might be less linear than described here.

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