

The mechanism for the unnatural-parity $^{10}\text{B}(\text{p},\text{p}'), 3^+ \rightarrow 0^+$ reaction

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We report measurements to complete the full set of polarization transfer coefficients for the $3^+ \rightarrow 0^+$, $\Delta T=1$, transition to the state at 1.74 MeV in the $^{10}\text{B}(\vec{\text{p}}, \vec{\text{p}}')^{10}\text{B}$ reaction at 197 MeV proton energy. A Distorted Wave Impulse Approximation analysis that includes coupled-channel effects in the distortions for the 3^+ high-spin state shows that this improvement to the calculation results in somewhat worse agreement with the data. A decomposition into terms sensitive to individual spin-dependent amplitudes, including comparisons to similar isovector transitions in ^{16}O and ^{28}Si , suggests that problems reproducing the spin observables can be traced to the effective interaction. Zero crossings in the real parts of the E - and F -amplitudes are well determined by experiment and constitute strong evidence against density dependence in these transitions, whether it arises from Pauli blocking, relativity, or the more speculative partial chiral restoration.

I. INTRODUCTION

The study of (p,p') reactions at intermediate energies offers an opportunity to extract information on the effective nucleon-nucleon (NN) interaction and the single-particle structure of nuclei, as these are the two basic ingredients in Distorted Wave Impulse Approximation (DWIA) calculations of these reactions. Effects that arise from the presence of nuclear matter, such as Pauli blocking, are usually incorporated through density-dependent modifications to the effective NN interaction. Unnatural-parity transitions are a special case. The measurement of a set of polarization observables consisting of the analyzing power, induced polarization, and polarization transfer coefficients permits the approximate separation of the cross section into parts that correspond to the transverse and longitudinal structure components and into parts that match the contributions of the spin operators in the Kerman-McManus-Thaler (KMT) [1] expansion of the NN interaction [2,3]. Most of the KMT spin-dependent terms are associated with the tensor parts of the effective interaction, which are relatively free of density-dependent effects. The largest density dependence appears instead for elastic scattering and collective transitions that depend on the isoscalar central and spin-orbit effective interaction terms. By choosing so-called “stretched” unnatural-parity transitions where the particle and hole angular momenta add to form the transferred angular momentum, $j_p + j_h = J_{tr}$, there is usually only one particle-hole contributions to the transition density and this can be constrained in the calculation using inelastic electron scattering data. This makes the DWIA calculation essentially free of ambiguity and an excellent test of how well theory can match experiment.

With this as a starting point, measurements of the cross section and a full set of polarization observables were made for a number of such transitions with the intention of searching for evidence of new forms of density dependence, in particular the rescaling of exchanged meson masses and coupling constants arising from partial chiral restoration in nuclear matter [4,5]. Initially, the results from such measurements seemed to indicate the presence of such a restoration [6–8]. Reductions of the rho meson mass had significant effects on the polarization transfer coefficients such as $D_{NN'}$

for ^{10}B [7], repairing differences between calculations and data. But the modifications made to the effective interaction in the analyses consisted of an *ad hoc* change to the spin-dependent amplitudes that failed to consider questions of the effects on other types of transitions or the internal consistency of the interaction itself. Eventually, a more detailed treatment of chiral restoration in the effective interaction became available [9] that included changing meson properties in a self-consistent way. When tested against data on oxygen and silicon targets [10], it was found that the transitions were generally insensitive to the effects of chiral restoration. This left the differences between the calculations and the polarization transfer measurements unexplained. The worst agreement was with $D_{NN'}$ where predictions at momentum transfers between 1 and 2 fm^{-1} are generally more negative than the data (on ^{10}B [7] and ^{28}Si [10]).

The ^{10}B case offers a chance to further investigate this issue because of two unique features. First, the final 0^+ state lies at low excitation where there is no continuum background. So it is possible to extend the measurements to higher momentum transfer where the interpretive issues are more pronounced. Data at 197 MeV now exist out to 3 fm^{-1} as a result of two experiments [7,11].

Second, one possibility for problems with these transitions lies in the omission of channel-coupling effects. This could come in the form of connections to other excited states, but perhaps the most likely possibility is that additional angular momentum can be absorbed in self coupling associated with the high-spin state. Normally, this state is the final state in the (p,p') reaction. But for ^{10}B the 3^+ state is the initial state and the reaction leads to an excited 0^+ state. This gives us the opportunity to use the (e,e') and (p,p') elastic scattering data on ^{10}B to constrain the coupled-channel calculation and to determine how well it describes the entrance channel distortions.

The details of the experiment have been described elsewhere [7,11] and will not be repeated here.

A previous analysis by Betker *et al.* [11] of the natural parity excitations in ^{10}B explored in detail the description of the coupling in the entrance channel. Two couplings were considered, the connection to the strong 4^+ collective state at 6.02 MeV and the coupling of the 3^+ state to itself through an $L = 2$ excitation. The inclusion of channel coupling was beneficial to the description of both final state observables.

The mix of properties in the currently available DWIA programs does not allow us to bring together all the aspects that would be needed to test the channel-coupling hypothesis for an unnatural-parity transition into a single calculation. In particular, isovector transitions such as that in ^{10}B proceed almost entirely through the tensor interaction, and this requires that we use finite range DWIA to treat the exchange parts of the transition. Programs that include channel coupling are limited to a "direct only" formalism. However, the quality of the direct-only approximation improves with increasing J -transfer, so we can use these calculations as a guide provided adequate care is exercised in the construction of the effective interaction.

A second feature of the finite-range DWIA calculations is that they cannot be used with empirical interactions such as that used in the analysis of the natural-parity transitions [11,12]. So we must incorporate density dependence into the theoretical construction of the effective interaction. In Section II we will re-examine the calculations for elastic scattering so as to evaluate the substitution of a theoretical treatment of the density dependence for an empirical one. Then in Section III we will make a number of calculations for the unnatural-parity transition and discuss the effects of channel coupling. We will find that the channel coupling is not the solution to problems with calculations for these transitions. So we will end this section with a comparison to similar data on ^{16}O and ^{28}Si and discuss trends in the data and calculations.

All of these experiments were performed at 197 MeV at the Indiana University Cyclotron Facility. These data have the highest statistical precision for polarization transfer of any excitations to discreet final states, and thus are the best available for an exploration of the reaction mechanism issues.

II. ELASTIC SCATTERING

In a previous analysis of proton elastic scattering on ^{10}B at 197 MeV [11], the $L = 0$ part of the entrance channel was described using an optical potential with complex central and spin-orbit potential terms. To this potential model, particle-hole transition densities were added to describe the excitation of the 4^+ state in ^{10}B at 6.02 MeV and the coupling of the ground state to itself through an $L = 2$ term. Both of these terms were coupled back to the entrance channel. The optical model parameters were adjusted to reproduce the cross section at all angles where there was data and the analyzing power at angles less than 25° . This procedure resulted in better agreement with the elastic scattering analyzing power at angles larger than 25° and all observables for the 4^+ state, in spite of the fact that these data were not included in the optical potential parameter search. The authors concluded that the measurements supported the coupled-channel treatment as a more complete description of the entrance channel wavefunction.

Such a treatment is not available in a DWIA calculation that includes finite-range exchange, which is the preferred treatment of unnatural-parity transitions due to the importance of the tensor exchange interaction. In a previous

study of similar transitions [10], the entrance and exit channel distortions have been based on a folding model using as input the ground state point nucleon density and the same density-dependent interaction that is used for the transition. We will continue to use this model here. In order to investigate the effects of channel coupling, we will need to make two compromises.

First, we will make the coupled-channel calculations using a “direct only” formulation provided by the program LEA [13]. The interaction used will be the sum of the direct and exchange parts added using a scheme that approximates the crossed momentum transfer (see Appendix B of Sammarruca [14]). This approximation will be discussed in the next section.

Second, in order to make the LEA calculation more like the earlier unnatural-parity DWIA calculations using the program DWBA86 [15], we will replace the parametrized optical potential with a folding model potential. The treatment of channel coupling, including its parametrization, will remain the same. In earlier investigations, it was concluded that folding model distortions worked well for inelastic scattering when both Pauli blocking and relativistic effects were included in the effective interaction [14]. This conclusion was mainly supported by data on natural-parity transitions using $N = Z$ 0^+ targets. On this basis, we will use both mechanisms as a part of our density dependence.

These choices raise the question of whether the treatment of the entrance channel wavefunctions remains adequate for an evaluation of channel coupling. In order to answer this, we will make two sets of calculations that explore the effects of either the channel coupling or density dependence on our description of elastic scattering.

In Fig. 1 we start with a comparison to the elastic scattering cross section and analyzing power data. The short-dash curves use only the folding model potential. The density-dependent interaction for all of the calculations shown in Fig. 1 contains both Pauli blocking and relativistic effects (Dirac-Brueckner-Hartree-Fock, or DBHF). The oscillatory pattern in the analyzing power is typical of proton elastic scattering for 0^+ nuclei in this mass range [16]. The main problems to be solved in getting better agreement with the data are to damp the analyzing power oscillations and to raise the cross section at the larger angles. The inclusion of just the self-coupling in the ground state (long-dash curves) goes a considerable way toward achieving this. The best description of the analyzing power comes when coupling to the 4^+ excited state is included as well. The cross section, however, now becomes too large, a problem that is associated with the treatment of the density dependence. We will discuss that next. For now, it would appear that the polarization observables prefer the calculations with both couplings included. This is reasonable as it comes closest to what is the real physical situation. We should note that this folding potential does a better job of suppressing the oscillations in the larger angle analyzing power than did the optical potential that was adjusted to match the cross section and small angle analyzing power data. It is hard to know whether this is an artifact of the optical model parameter search process or represents some superiority in the DBHF folding model. There is no improvement here with the calculation for D_{NN} which missed most of the spin-flip in the elastic channel [11].

In Fig. 2 we examine the same calculation, this time with different treatments of the density dependence in the folded optical potential. All of the curves in Fig. 2 include both channels in the coupling. The solid curves represent the inclusion of both Pauli blocking and relativity in the effective interaction, and is the same as the solid curves in Fig. 1. In a previous study that considered elastic scattering [14], it was noted that the infinite nuclear matter treatment of the density dependence overestimated the in-medium repulsion for the elastic scattering channel only [17]. A closer representation of the data is usually given by a density dependence that considers only Pauli blocking (BHF) [14]. That case for ^{10}B is shown in Fig. 2 by the long-dash curves. One of the problems that this change solves is the overestimate of the large angle cross section. This result is consistent with the previous findings [14]. But unlike the previous work on 0^+ target nuclei, the switch to the BHF density dependence makes the analyzing power more oscillatory. This takes the calculation away from the data. For ^{10}B we do not find that the BHF calculation is consistently better as earlier experience would suggest. The case for no density dependence is shown by the short-dash curves. These calculations resemble earlier results [14] in that they show an increase in the cross section as the density dependence adds more repulsive terms. Both Pauli blocking and relativistic effects do this. There is also a rise toward more positive values in the analyzing power as the amount of repulsion in the nuclear medium is reduced.

For the treatment of inelastic scattering, it is most crucial that the forward angle elastic scattering reproduce well the cross section and analyzing power. This is accomplished by the solid curves in Figs. 1 and 2. So the switch from a parametrized optical potential to a folding model potential does not appear to have caused great harm to our ability to describe elastic scattering. In fact, the description of the analyzing power, and by implication the description of the spin effects in the distorted waves, appears to have improved. So we will use the folding potential and DBHF density dependence in our investigation of the unnatural-parity $3^+ \rightarrow 0^+$ transition.

III. THE STRETCHED ISOVECTOR TRANSITION

The examination of the $3^+ \rightarrow 0^+$ transition in $^{10}\text{B}(\vec{p}, \vec{p}')^{10}\text{B}$ at 197 MeV now includes a complete set of polarization transfer measurements, more than was available to Baghaei *et al.* [7]. In this paper, we wish to try entrance channel distorted waves that include coupled-channel effects. This part of the calculation has been described in the previous section. In the exit channel, which involves the ^{10}B nucleus in its 0^+ excited state at 1.74 MeV, the distortions are treated in the usual way with a folding model optical potential based on the nuclear density and the DBHF density-dependent effective interaction. The DBHF effective interaction will also be used as the transition potential in the DWIA calculation of the $3^+ \rightarrow 0^+$ reaction.

The remaining task is to specify the particle-hole configuration for the transition density. To constrain this, we will compare with the inelastic electron scattering measurement of the transverse formfactor reported by Hicks *et al.* [18]. Figure 3 shows these data. The stretched spin coupling is described by a $p_{3/2}$ particle and a $p_{3/2}$ hole combined to give a 3^+ spin transfer. Since $p_{3/2}$ is the last occupied shell model orbit, it is the only particle-hole configuration that we consider. In order to obtain the asymmetric shape of the transverse formfactor data, we used a Woods-Saxon potential for the neutron and proton single particle wavefunctions. Both are needed to describe this isovector transition. The well shape parameters, radius r_0 and diffuseness a_0 , were adjusted to obtain agreement with the shape of the (e, e') data. The potential depth was chosen to produce a state with the correct binding energy for the neutron or proton. A best fit was found with $V = -7.09$ MeV, $r_0 = 0.704$ fm, and $a_0 = 0.90$ fm. In the proton case, an additional Coulomb potential was added using a uniform charged sphere of radius $r_c = 1.47$ fm, the same value that was used for the analysis of the natural-parity transitions [11]. The resulting curve with an arbitrary normalization is shown in Fig. 3. Agreement with the (e, e') data is excellent. For the DWIA calculation, the spectroscopic strength of the transition was chosen to match the value of the (p, p') cross section at its peak.

Measurements of $D_{SS'}$, $D_{LL'}$, $D_{SL'}$, and $D_{LS'}$ were made at the same angles where $D_{NN'}$ had been measured previously [7]. The experiment has been described by Betker [11]. Figure 4 shows the full set of measurements.

The present status of the finite-range calculation (with a DBHF density-dependent interaction but no channel coupling) is shown by the solid curves in Fig. 4. The previous calculation [7] was done with the Franey-Love interaction [19], which contains no density-dependence. In the original calculation, there was good agreement with the slope of the cross section past the peak. In the current calculation, the cross section is too large at large angles, a systematic problem that appears to be associated with the large repulsion introduced into the nuclear medium by the combination of Pauli blocking and relativistic effects. We are using the DBHF scheme because of its success in describing polarization observables, the main issue in the discussion of chiral restoration. The induced polarization P is well described, but the calculation falls below the analyzing power data. The data for the polarization and analyzing power are similar, a result that has been associated with small nuclear currents in the transition [20]. The calculation has a larger $P - A$ difference, one of the signatures of such currents. The other signature is the sum of $D_{SL'}$ and $D_{LS'}$ (similar to $D_{qQ} + D_{Qq}$ in Ref. [20]). Again, the calculation shows a larger effect than the data. The large difference noted previously [7] between the $D_{NN'}$ data and the calculations is now about half as large, with the calculation still too negative.

Of the new polarization transfer measurements, $D_{LL'}$ and $D_{SL'}$ are fairly well reproduced. The $D_{SS'}$ calculations are too positive by an amount similar to the difference seen for $D_{NN'}$. The $D_{LS'}$ calculations miss the last two angles on the negative side. So problems reproducing the polarization observables remain, and are extended to some of the new data. We will return at the end of this section to a more detailed discussion of these differences.

The first question that we want to investigate is whether the inclusion of channel coupling can help to address any of the differences that remain between the calculation and these data. To do this, we will repeat the calculation of the $3^+ \rightarrow 0^+$ transition using a “direct only” formalism, which is the zero-range limit of our present DWIA result. In this treatment, the direct and exchange parts of the interaction are summed and the result used in the DWIA calculation as if it were entirely direct. In making this sum, the exchange parts are a function of the crossed momentum transfer, Q . This variable has to be related to the momentum transfer q that is the independent variable in the direct part when the sum is taken. The q -dependent amplitudes for the resulting NN interaction are read into LEA and used in that form (whereas DWBA86 makes its calculation in coordinate space). In the free interaction, $q^2 + Q^2 = 4k^2$ where k is the nucleon momentum in the NN center of mass. For proton inelastic scattering in a heavy nucleus, this is a poor approximation. At large angles, q can reach almost twice the size allowed by this equation. In most calculations made with LEA, Q is approximated by $Q(q) = Q(0) = 2k$, which is satisfactory only for low momentum transfer. We are examining data well beyond that limit. So we have added the two parts of the interaction assuming that the projectile strikes a nucleon in motion and that the scattering is otherwise on shell [14]. The struck nucleon is given the smallest possible momentum relative to the target nucleus that is consistent with the momentum transfer in the (p, p') reaction. This momentum varies with the (p, p') scattering angle. Calculations made for the $3^+ \rightarrow 0^+$ transition using LEA and an effective interaction constructed in this way is shown by the short-dash curves. (This approximate

treatment becomes progressively worse as the spin transfer decreases.)

Comparing the polarization calculations for the short-dash (zero-range) and solid (finite-range) curves shows that there is reasonably good correspondence between the two calculations in the absence of channel coupling. The most notable difference is for the cross section where the zero-range calculation is larger than the finite-range by almost an order of magnitude at large angles. On top of a DBHF calculation that was already too large, the difference with the data is now serious. Nevertheless, we hope to learn from this calculation how channel coupling can affect the polarization observables.

Figure 4 shows the coupled-channel zero-range calculation with the long-dash curves. There are significant changes in the polarization observables only for $D_{SS'}$ and $D_{LS'}$. Otherwise, the two results track each other closely. Assuming that the effect of channel coupling on the finite-range result is similar, it becomes possible to judge whether or not channel-coupling of the sort required for ^{10}B elastic scattering helps to understand the inelastic polarization observables. For the observables A , P , $D_{SL'}$ and $D_{LS'}$ in Fig. 4, these changes would reduce the effects that we noted earlier as evidence of nuclear currents. All of these observables except for the polarization P would show better agreement with the data. There are only small changes for $D_{LL'}$ and $D_{NN'}$. But for all three of the diagonal observables, $D_{NN'}$, $D_{SS'}$, and $D_{LL'}$, the application of channel coupling would make agreement with the data worse. This appears to be systematically true at all scattering angles. Thus we reach the first major result of this paper, namely that the differences that drove the argument for chiral restoration are made even stronger when channel coupling is included for the high spin state distortions. We also note that channel coupling has reduced the large angle cross section significantly. If this were to be applied to the finite-range calculation, the reproduction of the data would improve significantly.

Another way to present the information in Fig. 4 is to make combinations of the polarization transfer coefficients that select out (in the plane-wave limit) particular KMT amplitudes. We denote these by D_{ls} , D_q , D_n , and D_Q where

$$D_{ls} = \frac{C^2 \chi_T^2}{\sigma} = [1 + D_{NN'} + (D_{SS'} + D_{LL'}) \cos \theta - (D_{LS'} - D_{SL'}) \sin \theta]/4 \quad (3.1)$$

$$D_q = \frac{E^2 \chi_L^2}{\sigma} = [1 - D_{NN'} + D_{SS'} - D_{LL'}]/4 \quad (3.2)$$

$$D_n = \frac{B^2 \chi_T^2}{\sigma} = [1 + D_{NN'} - (D_{SS'} + D_{LL'}) \cos \theta - (D_{LS'} - D_{SL'}) \sin \theta]/4 \quad (3.3)$$

$$D_Q = \frac{F^2 \chi_T^2}{\sigma} = [1 - D_{NN'} - D_{SS'} + D_{LL'}]/4 \quad (3.4)$$

with χ_L and χ_T the spin-longitudinal and transverse structure functions, and B , C , E , and F the KMT amplitudes associated with the $\sigma_{1n}\sigma_{2n}$, $\sigma_{1n} + \sigma_{2n}$, $\sigma_{1q}\sigma_{2q}$, and $\sigma_{1Q}\sigma_{2Q}$ spin operators. The D_i are normalized so that $D_{ls} + D_q + D_n + D_Q = 1$; thus only three of the four D_i are independent.

Figure 5 shows the D_i using an \mathbf{x} for each ^{10}B data point. The corresponding finite-range calculations are shown by the short-dash curves. In order to gain an understanding of the extent to which the trends shown here are signatures of isovector stretched (p,p') transitions, we include data from two other nuclei. The solid points and curves are the data and calculations for the $0^+ \rightarrow 4^-$ transition to the state at 18.98 MeV in ^{16}O , and the open points and long-dash curves are the data and calculations for the $0^+ \rightarrow 6^-$ transition to the state at 14.35 MeV in ^{28}Si [14]. Given that these data represent different spin transfers in different nuclei, they all appear to follow a common trend. D_q rises to a peak and then falls. D_n tapers down slowly. D_{ls} rises slowly. D_Q goes through a valley. The sum of D_n and D_{ls} is roughly constant. Since the sum of all four D_i is one, the peak in D_q mirrors the valley in D_Q .

In general, the trend of D_{ls} and D_Q with angle is reproduced by the calculation. The main problem is apparent in the comparison of D_q with D_n . Again with a similar level of deviation, D_q is overestimated and D_n is underestimated. The discrepancy increases with angle. In a striking way, the value of D_n tends to vanish at the larger angles while the data from ^{10}B are still at 0.2. Since D_{ls} and D_Q are both reproduced and D_n as well as D_{ls} and D_Q all share the transverse structure function, it is likely that the problem at the larger angles lies with the model of the effective interaction. It may be significant to note that at the largest angles for which we have data, the momentum transfer passes through 3.1 fm^{-1} , the maximal value that it can have in the NN center of mass. Beyond this point the scattering is off shell (for a stationary target nucleon) and not constrained by measurements from NN scattering. If the disappearance of the KMT B -amplitude at the larger angles is really an issue with the effective interaction, then so is the mirror effect in the overestimate of D_q . This argument steers us away from issues of nuclear structure as a solution to the problem of agreement with the data.

In Figs. 6 and 7 of Sammarruca *et al.* [10], the data for the σD_i were shown for the transitions in ^{28}Si and ^{16}O . In both cases, $\sigma D_n > \sigma D_q$. Yet the calculations show this behavior only for ^{16}O . In ^{28}Si , the calculated σD_q is larger

than σD_n . This seeming disparity in the calculations arises from the steep angle dependence of the calculations shown in Fig. 5 and the fact that the $J_{tr} = 6$ of ^{28}Si forces the system to sample the σD_i at larger angles than the $J_{tr} = 4$ of ^{16}O .

The tensor part of the effective interaction for isovector transitions is large and comes from a combination of attractive, long-range pion exchange and repulsive, short-range rho exchange. Any sensitivity of the polarization observables to chiral restoration comes as a result of lowering the rho-meson mass relative to the pion mass and increasing the repulsive contribution to the tensor effective interaction. The most sensitive gauge of this balance may be the zero crossings of the real parts of the KMT amplitudes. These occur in Fig. 5 at $\sim 16^\circ$ for E (see D_q) and at $\sim 41^\circ$ for F (see D_Q) where the respective D_i go through a minimum that almost reaches zero. The minimum in D_q is connected to the minimum at 0.7 fm^{-1} in the (b) panel of Fig. 2 in Baghaei [7]. This momentum transfer reflects mostly the rising strength of the pion, tempered by the rho meson, at low momentum in the free interaction. The rescaling to $m^*/m = 0.9$ for the rho-meson mass moves this zero crossing past 1 fm^{-1} . That is in the vicinity of 20° in Fig. 5. A zero crossing there seems to be excluded by the data shown near 20° . Additional support for having the zero crossing near 0.7 fm^{-1} comes from measurements on the $0^+ \rightarrow 0^-$, $\Delta T = 1$ transition to the state at 12.80 MeV in ^{16}O as reported by Stephenson [21]. This transition can proceed only through the E -amplitude and the zero crossing appears as a minimum in the cross section. The location of the E -amplitude zero crossing moves to larger momentum transfer values as the nuclear density increases in the DBHF effective interaction. So the experimental support for locating the zero crossing near 0.7 fm^{-1} also argues against a large density dependence of the usual sort (DBHF) in these transitions.

The result is the same for the F -amplitude near 2.1 fm^{-1} (41°). The momentum transfer value at the zero crossing is consistent with the free interaction. DBHF density dependence would move this crossing to smaller angles as the density increases. So this result also supports a small density dependence at 2.1 fm^{-1} , whether from DBHF effects or a rebalance of the contributions from the pi and rho mesons. Since these zero crossings agree with the value from the free interaction, independent of any DWIA calculation, they constitute strong evidence for the absence of any significant density dependence in these transitions. The trends of the three nuclei considered here are in agreement. The DWIA calculations support this conclusion.

IV. CONCLUSIONS

We reported here the measurement of the four in-plane polarization transfer coefficients for the $3^+ \rightarrow 0^+$ transition in $^{10}\text{B}(\vec{p}, \vec{p}')^{10}\text{B}$. Earlier measurements of $D_{NN'}$ had been used to argue that there was evidence for a partial chiral restoration of the rho meson mass in nuclear matter on the basis of a simple change to the effective interaction amplitudes. A more comprehensive analysis that included partial chiral restoration but retained consistency with the properties of nuclear matter at saturation showed that stretched isovector unnatural-parity transitions such as this one were insensitive to such medium modifications. With the additional data now available, we undertook a more detailed analysis to explore other ways to understand these polarization data.

The first question that we examined was whether or not the distortions in the channel containing the high spin state were affected by channel coupling effects. This study took advantage of the unique character of the ^{10}B transition, namely that it starts in the high spin state (3^+) and proceeds to an excited 0^+ state, essentially running in reverse. Since the high spin state is a stable target and available for investigation, this allowed us to test the quality of any coupled-channel calculations. In a previous analysis, we were able to formulate a coupling scheme that was consistent with the measured spin-flip amplitudes in electron scattering and followed as closely as possible the shell model matrix elements for each transition, including elastic scattering. We applied these new distortions in a zero-range approximation, after verifying that this approximation was adequate for the study of this unnatural-parity transition. We found that there were only two improvements to be gained from the channel coupling, namely the reduction of the much too large cross section calculation, and the reduction of the differences associated with nuclear currents to better resemble the measurements. Unfortunately, the channel coupling made the differences with the diagonal polarization transfer coefficients that had been the basis of the partial chiral restoration argument even larger. This effect may be expected to appear for all such stretched isovector transitions.

With the problem of agreement with the measurements still unresolved, we turned to a comparison with other measurements at the same proton bombarding energy for further insight. We compared these data using observables that are connected in plane wave with particular spin-operator terms in the KMT expansion of the effective interaction. The measurements reported here on ^{10}B agree with the trends of other similar transitions with higher spin transfer on ^{16}O and ^{28}Si and extend those trends to much higher momentum transfer. Now it is possible to see clearly that the disagreement between theory and experiment increases with momentum transfer, and is a positive error for D_q and a mirror negative error for D_n . Since the particle-hole structure for such stretched transitions is without nodes

and connected for all these observables by a simple spin factor, it seems reasonable to attribute the problem to the effective interaction. Even if we included the structure as a source of difficulties, we would have to then have to cancel this using problems with the interaction in order that two of the four observables would agree with the data trends. One way to characterize this problem is to note that the B -amplitude associated with D_n approaches zero as the momentum transfer approaches the edge of the on-shell region.

A reconciliation of this issue is difficult since the spin dependence in the (p,p') observables arises essentially from the spin dependence of the free NN interaction. It has been noted before that the usual sorts of density dependence have little effect on these transitions, a result that may come from the tendency of the large angular momentum transfer to cause the overlap in the DWIA integral to occur a large radius well outside the bulk of the nuclear matter distribution. This conclusion was strongly reinforced by an examination of two zero crossings that occur for the real parts of the E - and F -amplitudes. These result in values of the corresponding D_i that come close to zero in a sharp minimum. As such, they are easy to locate in angle or momentum transfer. Their locations support, along with other measurements on the $0^+ \rightarrow 0^-$ transition in ^{16}O , values that are consistent with the free interaction. There is no evidence here for either DBHF density dependence or the effects of partial chiral restoration. We are left to conclude that the origin of this large momentum transfer problem in D_q and D_n , whether it be in the effective interaction or the reaction mechanism, remains unknown.

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- [1] A.K. Kerman, H. MacManus, and R.M. Thaler, *Ann. Phys. (N.Y.)* **8**, 551 (1959).
 - [2] J.M. Moss, *Phys. Rev. C* **26**, 727 (1982).
 - [3] E. Bleszynski, M. Bleszynski, and C.A. Whitten, Jr., *Phys. Rev. C* **26**, 2063 (1982)
 - [4] G.E. Brown and Manneque Rho, *Phys. Lett. B* **237**, 3 (1990); *Phys. Rev. Lett.* **66**, 2720 (1991); *Phys. Rep.* **269**, 334 (1996).
 - [5] G.E. Brown, M. Buballa, Zi Bang Li, and J. Wambach, *Nucl. Phys.* **A593**, 295 (1995).
 - [6] E.J. Stephenson and J.A. Tostevin, in *Spin and Isospin in Nuclear Reactions*, edited by S.W. Wissink *et al.* (Plenum, New York, 1992), p. 281.
 - [7] H. Baghaei *et al.*, *Phys. Rev. Lett.* **69**, 2054 (1992).
 - [8] E.J. Stephenson, J. Liu, A.D. Bacher, S.M. Bowyer, S. Chang, C. Olmer, S.P. Wells, and S.W. Wissink, *Phys. Rev. Lett.* **78**, 1636 (1997).
 - [9] R. Rapp, R. Machleidt, R. Durso, and G.E. Brown, *Phys. Rev. Lett.* **82**, 1827 (1999).
 - [10] F. Sammarruca, E.J. Stephenson, K. Jiang, J. Liu, C. Olmer, A.K. Opper, and S.W. Wissink, *Phys. Rev. C* **61**, 014309 (1999).
 - [11] A.S. Betker *et al.*, submitted for publication.
 - [12] H. Seifert *et al.*, *Phys. Rev. C* **47**, 1615 (1993).
 - [13] James J. Kelly, program manual for LEA, 1995.
 - [14] F. Sammarruca, E.J. Stephenson, and K. Jiang, *Phys. Rev. C* **60**, 064610 (1999).
 - [15] R. Schaeffer and J. Raynal, program DWBA70; S. Austin, W.G. Love, J.R. Comfort, and C. Olmer, extended version DWBA86 (unpublished).
 - [16] H.O. Meyer, P. Schwandt, W.W. Jacobs, and J.R. Hall, *Phys. Rev. C* **27**, 459 (1983).
 - [17] R.J. Furnstahl and S.J. Wallace, *Phys. Rev. C* **47**, 2812 (1993).
 - [18] R.S. Hicks *et al.*, *Phys. Rev. Lett.* **60** 905 (1988).
 - [19] M.A. Franey and W.G. Love, *Phys. Rev. Lett.* **31**, 488 (1985).
 - [20] W.G. Love and J.R. Comfort, *Phys. Rev. C* **29**, 2135 (1984).
 - [21] E.J. Stephenson, in *Nuclear Many-Body and Medium Effects in Nuclear Interactions and Reactions*, eds. K. Hatanaka *et al.*, (World Scientific, Singapore, 2003) p. 253.

FIG. 1. Measurements of the elastic scattering cross section and analyzing power for 197-MeV protons scattering from ^{10}B . The curves include no channel coupling (short-dash), self-coupling of the ground state (long-dash), and coupling to both the ground state and the 4^+ state (solid). All calculations use the DBHF effective interaction.

FIG. 2. Measurements of the elastic scattering cross section and analyzing power for 197-MeV protons scattering from ^{10}B . The curves are based on the free interaction (short-dash), BHF density dependence (long-dash), or DBHF density dependence (solid). All calculations include coupling to the ground state and the 4^+ state in ^{10}B .

FIG. 3. Measurements of the transverse electron scattering formfactor for the $3^+ \rightarrow 0^+$ transition in ^{10}B . The curve is a best fit using Woods-Saxon wells for the neutron and proton single particle states.

FIG. 4. Measurements of the cross section, analyzing power, induced polarization, and five polarization transfer coefficients for the $3^+ \rightarrow 0^+$ transition in $^{10}\text{B}(\text{p},\text{p}')$. The solid curve was made using a finite-range DWIA calculation. The remaining zero-range calculations used either no (short-dash) channel coupling or full (long-dash) channel coupling.

FIG. 5. Measurements of D_q , D_n , D_{ls} , and D_Q for the stretched isovector transitions in ^{16}O (solid), ^{28}Si (open), and ^{10}B (\times). The curves are finite-range DWIA calculations using the DBHF interaction for ^{16}O (solid), ^{28}Si (long-dash), and ^{10}B (short-dash).