Relativistic predictions of exclusive ^{208}Pb$(\vec{p},2p)^{207}$Tl analyzing powers at an incident energy of 202 MeV

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(Received 12 December 2002; published 10 June 2003)

Within the framework of the relativistic distorted wave impulse approximation (DWIA), we investigate the sensitivity of the analyzing power—for exclusive proton knockout from the $3s_{1/2}$, $2d_{3/2}$, and $2d_{5/2}$ states in ^{208}Pb, at an incident laboratory kinetic energy of 202 MeV, and for coincident coplanar scattering angles $(28.0°, -54.6°)$—to different distorting optical potentials, finite-range (FR) versus zero-range (ZR) approximations to the DWIA, as well as medium-modified coupling constants and meson masses. Results are also compared to the nonrelativistic DWIA predictions based on the Schrödinger equation. Whereas the nonrelativistic model fails severely, both ZR and FR relativistic DWIA models provide an excellent description of the data. For the FR predictions, it is necessary to invoke a 20% reduction of σ-nucleon and ω-nucleon coupling constants as well as for σ-, ρ-, and ω-meson masses, by the nuclear medium. On the other hand, the ZR predictions suggest that the strong interaction in the nuclear medium is adequately represented by the free nucleon-nucleon interaction associated with the impulse approximation. We also demonstrate that, although the analyzing power is relatively insensitive to the use of different relativistic global optical potential parameter sets, the prominent oscillatory behavior of this observable is largely attributed to distortion of the scattering wave functions relative to their plane wave values.

DOI: 10.1103/PhysRevC.67.064604 PACS number(s): 24.10.Jv, 24.70.+s, 25.40.−h

I. INTRODUCTION

Recently, Neveling *et al.* [1] reported that both relativistic (Dirac equation) and nonrelativistic (Schrödinger equation) models, based on the distorted wave impulse approximation (DWIA), severely fail to reproduce exclusive $(\vec{p},2p)$ analyzing power data for proton knockout from the $3s_{1/2}$ and $2d_{3/2}$ states in ^{208}Pb, at an incident laboratory kinetic energy of 202 MeV, and for coincident coplanar scattering angles $(28.0°, -54.6°)$. For the prediction of energy-sharing cross sections, on the other hand, both dynamical models yield spectroscopic factors that are in good agreement with those extracted from $(e,e'p)$ studies.

Systematic corrections to the nonrelativistic model—such as different kinematic prescriptions for the nucleon-nucleon (*NN*) amplitudes, nonlocal corrections to the scattering wave functions, density-dependent modifications to the free *NN* scattering amplitudes, as well as the influence of different scattering and bound state potentials—fail to remedy the analyzing power dilemma; and hence, it is not clear how to improve existing Schrödinger-based analyses. However, such an exhaustive analysis has not yet been performed within the context of the relativistic DWIA and, hence, improvements to relativistic models could still prove to be important in resolving the problem. Capitalizing on the fact that spin is an intrinsically relativistic phenomenon, as well as the success of Dirac phenomenology in describing the properties of nuclear matter, nuclear structure [2], as well as proton-induced spin observables for elastic [3] and inelastic [4] scattering, we focus in this paper, on systematic corrections to the DWIA based on the Dirac equation as the underlying dynamical equation of motion. Another advantage of considering a relativistic approach is that both real and imaginary components of the spin-orbit potential, which are crucial for describing analyzing powers for *s*-state knockout in $(p,2p)$ reactions, are directly related to the Lorentz properties of mesons propagating the strong interaction. This microscopic connection does not exist within the framework of the nonrelativistic Schrödinger equation, where the spin-orbit interaction is usually introduced and adjusted merely to provide a good phenomenological description of elastic scattering data.

Motivated by the above considerations, we adopt a relativistic framework and study the sensitivity of exclusive analyzing powers to distorting optical potentials, finite-range (FR) versus zero-range (ZR) approximations to the DWIA, as well as nuclear medium modifications to the *NN* interaction. As already mentioned, we focus specifically on proton knockout from the $3s_{1/2}$, $2d_{3/2}$, and $2d_{5/2}$ states in ^{208}Pb at an incident laboratory kinetic energy of 202 MeV, and for coincident coplanar scattering angles $(28.0°, -54.6°)$. Predictions are naturally compared to the corresponding nonrelativistic results.

One of the most challenging problems in nuclear physics is to understand how the properties of the strong interaction are modified inside nuclear matter. Various theoretical models [2,5,6] predict the modification of coupling constants as well as nucleon and meson masses in normal nuclear matter. To date, there is no direct experimental evidence supporting these predictions. However, the exclusive nature of $(p,2p)$ reactions can be exploited to knock out protons from deep-

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to low-lying single-particle states in nuclei, thus yielding information on the density dependence of the *NN* interaction [7], and hence providing a stringent testing ground for theoretical models. In order to extract reliable information on *NN* medium modifications, it is important to understand the role of various approximations and model ingredients of the DWIA. In particular, an explanation for the failure of the relativistic predictions reported in Ref. [1] could possibly be attributed to the use of unreliable relativistic microscopic optical potentials for generating the scattering wave functions of the Dirac equation (see Sec. II). To assess the validity of this conjecture, we study the sensitivity of the analyzing power to different relativistic distorting potentials. Furthermore, current qualitative arguments suggest that since analyzing powers are ratios of polarized cross sections, distortion effects on the scattering wave functions effectively cancel, and hence simple plane wave models (ignoring nuclear distortion) should be appropriate for studying polarization phenomena [4,8]. This claim, however, has never been studied quantitatively, within the context of relativistic models, and hence we study this issue by comparing the distorted wave results of the analyzing power to corresponding plane wave predictions for zero scattering potentials. Our choice of a heavy target nucleus, ^{208}Pb, and a relatively low incident energy of 202 MeV, is ideally suited for maximizing the influence of distortion effects, while still maintaining the validity of the impulse approximation, and also avoiding complications associated with the inclusion of recoil corrections in the relativistic Dirac equation [9,10].

In principle, a FR approximation is more sophisticated than a ZR approximation to the DWIA. However, in practice, FR predictions are subject to numerical errors due to extensive computational procedures (compared to ZR calculations). In this paper, we study the sensitivity of the analyzing power to both FR and ZR approximations. The only existing study in this regard was done by Ikebata [11] for the knockout of $1d_{3/2}$ and $1d_{5/2}$ protons from ^{40}Ca at incident energies of 200 MeV and 300 MeV; no definite conclusion could be drawn as to which model gives a consistently better description of the data. For the case of a nucleus with a larger radius, such as ^{208}Pb, we expect more pronounced differences between ZR and FR predictions. For estimating the influence of nuclear-medium modifications of the *NN* interaction on the analyzing power, we adopt the Brown-Rho scaling conjecture [5] which attributes nuclear-medium modifications of coupling constants, as well as nucleon and meson masses, to partial restoration of chiral symmetry. An additional aim of this paper is to identify whether the analyzing power is an observable that demonstrates a preference for the Schrödinger or Dirac equation as the underlying dynamical equation.

II. RELATIVISTIC DISTORTED WAVE IMPULSE APPROXIMATION

Both ZR and FR approximations to the relativistic DWIA have been discussed in detail in Refs. [11,12], respectively. We briefly describe the main ingredients of these models. For notational purposes, we denote an exclusive $(p,2p)$ reaction by $A(a,a'b)C$, whereby an incident proton a knocks out a bound proton b from a specific orbital in the target nucleus A resulting in three particles in the final state, namely, the recoil residual nucleus C and two outgoing protons a' and b, which are detected in coincidence at coplanar laboratory scattering angles (on opposite sides of the incident beam) $\theta_{a'}$ and θ_b, respectively. All kinematic quantities are completely determined by specifying the rest masses m_i of particles [where $i=(a,\ A,\ a',\ b,\ C)$], the laboratory kinetic energy T_a of the incident particle a, the laboratory kinetic energy $T_{a'}$ of the scattered particle a', the laboratory scattering angles $\theta_{a'}$ and θ_b, and also the binding energy of the proton that is to be knocked out of the target nucleus.

For a FR approximation to the DWIA, the relativistic distorted wave transition matrix element is given by

$$\begin{aligned} T_{LJM_J}(s_a,s_{a'},s_b) = \int d\vec{r}d\vec{r}'[\overline{\psi}^{(-)}(\vec{r},\vec{k}_{a'C},s_{a'}) \\ \otimes \overline{\psi}^{(-)}(\vec{r}',\vec{k}_{bC},s_b)]\hat{t}_{NN}(|\vec{r}-\vec{r}'|) \\ \times[\psi^{(+)}(\vec{r},\vec{k}_{aA},s_a)\otimes\phi^{B}_{LJM_J}(\vec{r}')], \quad (1) \end{aligned}$$

where $\otimes$ denotes the Kronecker product. The four-component scattering wave functions $\psi(\vec{r},\vec{k}_i,s_i)$ are solutions to the fixed-energy Dirac equation with spherical scalar and timelike vector nuclear optical potentials: $\psi^{(+)}(\vec{r},\vec{k}_{aA},s_a)$ is the relativistic scattering wave function of the incident particle a, with outgoing boundary conditions [indicated by the superscript $(+)$], where $\vec{k}_{aA}$ is the momentum of particle a in the $(a+A)$ center-of-mass system and s_a is the spin projection of particle a with respect to $\vec{k}_{aA}$ as the $\hat{z}$-quantization axis. $\overline{\psi}^{(-)}(\vec{r},\vec{k}_{jC},s_j)$ is the adjoint relativistic scattering wave function for particle j [$j=(a',b)$] with incoming boundary conditions [indicated by the superscript $(-)$], where $\vec{k}_{jC}$ is the momentum of particle j in the $(j+C)$ center-of-mass system, and s_j is the spin projection of particle j with respect to $\vec{k}_{jC}$ as the $\hat{z}$-quantization axis. The bound state proton wave function $\phi^{B}_{LJM_J}(\vec{r})$ with single-particle quantum numbers L, J, and M_J, is obtained via self-consistent solution to the Dirac-Hartree field equations of quantum hadrodynamics [13]. In addition, we adopt the impulse approximation which assumes that the form of the *NN* scattering matrix in the nuclear medium is the same as that for free *NN* scattering: the antisymmetrized *NN* scattering matrix, $\hat{t}_{NN}(|\vec{r}-\vec{r}'|)$, is parametrized in terms of five Lorentz invariants (scalar, pseudoscalar, vector, axial-vector, and tensor). In principle, the *NN* t matrix can be obtained via solution of the Bethe-Salpeter equation, where the on-shell *NN* amplitudes are matrix elements of this t matrix. However, the complexity of this approach gives limited physical insight into the resulting amplitudes. An alternative approach is to fit the amplitudes directly with some phenomenological form, rather than generating the t matrix from a microscopic interaction. Although the microscopic approach is certainly more fundamental, the advantage of phenomenological fits lies in their simple analytical form, which allows them to be conveniently incorporated in calculations requiring the *NN t* matrix as input. The *NN t* matrix employed in this paper is based on the relativistic meson-exchange model described in Ref. [14], the so-called relativistic Horowitz-Love-Franey (HLF) model, whereby the direct and exchange contributions to the amplitudes are parametrized separately in terms of a number of Yukawa-type meson exchanges in first-order Born approximation. The parameters of this interaction, namely, the meson masses, meson-nucleon coupling constants, and the cutoff parameters, have been adjusted to reproduce the free *NN* elastic scattering observables.

Adopting a much simpler ZR approximation, namely,

$$\hat{t}_{NN}(|\vec{r}-\vec{r}\,'|)=\hat{t}_{NN}(T_{\rm eff}^{\rm lab},\theta_{\rm eff}^{\rm c.m.})\,\delta(\vec{r}-\vec{r}\,'), \tag{2}$$

the relativistic distorted wave transition matrix element in Eq. (1) reduces to

$$\begin{aligned} T_{LJM_J}(s_a,s_{a'},s_b)=\int d\vec{r}[\overline{\psi}^{(-)}(\vec{r},\vec{k}_{a'C},s_{a'}) \\ \otimes\overline{\psi}^{(-)}(\vec{r},\vec{k}_{bC},s_b)]\hat{t}_{NN}(T_{\rm eff}^{\rm lab},\theta_{\rm eff}^{\rm c.m.}) \\ \times[\psi^{(+)}(\vec{r},\vec{k}_{aA},s_a)\otimes\phi^{B}_{LJM_J}(\vec{r})], \end{aligned} \tag{3}$$

where $T_{\rm eff}^{\rm lab}$ and $\theta_{\rm eff}^{\rm c.m.}$ represent the effective two-body laboratory kinetic energy and effective center-of-mass scattering angles, respectively.

As already mentioned, a FR approximation to the DWIA is inherently more sophisticated than a ZR approximation. However, in practice, the numerical evaluation of the six-dimensional FR transition matrix elements, given by Eq. (1), is nontrivial and subject to numerical uncertainties. On the other hand, for the ZR approximation, the three-dimensional integrand given by Eq. (3) ensures numerical stability and rapid convergence (and hence faster computational time). Another advantage of the ZR approximation is that one can directly employ experimental *NN* scattering amplitudes, rather than rely on a relativistic meson-exchange model; and hence, one is insensitive to uncertainties associated with interpolations and/or extrapolations of the limited meson-exchange parameter sets. In this paper, we compare FR and ZR predictions of the analyzing power.

The scalar and vector scattering potentials employed in the relativistic FR-DWIA calculations reported in Ref. [1] are microscopic in the sense that they are generated by folding the *NN t* matrix, based on the HLF model, with the appropriate Lorentz densities via the $t\rho$ approximation. An attractive feature of the $t\rho$ approximation is self-consistency, that is, the HLF model is used for generating both scattering amplitudes and optical potentials. However, for the kinematic region of interest to this paper, we consider it inappropriate to employ microscopic $t\rho$ optical potentials, the reason being that HLF parameter sets only exist at 135 MeV and 200 MeV, whereas optical potentials for the outgoing protons are required at energies ranging between 24 and 170 MeV. Thus, enforcing self-consistency would involve large, and relatively crude, interpolations/extrapolations, leading to inaccurate predictions of the analyzing power, as evidenced in Ref. [1]. Furthermore, the validity of the impulse approximation, to generate microscopic $t\rho$ optical potentials at energies lower than 100 MeV, is questionable. Hence, in this paper we consider only global Dirac optical potentials, as opposed to microscopic $t\rho$ optical potentials, for obtaining the scattering wave functions of the Dirac equation.

For studying medium effects on the *NN* interaction, we make use of the scaling relations proposed by Brown and Rho [5], and also applied by Krein *et al.* [15] to $(p,2p)$ reactions, namely,

$$\frac{m_\sigma^*}{m_\sigma}\approx\frac{m_\rho^*}{m_\rho}\approx\frac{m_\omega^*}{m_\omega}\equiv\xi, \tag{4}$$

$$\frac{g_{\sigma N}^*}{g_{\sigma N}}\approx\frac{g_{\omega N}^*}{g_{\omega N}}\equiv\chi, \tag{5}$$

where the medium-modified and free meson masses are denoted by m_i^* and m_i, with $i\in(\sigma,\rho,\omega)$, respectively. Meson-nucleon coupling constants, with and without nuclear-medium modifications, are denoted by g_{jN}^* and g_{jN}, where $j\in(\sigma,\omega)$, respectively.

The spin observable of interest, the analyzing power A_y, is defined as

$$A_y=\frac{{\rm Tr}(T\sigma_y T^\dagger)}{{\rm Tr}(TT^\dagger)}, \tag{6}$$

where σ_y is the usual Pauli matrix, and the 2×2 matrix T is given by

$$T=\begin{pmatrix} T_{LJ}^{s_a=+1/2,s_{a'}=+1/2} & T_{LJ}^{s_a=-1/2,s_{a'}=+1/2} \\ T_{LJ}^{s_a=+1/2,s_{a'}=-1/2} & T_{LJ}^{s_a=-1/2,s_{a'}=-1/2} \end{pmatrix}, \tag{7}$$

where $s_a=\pm\frac{1}{2}$ and $s_{a'}=\pm\frac{1}{2}$ refer to the spin projections of particles a and a' along the $\hat{k}_{aA}=\hat{z}$ and $\hat{k}_{a'C}=\hat{z}'$ quantization axes, respectively, and the $\hat{y}$ axis is defined by $\hat{k}_{aA}\times\hat{k}_{a'C}$. The matrix elements $T_{LJ}^{s_a,s_{a'}}$ are related to the relativistic $(p,2p)$ ZR-DWIA and FR-DWIA transition matrix elements $T_{LJM_J}(s_a,s_{a'},s_b)$, defined by Eqs. (1) and (3), respectively, via

$$T_{LJ}^{s_a,s_{a'}}=\sum_{M_J,s_b}T_{LJM_J}(s_a,s_{a'},s_b). \tag{8}$$

III. RESULTS

In this section we investigate the sensitivity of the analyzing power—for the knockout of protons from the $3s_{1/2}$, $2d_{3/2}$, and $2d_{5/2}$ states in ^{208}Pb, at an incident energy of 202 MeV, and for coincident coplanar scattering angles (28.0°, −54.6°)—to distorting optical potentials, FR versus ZR approximations to the relativistic DWIA, as well as to medium-modified coupling constants and meson masses. We also compare our relativistic results to nonrelativistic DWIA predictions. Unless otherwise specified, all DWIA predictions are based on the energy-dependent mass-independent global

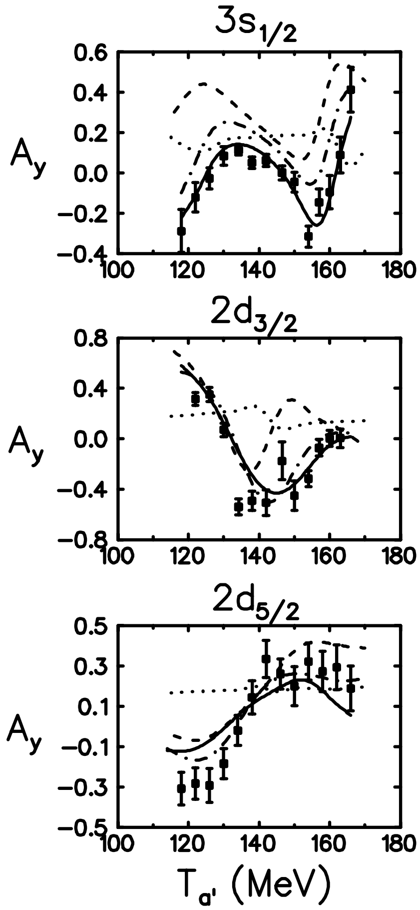

FIG. 1. Analyzing powers plotted as a function of the kinetic energy $T_{a'}$ for the knockout of protons from the $3s_{1/2}$, $2d_{3/2}$, and $2d_{5/2}$ states in ^{208}Pb, at an incident energy of 202 MeV, and for coincident coplanar scattering angles (28.0°, −54.6°). The different line types represent the following calculations: relativistic ZR-DWIA (solid line), relativistic plane wave (dotted line), nonrelativistic DWIA (dashed line), and relativistic FR-DWIA (dot-dashed line): all calculations exclude medium-modified coupling constants and meson masses. The data are from Ref. [1].

Dirac optical potential parameter set which has been constrained by ^{208}Pb(p,p) elastic scattering data for incident proton energies between 21 MeV and 1040 MeV; that is, we consider the parameter set "EDAI fit" for ^{208}Pb in Ref. [16].

First, we display the influence of relativistic nuclear distortion effects by comparing relativistic ZR-DWIA predictions to corresponding plane wave predictions (with zero scattering potentials) for knockout from all three states: in Fig. 1, the solid line indicates the relativistic distorted wave result and the dotted line represents the relativistic plane wave result. We see that the prominent oscillatory structure of the analyzing powers is mostly attributed to distortions of the scattering wave functions. This clearly illustrates the importance of nuclear distortion on the analyzing power, thus refuting, for the first time, qualitative claims that spin observables (being ratios of cross sections) are insensitive to nuclear distortion effects. In addition, we have also investigated the sensitivity of the analyzing powers to a variety of different global Dirac optical potential parameter sets [16]. Although these results are not displayed, we found that the analyzing powers are relatively insensitive to different global optical potentials, with differences between parameter sets being smaller than the experimental statistical error.

For the reaction kinematics of interest, *NN* amplitudes need to be evaluated at $T_{\mathrm{eff}}^{\mathrm{lab}} \approx 180$ MeV and $\theta_{\mathrm{eff}}^{\mathrm{c.m.}} \approx 60°$ (where c.m. is center of mass), but the closest HLF parameter sets exist at 135 MeV and 200 MeV. To improve the accuracy of our FR predictions, we have generated a new HLF parameter set at 180 MeV by fitting to the experimental *NN* amplitudes [14]. We have checked the validity of the HLF parameter set by comparing ZR calculations based on the HLF model to corresponding calculations based directly on the experimental amplitudes: the predicted $(p,2p)$ analyzing powers are identical.

Next, we compare relativistic FR to relativistic ZR predictions, excluding medium modifications to the *NN* interaction. In Fig. 1, we see that the ZR prediction (solid line) almost perfectly describes the data for knockout from the $3s_{1/2}$ and $2d_{3/2}$ states: recall that previous relativistic and nonrelativistic models fail to reproduce these data [1]. For the $3s_{1/2}$ state, the relativistic FR result (dot-dashed line) is consistently shifted above the data. Nevertheless, the relativistic FR prediction still provides a qualitative description of the data. For knockout from the $2d_{3/2}$ and $2d_{5/2}$ states, both relativistic ZR and FR models describe the data reasonably well.

We also compare our relativistic calculations to nonrelativistic (dashed line in Fig. 1) DWIA predictions, excluding medium modifications of the *NN* interaction recently reported in Ref. [1]: the nonrelativistic Schrödinger-based calculations are based on the computer code THREEDEE by Chant and Roos [17]. With the exception of the $2d_{5/2}$, it is clearly seen that the relativistic ZR (solid line) and FR (dot-dashed line) predictions in Fig. 1 are consistently superior compared to the corresponding nonrelativistic calculations. This suggests that the Dirac equation is the most appropriate dynamical equation for the description of analyzing powers. The latter statement is confirmed by similar claims for inclusive quasielastic proton-nucleus scattering [4,18] as well as elastic proton-nucleus scattering [3]. Our results for exclusive proton knockout provide one more compelling argument for using relativistic dynamics for the description of polarization phenomena in nuclear physics. Note, however, that for the knockout of protons from the $1p_{1/2}$ and $1p_{3/2}$ states in ^{16}O and the $1d_{3/2}$ and $1d_{5/2}$ states in ^{40}Ca at 200 MeV, both relativistic and nonrelativistic DWIA models describe analyzing power data equally well [12], and there is no preference to relativistic dynamics.

Although the $(p,2p)$ reaction of interest is mainly surface peaked, radial localization (radial contribution of the reaction to DWIA cross section) arguments [1] suggest that *s*-state knockout exhibits a larger contribution from the nuclear interior than the *d* states, and, hence, *s*-state knockout is more susceptible to nuclear medium modifications of the *NN* interaction. Thus, the inclusion of nuclear medium effects offers the possibility to improve the relativistic FR-DWIA prediction of the $3s_{1/2}$ analyzing power. We now study the sensitivity of the analyzing power to values of $\xi = \chi$ [see

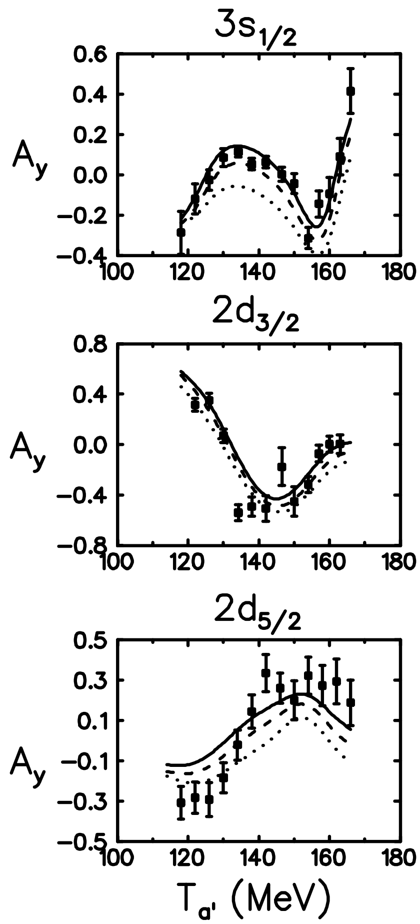

FIG. 2. Analyzing powers plotted as a function of the kinetic energy $T_{a'}$ for the knockout of protons from the $3s_{1/2}$, $2d_{3/2}$, and $2d_{5/2}$ states in ^{208}Pb, at an incident energy of 202 MeV, and for coincident coplanar scattering angles $(28.0°, -54.6°)$. The different line types represent the following calculations: relativistic ZR-DWIA excluding medium-modified coupling constants and meson masses (solid line), relativistic ZR-DWIA with a 10% reduction of the medium-modified coupling constants and meson masses (dashed line), and relativistic ZR-DWIA with a 20% reduction of the medium-modified coupling constants and meson masses (dotted line). The data are from Ref. [1].

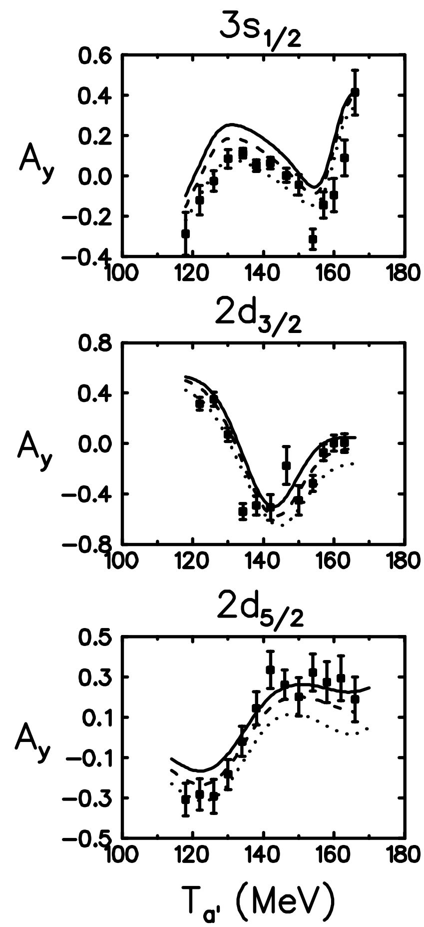

FIG. 3. Analyzing powers plotted as a function of the kinetic energy $T_{a'}$ for the knockout of protons from the $3s_{1/2}$, $2d_{3/2}$, and $2d_{5/2}$ states in ^{208}Pb, at an incident energy of 202 MeV, and for coincident coplanar scattering angles $(28.0°, -54.6°)$. The different line types represent the following calculations: relativistic FR-DWIA excluding medium-modified coupling constants and meson masses (solid line), relativistic FR-DWIA with a 10% reduction of the medium-modified coupling constants and meson masses (dashed line), and relativistic FR-DWIA with a 20% reduction of the medium-modified coupling constants and meson masses (dotted line). The data are from Ref. [1].

Eqs. (4) and (5)] less than unity for both relativistic ZR and relativistic FR approximations; that is, we assume that the effect of the nuclear medium is to reduce values of the masses and coupling constants of certain mesons relative to their corresponding free values. Note that, in principle, the coupling constants and meson masses are independent quantities, and hence there is no fundamental reason to set $\xi = \chi$. The latter equality is only assumed for simplicity, so as to get a feeling for the sensitivity of observables to changes in the relevant coupling constants and meson masses. In Fig. 2, we display relativistic ZR-DWIA results for $\xi = \chi \in (0.9, 0.8)$ corresponding to reductions of the meson masses and coupling constants by 10% (dashed line) and 20% (dotted line), respectively; results excluding medium modifications are indicated by the solid line. The choice of values for ξ and χ is motivated by the fact that the proton-knockout reactions of interest are mainly localized in the nuclear surface and, hence, the nuclear medium modifications are expected to play a relatively minor role. The corresponding relativistic FR-DWIA predictions are shown in Fig. 3.

Although not displayed, we have already established that values of $\xi = \chi < 0.8$ fail to reproduce the analyzing powers for both ZR and FR approximations. For the FR calculations, we see that a reduction of meson masses and coupling constants by between 10% (dashed line) and 20% (dotted line) consistently improves the predictions for knockout from all states: the agreement with the $3s_{1/2}$ analyzing power is particularly impressive. Similar qualitative behavior was observed for the nonrelativistic distorted wave predictions reported in Ref. [1], where the inclusion of empirical density-dependent correction to the analyzing power shifts predictions closer to the data. In addition, by analyzing the "effective polarization" for proton knockout from ^{16}O and ^{40}Ca at 200 MeV within the framework of the nonrelativistic

DWIA, Krein *et al.* [15] also reported on similar evidence for the modification of meson masses and coupling constants by the nuclear medium. On the other hand, relativistic ZR predictions without medium effects give a better description of the data: a 20% reduction fails to reproduce the $3s_{1/2}$ analyzing power. In general, one can conclude that both relativistic FR predictions with medium effects and relativistic ZR calculations excluding medium effects give a satisfactory description of the data. In order to make more definite statements on the importance of nuclear-medium effects for $(p,2p)$ reactions, one needs to measure and interpret complete sets of spin observables, as opposed to only the analyzing power: this will be studied in a future paper. Also, one needs to consider the knockout of protons from deeper lying states in ^{208}Pb, where the contribution from the nuclear interior is more substantial.

IV. SUMMARY AND CONCLUSIONS

In this work we have focused on a relativistic distorted wave description for exclusive proton knockout from the $3s_{1/2}$, $2d_{3/2}$, and $2d_{5/2}$ states in ^{208}Pb, at an incident energy of 202 MeV, and for coincident coplanar scattering angles $(28.0°, -54.6°)$. Previous relativistic and nonrelativistic models fail to describe the analyzing power for $3s_{1/2}$- and $2d_{3/2}$- knockout [1]. Exhaustive corrections to the nonrelativistic model fail to resolve the dilemma. On the other hand, this is the first time that such systematic analyses have now been performed within the context of the relativistic DWIA. We have identified two possible reasons for the failure of the relativistic FR-DWIA predictions reported in Ref. [1]. First of all, for the reaction kinematics of interest, the microscopic optical potentials generated via the $t\rho$ approach were not refined enough. Second, the influence of density-dependent corrections to the *NN* interaction was previously not considered, and thus previous relativistic FR-DWIA predictions [1] implicitly underestimated an important ingredient of the theoretical treatment.

These shortcomings have been addressed by employing appropriate global Dirac optical potentials and also by studying the role of medium-modified meson masses and coupling constants, constrained by the Brown-Rho scaling conjecture, for both relativistic ZR- and FR-DWIA calculations of the analyzing power. We also compare relativistic predictions to the nonrelativistic results quoted in Ref. [1].

In this paper we have demonstrated the superiority of the relativistic Dirac equation, as compared to the nonrelativistic Schrödinger equation, for the description of the exclusive $(\vec{p},2p)$ analyzing powers, for proton knockout from ^{208}Pb at 200 MeV, within the context of the DWIA. It is essential to check the consistency of the latter claim for the knockout of protons from ^{208}Pb at higher energies. Indeed, such experiments are being planned at the Research Center for Nuclear Physics in Osaka, Japan. Both relativistic ZR and FR approximations to the DWIA provide an excellent description of the analyzing power data. On one hand, the relativistic ZR predictions suggest that the scattering matrix for *NN* scattering in the nuclear medium is adequately represented by the corresponding matrix for free *NN* scattering and, hence it is not necessary to consider nuclear-medium modifications to the *NN* interaction. On the other hand, the relativistic FR results suggest that a 10–20 % reduction of meson-coupling constants and meson masses by the nuclear medium is essential for providing a consistent description of the $3s_{1/2}$, $2d_{3/2}$, and $2d_{5/2}$ analyzing powers. In order to extract more conclusive information regarding the influence of the nuclear medium on the properties of the strong interaction, it is necessary to study complete sets of polarization transfer observables for the exclusive knockout of protons from deeper-lying states in a variety of nuclei.

We have also established that the analyzing power is relatively insensitive to different global Dirac optical potential parameter sets. In addition, by comparing relativistic ZR-DWIA predictions to corresponding plane wave predictions (zero scattering potentials), we have demonstrated the importance of distorting potentials for describing the oscillatory behavior of the analyzing powers; thus refuting qualitative arguments that spin observables are insensitive to nuclear distortion effects.

ACKNOWLEDGMENTS

G.C.H. acknowledges financial support from the Japanese Ministry of Education, Science and Technology for research conducted at the Research Center for Nuclear Physics, Osaka University, Osaka, Japan. This material is based upon work supported by the National Research Foundation under Grants Nos. GUN 2058507, 2053786, and 2053773.

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