Test of a density-dependent interaction using in-plane $^{28}Si(\vec{p},\vec{p}\,')^{28}Si$ polarization transfer measurements

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We report measurements of in-plane polarization transfer for nine natural-parity isoscalar transitions in the $^{28}Si(\vec{p},\vec{p}\,')^{28}Si$ reaction using a 198.5 MeV polarized proton beam. These measurements test in a new way the validity of an empirical effective NN interaction derived from cross section and analyzing power measurements for similar transitions. The test is successful, demonstrating the need to modify the free NN interaction in the nuclear medium.

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I. INTRODUCTION

At intermediate energies, one reasonably successful model of proton inelastic scattering involves the use of the distorted wave impulse approximation in which the driving term is a t matrix that reproduces the amplitudes for free nucleon-nucleon scattering. Agreement with inelastic scattering data is improved if the t matrix is allowed to vary with the local nuclear density in a manner suggested by a consideration of the Pauli blocking of the scattered nucleon and the binding of the nucleons in the nucleus. In this paper, we will examine the empirical effective interaction developed by Kelly and co-workers [1–8]. Their version of the effective interaction was adjusted empirically to reproduce proton inelastic scattering in a number of nuclei and for bombarding energies ranging from 100 to 500 MeV. Near 200 MeV, the data for their analysis consisted of angular distributions of cross section and analyzing power. Here, we report new measurements of polarization transfer for several natural parity transitions in $^{28}Si(\vec{p},\vec{p}\,')^{28}Si$ at 198.5 MeV. We will compare these data with the most recent version of the empirical interaction available at 200 MeV from Seifert *et al.* [8], who worked with measurements on ^{16}O and ^{40}Ca. His results do well for both of these nuclei using the same adjustment. We would thus expect that this interaction would work for other closed-shell nuclei such as ^{28}Si that lie in the same mass region. We will show that our measurements in fact agree well with this empirical interaction and support the use of these density-dependent modifications to the t matrix. We will present arguments why these measurements represent a test of this effective interaction that is sensitive to the spin dependence in the reaction calculation in a way that is different from the information available through cross section and analyzing power alone.

In choosing transitions for study, Kelly and co-workers concentrated on strong collective states in nuclei where $N=Z$. This has a number of advantages. Good electron scattering data are often available for these transitions, and these data were used to constrain the transition form factors. By investigating only $N=Z$ nuclei where charge symmetry can be assumed to be a good approximation, it was reasonable to set the neutron form factors to be identical to those for the proton. This circumvents the problem that the longitudinal electron scattering form factor is sensitive mainly to the proton part of the transition and could not help determine the neutron form factor. So this procedure constrains the structure model used in the (p,p') reaction calculations and, to the extent that a one-step reaction mechanism is appropriate, minimizes structure undertainties when trying to compare calculations with data. Within the first few 2^+ excited states of ^{28}Si, there are cases with distinctively different radial formfactors. Despite the fact that these reactions tend to occur mostly in the nuclear surface, these 2^+ states allow some sampling over a range of nuclear densities. It thus becomes possible to investigate to a limited extent the density dependence used in the empirical effective interaction.

There are a number of theoretical studies of the density dependence of the effective interaction [9–11] whose conclusions formed the basis for Kelly's work. Each study began with a "free" t matrix that reproduced $p+p$ and $p+n$ scattering. Then modifications were made that excluded some scattering states because they were filled in a Fermi gas model of nuclear matter. The Fermi momentum became the scaling parameter associated with the local nuclear matter density. Changes were also incorporated that included binding in the nuclear mean field. This led to an effective t matrix in which large density-dependent changes were seen for the isoscalar central and spin-orbit terms. These are also the terms that contribute most heavily in proton inelastic scattering to collective, natural-parity states. Studying inelastic pro-

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ton scattering to these states should serve as an excellent means of testing and refining these changes to the effective interaction.

Kelly and co-workers introduced a parametrization of the effective t matrix that added a phenomenological, density-dependent part to an existing free interaction. Their free interaction was chosen from the literature (for example, [9,12]); and each term (either real and imaginary, or associated with each spin-isospin operator) was allowed an independent normalization. The density-dependent parts were parametrized to reproduce the density-dependent changes found in the theoretical work, despite considerable differences from one study to another in the size of the effects [1,2]. Then, the parameters in this formulation were varied to best reproduce (p,p') cross section and analyzing power angular distributions. The normalization of each of the free interaction terms was found to be 65–80 % rather than one, a result not anticipated by the theoretical work. While its origins are not understood, this downward renormalization is helpful in understanding other cases, including a large body of intermediate-energy neutron total cross section measurements [13]. Once the free interaction was reduced, the parameters found for the density-dependent parts were similar to ones that match the theoretical predictions. In this sense, Kelly's results support the idea that density-dependent changes to the t matrix inside nuclei arise out of Pauli blocking and nuclear binding effects.

If these modifications to the t matrix indeed have general validity, it is important to test the limits of their application. One such test involves comparisons with a wider class of polarization observables. A full set of $(\vec{p},\vec{p}')$ polarization transfer measurements were made for the excited states of ^{16}O at 500 MeV [6]. While agreement was satisfactory within the experimental errors, these errors were typically rather large and perhaps some systematic problems with the empirical interaction were missed. We report data for a combination, D_c, of in-plane polarization transfer observables measured at $\theta_{\rm c.m.}=19.8°$ and 24.0° for the ^{28}Si$(\vec{p},\vec{p}')^{28}$Si reaction using 198.5 MeV polarized protons. The focal plane polarimeter of the K600 magnetic spectrometer was sensitive to the sideways component of the scattered proton polarization following spin precession in the K600 dipole magnets. This component gives rise to a vertical asymmetry at the polarimeter,

$$\epsilon_{\rm FPP}=pA_{\rm FPP}D_c \tag{1}$$

where $p=\sqrt{p_S^2+p_L^2}$ is the magnitude of the in-plane polarization at the silicon target, $A_{\rm FPP}$ if the effective analyzing power of the focal plane polarimeter, and D_c is the combination of polarization transfer coefficients given by

$$D_c=\frac{p_S}{p}(D_{SS'}\cos\alpha+D_{SL'}\sin\alpha) + \frac{p_L}{p}(D_{LS'}\cos\alpha+D_{LL'}\sin\alpha), \tag{2}$$

where α was the typical spin precession angle in the K600. The transfer coefficients, D_{ij}, refer to a coordinate system in which $\hat{L}$ lies along incident proton momentum, $\hat{N}$ is normal to the scattering plane, and $\hat{S}=\hat{N}\times\hat{L}$. The primed system refers to the outgoing proton polarization where $\hat{L}'$ lies along the scattered proton momentum. The transitions considered in this analysis excite the 0^+ state at 4.98 MeV, the 1^- state at 8.90 MeV, the 2^+ states at 1.78, 7.38, 7.42, 7.93, and 8.26 MeV, the 4^+ state at 4.62 MeV and the 5^- state at 9.70 MeV.

Subsequent sections of this paper will describe the details of the measurement and present the data in comparison with predictions based on the effective interaction. At the end of the presentation of the results, we will discuss the question of the uniqueness of this test by comparing the calculations with general relationships that apply to proton elastic scattering from a spin-0 target.

II. EXPERIMENT

In this section, we review the important details of our experiment. The ^{28}Si$(\vec{p},\vec{p}')^{28}$Si measurement was performed at the Indiana University Cyclotron Facility. The beam energy was determined by measuring the time for beam bursts to travel a known distance between two pickups in the beam line. The energy was 198.5 ± 0.1 MeV.

An atomic beam polarized ion source [14] provided a polarized proton beam with a typical polarization of 0.75. The direction of polarization was reversed every 20 s to cancel systematic errors. The difference in magnitude between the two polarization states from the atomic beam source was checked in a polarimeter based on $p+{}^4$He scattering located between the two IUCF cyclotrons. There the beam energy is about 15 MeV, and the analyzing power at $\theta_{\rm lab}=112°$ from a phase shift analysis [15] is 0.99. The difference was $p_+-|p_-|=0.010\pm0.006$, small enough to have a negligible impact on the measurements reported here.

The quantization axis of the polarized beam emerges from the cyclotrons in a direction that is nearly perpendicular to the scattering plane at the K600 spectrometer. It was rotated into the scattering plane using two superconducting solenoids located in the beam line after the main stage cyclotron. Each solenoid is followed by a beam line polarimeter consisting of a CD_2 target and a set of scintillators arranged to observe $p+d$ elastic scattering events. The polarimeters measure both vertical and sideways components of the beam polarization. A full description of the polarimeters including calibration information may be found in Wells *et al.* [16]. The two solenoids with their polarimeters are separated by a 45° bending magnet that makes it possible to observe and adjust all three components of the polarization incident on the K600 target. From earlier measurements with a third polarimeter, it had been determined that the sum of all subsequent horizontal bends between the last polarimeter and the K600 target was $130.4°\pm0.4°$ [17]. Using this value, the polarization on target during the experiment was determined to be $p_S=0.700\pm0.007$ and $p_L=-0.277\pm0.010$. The target consisted of natural silicon 5.7 ± 0.6 mg/cm^2 thick.

The K600 spectrometer angle was calibrated by observing the kinematic crossing near $\theta_{\rm lab}=18.2°$ of protons scattered from the ground state of ^{12}C and the 1.45-MeV state of ^{58}Ni. This angle determination had a accuracy of about 0.1°.

The entrance to the spectrometer was defined by a rounded rectangular slot with a solid angle of 0.618 ± 0.006 msr and a horizontal opening angle of about 1.0°.

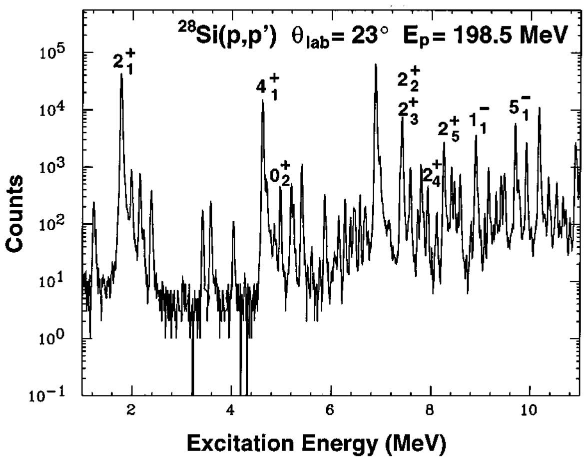

FIG. 1. The excitation energy spectrum for inelastic states in the $^{28}\mathrm{Si}(\vec{p},\vec{p}\,')^{28}\mathrm{Si}$ reaction at $\theta_{\mathrm{lab}}=23.0°$ ($\theta_{\mathrm{c.m.}}=24.0°$). The states used in this analysis are identified by spin and parity, and numbered sequentially with excitation energy.

The scattered protons were momentum analyzed using the K600 magnetic spectrometer. Correction coils compensated for kinematic shifts in the scattered proton energy across the entrance aperture. After adjusting the beam focusing and dispersion on target to match the spectrometer, an energy resolution of 50 keV (FWHM) was maintained throughout the experiment. A sample spectrum is shown in Fig. 1 where the states of interest are marked with their spin and parity, and numbered sequentially with increasing excitation energy.

The K600 focal plane detector system consists of two "vertical drift" wire chambers [18] for precision position measurements in the spectrometer bend plane, four "horizontal drift" wire chambers [19] for vertical position measurements, and a trigger scintillator that provides the reference for the wire chamber drift time. A second scintillator just before the polarimeter confirms the trigger signal and, with the first scintillator, identifies the scattered particles as protons. The beam current on target was regulated so that the electronic live time was 90% or better.

The sideways component of the scattered proton polarization was measured by a focal plane polarimeter located downstream of the focal plane detectors. The central momentum ray was nearly perpendicular to the analyzer target, which consisted of a 5.1-cm thick block of graphite with a density of about 1.78 g/cm^3 [20]. Following the analyzer were two x-y multi-wire proportional chambers [21] and two planes of plastic scintillator. When combined with information from the focal plane detectors, the polarimeter multiwire chambers provided scattering angle information as well as verification that the scattering occurred within the carbon analyzer target. The preliminary hit pattern from these chambers was used as a second level trigger to eliminate events with small analyzer scattering angles from the data stream. This made possible larger good event rates and better statistics in the measurement of the polarization transfer. A selection was made in replay to accept protons scattered between 5.5° and 22.0° in a vertical direction for use in measuring the sideways polarization component. The horizontal angle was unrestricted. The 0° direction was determined to $\pm 0.02°$ through a parametrization of the polarimeter geometry based on a large number of proton calibration events.

The two scintillators at the rear of the focal plane polarimeter are 0.6 and 7.6 cm thick. Based on the geometry of rays passing through the polarimeter, a calculation was made of the expected energy loss in these two scintillators (which did not stop the scattered protons), assuming that the scattering in the analyzer was elastic. If the calibrated pulse height in both scintillators agreed (to within ± 3.5 MeV for the thick scintillator), the event was retained for spin-dependent analysis. This cut permitted a separation of events that were close to elastic from either quasielastic or inelastic scattering processes. For protons near 200 MeV, this cut increases the polarimeter figure of merit.

The effective analyzing power of the focal plane polarimeter depends on the energy E' of the protons scattered from the K600 target. At scattered proton energies between 170 and 200 MeV, an earlier calibration with vertical ($\hat{N}'$) polarization resulted in the curve [22]

$$A_{\mathrm{FPP}}(\hat{N}')=0.461+4.15\times10^{-3}(E'-E_0)-2.07\times10^{-5}(E'-E_0)^2, \qquad (3)$$

where $E_0=184.03$ MeV. As a check, we also measured the analyzing power of the focal plane polarimeter for sideways-polarized beam at an energy of $E'=196.9$ MeV using a previously established procedure [23]. At this energy, we determined that $A_{\mathrm{FPP}}(\hat{S}')=0.483\pm0.014$, a value somewhat lower that that obtained from the normal component calibration curve given in Eq. (3). The selection of scattering angles should be the same both horizontally and vertically, since identical wire spacing and detector plane separation exists in both dimensions. The calibration change most likely arose from a deterioration of the resolution from the thin (0.6 cm) scintillator, whose light guides were found to be damaged following the experiment. To match our calibration point, which lies within the range of scattered proton energies observed in this experiment ($E'=188.3-197.6$ MeV), we scaled Eq. (3) by 0.945 and used these new values for our analysis. If we had assumed instead that the calibration curve joins smoothly to Eq. (3) near 170 MeV (where the scattered protons stop within the thick scintillator and the cut on energy deposited in the thin scintillator no longer matters), the differences would have been less than the error in our calibration point. This error was included in our final measurements.

Any interpretation of the sideways asymmetry measured at the focal plane polarimeter requires that we know the precession of the proton spin as it travels through the K600 spectrometer. This was determined from the bend angle of the proton trajectories and the relation $\alpha=\gamma(\mu-1)\theta_{\mathrm{bend}}$, where γ is the relativistic factor associated with the scattered proton energy E' and $\mu=2.793$ is the anomalous proton magnetic moment. The bend angle is the sum of the angle of the trajectories at the focal plane detectors (typically 34°) and the angle of the detectors with respect to the direction of the central ray at the K600 spectrometer entrance ($77.90°\pm0.05°$) [17]. The precession angle was about $\alpha=242.5°$ for the measurements reported here with variations from one transition to another no larger than $\pm0.6°$

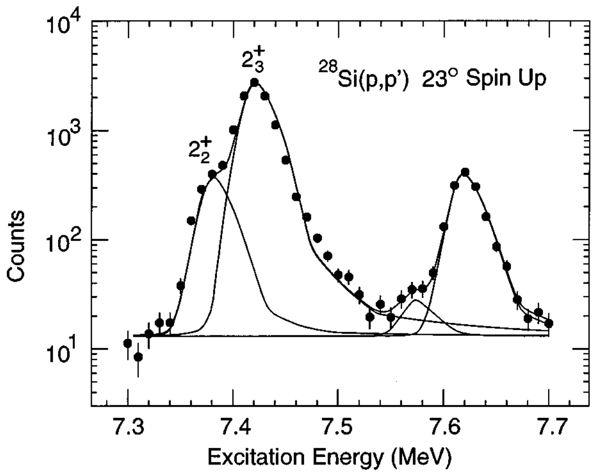

FIG. 2. A part of the excitation energy spectrum in the neighborhood of the 2_2^+ and 2_3^+ transitions. The curves represent a reproduction of the spectrum that was used to extract peak sums.

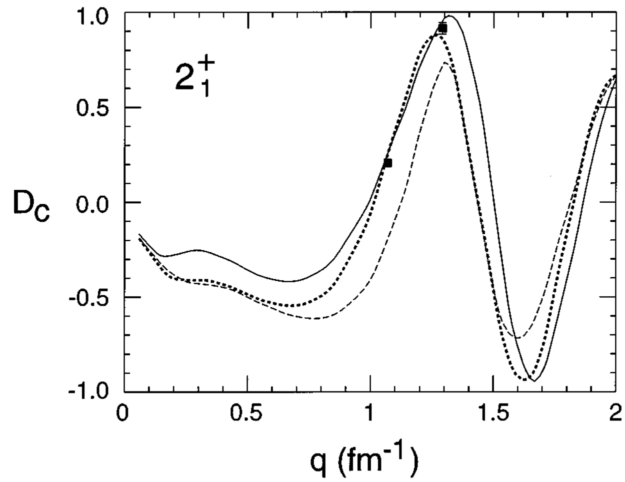

FIG. 3. Measurements of D_c for the 2_1^+ state in ^{28}Si. The solid curve is the empirical effective interaction of Seifert [8]. The long- and short-dashed curves are the free and density-dependent interactions of von Geramb [9].

from this value. This average value was also used in the theoretical calculation of D_c using Eq. (2).

Some of the transitions lie at excitation energies where the density of states is significant, and it was necessary to use peak-fitting techniques to determine the number of events for a given beam polarization direction and cut on focal plane polarimeter information. Figure 2 shows an example for the 2_2^+ and 2_3^+ states near 7.4 MeV excitation, two states that overlap. The peak shape reproduces the 2_1^+ state at 1.78 MeV. Over this narrow region of the spectrum, a linear background was assumed. Other peaks were added as needed based on known states in ^{28}Si [24] to allow the combined curve to reproduce the primary spectrum in the neighborhood of the peaks of interest. Widths, positions, and amplitudes were adjusted to minimize the differences with the original data. All spectra for a given scttering angle were analyzed together with only the peak amplitudes allowed to vary in a spin-dependent way. Contributions based on the quality of the fit were added to the statistical errors for the polarization transfer coefficient D_c. Also included were uncertainties in the analyzing power of the focal plane polarimeter and in the beam polarization.

III. RESULTS

We wanted to test the empirical effective interaction developed by Kelly against our measurements of D_c made at 198.5 MeV. The only other similar analysis of transitions in ^{28}Si to determine the empirical effective interaction is that reported by Chen [4] at 180 MeV. However, Chen's sign for the density dependence of the spin-orbit part is different from other analyses from this group, and indeed from Chen's analysis of transitions in ^{16}O (see Table II of [4]). Studies of other energies and targets have produced remarkably consistent parametrizations of the effective interaction. Since Chen's result on ^{28}Si may be suspect, we chose instead to use the empirical interaction from Seifert at 200 MeV [8]. His analysis included both ^{16}O and ^{40}Ca and thus spans the mass range of ^{28}Si. We chose his PH3 interaction (see Table II of [8]) as the best of those including both ^{16}O and ^{40}Ca. This interaction is based on the density-dependent interaction from von Geramb [9] that begins with the Paris potential for NN scattering [25]. Seifert's analysis is also close in bombarding energy to our experiment. In fact, calculations of D_c made with Chen's parameters (^{28}Si set of Table II [4]) are close to those we present here [26]. Agreement with Seifert's parameters is either the same or better for most states, but is worse for the 5_1^+ state at 9.70 MeV. The conclusions of this paper would be generally unaffected by the substitution of Chen's interaction.

From this point on, we wanted to follow as closely as possible the scheme used to make the calculations in the original analysis [4]. We obtained the linear expansion analysis (LEA) program from Kelly [27] for making the distorted wave impulse approximation calculations.

Optical potentials in the entrance and exit channels were based on the $t\rho$ folding model incorporated into LEA. The nuclear density for the folding calculation was taken from the ^{28}Si charge density by unfolding with the proton form factor [27]. The charge density followed the $3pF$ form of de Vries [28]. The use of a Fourier-Bessel expansion of the ground state density [28] made no significant difference in our results.

Transition form factors were taken from Table I of Chen [4]. The proton and neutron densities were assumed to be the same. Density-dependent modifications for the elastic and inelastic channels were related according to the prescription of Cheon [29].

The first question is whether these calculations reproduce the measurements of D_c. For the purposes of this part of the discussion, we will concentrate on the transition to the 2_1^+ state at 1.78 MeV shown in Fig. 3. The solid line is the calculation generated by LEA in the manner described above. It agrees well with the measurements at both angles, and the empirical effective interaction from Seifert [8] is successful.

To better appreciate this agreement, it is also important to ask to what extent the changes from the free interaction matter for D_c. The long-dashed line in Fig. 3 represents the free part of the von Geramb interaction only. Clearly this agree-

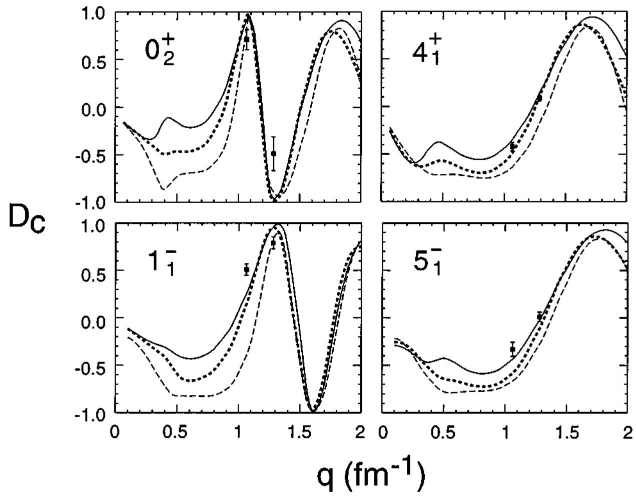

FIG. 4. Measurements of D_c for the 0_1^+, 1_1^-, 4_1^+, and 5_1^- states in ^{28}Si along with the calculations described in Fig. 3.

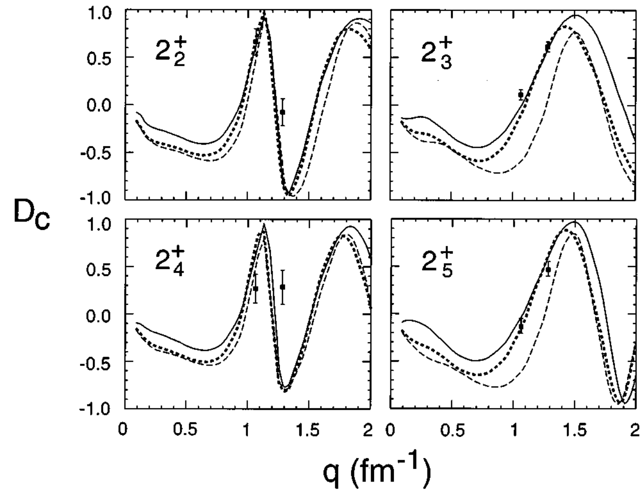

FIG. 5. Measurements of D_c for the 2_2^+, 2_3^+, 2_4^+, and 2_5^+ states in ^{28}Si along with the calculations described in Fig. 3.

ment is not good and changes are needed. The short-dashed line uses the original density-dependent interaction of von Geramb [9] without the changes made by Seifert [8]. At the momentum transfers where we have data, this calculation agrees well with both the data and Seifert's empirical interaction. At other angles, it disagrees with Seifert. We can understand this result by reviewing the momentum transfer dependence of the effective t matrix. In the region of our measurements, the real central term is passing through zero. The dominant contributions in this region therefore come from the imaginary central and real spin-orbit terms, for which the change from the free to the empirical interactions appears primarily as a renormalization. Because these two terms were renormalized downward by similar factors (0.771 and 0.853) and the empirical density dependence differs little from that proposed by von Geramb, the von Geramb and Seifert interactions give similar predictions for D_c at these angles. It is only when one moves to other values of momentum transfer that the more complicated changes to the real central term give rise to significant differences between these two curves.

In Fig. 4 we present the same calculations for states with different values of spin. Agreement with the 0_2^+ state at 4.98 MeV is qualitative, although the experimental errors in this case are large. The 1_1^- state at 8.90 MeV again shows qualitative agreement, and the same close overlap between the von Geramb and Seifert interactions near the measurements. These two transitions were not included in the original analysis of Chen because it was felt that the form factor data from (e,e') measurements were too poor to support the phenomenology. We may be seeing the effects of that in the lack of tight agreement for these two states.

Also in Fig. 4 are the 4_1^+ and 5_1^- states at 4.62 and 9.70 MeV that are used in Chen's analysis. Here the agreement with the empirical interaction is very good, and the precision of the measurements is also adequate. The close association of the von Geramb and Seifert interactions is not as precise, and the data for the 5_1^- state prefers the Seifert interaction. In both cases the free interaction does not provide an adequate description of the data.

Figure 5 shows the remaining 2^+ transitions. Of these, only the 2_3^+ was used in the original work of Chen [4], again because of concerns about the quality of the (e,e') form factor information. For this state the result is very similar to that for the 2_1^+. The agreement with the values of D_c is good, the free interaction does poorly, and the von Geramb and Seifert interactions overlap near the data. The results for the 2_5^+ are similar. The other two 2^+ states, however, have surface-peaked form factors (illustrated in Chen [4] and again not well known) and may serve to tell us about the quality of the density dependence in the interaction. The surface-peaking results in a diffraction pattern that, because of the larger reaction radius, oscillates more rapidly in momentum transfer. The measurements of D_c follow this shift. For the 2_4^+ state at 7.93 MeV, the measurements appear to be out of phase with the diffraction pattern, suggesting somewhat less surface peaking in the transition form factor than we have now. These two surface-peaked states show much less difference among the calculations because of the lower density. The poorer agreement with even the Seifert interaction would suggest that the problems lie not with the interaction but with the nuclear form factors used in the calculations for these two states. Qualitatively, agreement would improve if the form factors were larger at smaller radii so that oscillations in the angular distribution would be spread in angle.

Since the empirical effective interaction does well with these measurements of D_c when the form factor is well determined through electron scattering, it is important to understand whether something new has actually been tested and whether other polarization observables might provide additional constraints. Answering these questions requires that we understand the amount of independent information contained in these transitions. As a guide, we will use the effective interaction calculations just shown to work well.

Sets of polarization transfer measurements have been made for some 3^- and 5^- transition in ^{28}Si, ^{40}Ca, and ^{208}Pb near 500 MeV [6,30–32]. It is striking that these observables follow the relationships for the elastic scattering of spin-1/2 on spin-0 within their experimental errors (see es-

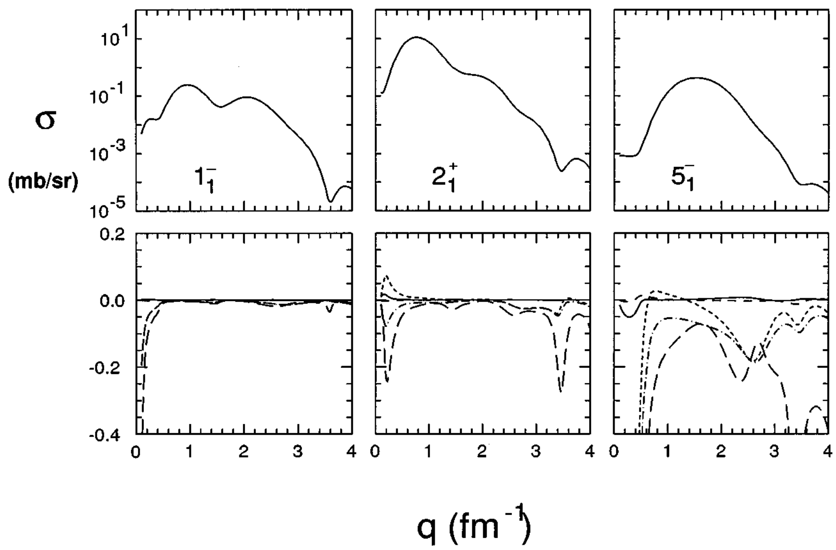

FIG. 6. Calculations of the cross section and the five elastic scattering relationships for the 1_1^-, 4_1^+, and 5_1^- transitions in the $^{28}Si(\vec{p},\vec{p}\,')^{28}Si$ reaction. The five relationships are show by a solid line (a), a dot-dashed line (b), a short-dashed line (c), a medium-dashed line (d), and a long-dashed line (e).

pecially [30]). If other low-lying natural-parity collective states also approximately follow these relationships at 200 MeV, then one could consider using the elastic scattering relationships as a model of the information content of these transitions in ^{28}Si.

Besides the differential cross section $\sigma(\theta)$, parity conservation and time-reversal invariance restricts the nonvanishing polarization observables for $(\vec{p},\vec{p}\,')$ to the analyzing power $A(\theta)$, the induced polarization $P(\theta)$, and the five polarization transfer coefficients, $D_{NN'}(\theta)$, $D_{SS'}(\theta)$, $D_{SL'}(\theta)$, $D_{LS'}(\theta)$, and $D_{LL'}(\theta)$. A more complete discussion may be found in Ohlsen [33]. In the case of spin-1/2 scattering from spin 0, there are only three independent amplitudes aside from an arbitrary phase, and thus there are five relationships among this set of observables. These connections may be written in terms of quantities that vanish:

$$\text{(a)} \quad P-A=0, \tag{4}$$

$$\text{(b)} \quad D_{NN'}-1=0, \tag{5}$$

$$\text{(c)} \quad D_{LL'}-D_{SS'}=0, \tag{6}$$

$$\text{(d)} \quad D_{LS'}+D_{SL'}=0, \tag{7}$$

$$\text{(e)} \quad D^2_{LL'}+D^2_{SL'}+A^2-1=0. \tag{8}$$

If these elastic scattering relationships apply as well to other natural-parity, collective states, then these relationships will be obeyed for the transitions studied here.

In Fig. 6, we have chosen three transitions (to the 1_1^-, 2_1^+, and 5_1^- states) for illustration. The top panels contain the differential cross section calculated by LEA for these transitions. The bottom panels show the predicted values for the five relationships (a)–(e) defined above. For the 1_1^- and 2_1^+ states, agreement with these relationships is good at angles where the cross section is relatively large. Where there are minima, there are substantial departures from zero. The data in this paper fall near 1.07 and 1.29 fm^{-1}, places where the agreement with the five relationships is good. The quality of the agreement is somewhat worse for the more highly excited 2^+ states (not shown), and becomes dramatically worse as the spin of the state increases. Shown in the last panel are the relationships for the 5_1^- state (the results for the 4_1^+ state are similar). Agreement with relationships (a) and (d) is still satisfactory. The quality of agreement for the other three cases has deteriorated substantially, with the worst being relationship (e). This would suggest that spin-flip processes, which would appear for example as a departure of $D_{NN'}$ from unity, are more important for larger spin states. Relationships (a) and (d) tend to be broken by nuclear current terms [34,35], and these do not appear to be large for collective, natural-parity transitions. At higher energies, it has been shown that the good agreement for relationships (a) and (d) is a consequence of adiabaticity, or the smallness of the excitation energy of the transition in relation to the projectile bombarding energy [30].

For the lower spin states, the generally good agreement with relationships (a)–(e) would suggest that elastic scattering of spin 1/2 from spin 0 is a good representation of the information content of these transitions. In elastic scattering, the amplitudes can be separated into non-spin-flip (g) and spin-flip (h) parts. The full amplitude (f) is expressed as $f=g+ih\sigma_y$ where σ_y is the Pauli spin matrix. Three independent observables can be written in terms of g and h as the unpolarized cross section, $\sigma=|g|^2+|h|^2$, and two polarized cross sections, $\sigma A=\mathrm{Re}\,g^*h$ and $\sigma Q=\mathrm{Im}\,g^*h$. To the extent that the physics content of these transitions in ^{28}Si resembles elastic proton scattering from a 0^+ target, then even inelastic scattering can be described in terms of three analogous observables. Two of these, σ and A, were used in the development of the empirical effective interaction. Because of the connections among in-plane observables in relationships (c)–(e), a measurement of any one of them or any combination carries the same information as does Q for elastic scattering. Thus the measurements of D_c that we present here represent new information about the scattering mechanism. That the model of the effective interaction successfully predicts D_c supports the idea that an effective, density-dependent interaction constrained by σ and A data captures the essential physics of these natural-parity inelastic scattering reactions. To the extent that the relationships (a)–(e) hold, there is no new information to be gleaned by measurements of a larger set of polarization observables. This conclusion is weaker for the higher spin states where the elastic scattering relationships appear to be less valid.

IV. CONCLUSIONS

We have measured a combination of the in-plane polarization transfer coefficients, D_c, for a number of isoscalar, natural-parity transitions in $^{28}Si(\vec{p},\vec{p}')^{28}Si$ at 198.5 MeV. These measurements test in a new way the validity of an empirical effective *NN* interaction derived from cross section and analyzing power measurements for similar transitions. The test is successful, indicating the utility of this interaction for collective, natural-parity transitions dominated by the central and spin-orbit terms in the effective interaction. Interactions that reproduce elastic *NN* scattering and are not modified for the nuclear medium do poorly in comparison to the values of D_c. At the momentum transfers reported here, we cannot distinguish between different forms of the density dependence.

In the process of studying these transitions, we have also learned that the reaction mechanism at 200 MeV for collective, natural-parity transitions seems largely constrained by the same relationships that hold among the elastic scattering observables. Thus, the spin information in these transitions is limited to about three independent amplitudes. While the data reported here do extend the test of this interaction into new territory, measurements of other polarization observables are not expected to generate independent, and therefore useful, information.

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