Sensitivity of $p_{\text{pol}} + A_{\text{pol}}$ Elastic Spin Observables to Relativistic Aspects of Nuclear Structure

L. Ray, G. W. Hoffmann, and M. L. Barlett
Department of Physics, University of Texas, Austin, Texas 78712

J. J. Jarmer
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

B. C. Clark and R. E. Kozack
Department of Physics, Ohio State University, Columbus, Ohio 43210

R. L. Mercer
IBM Watson Research Laboratories, Yorktown Heights, New York 10598

G. R. Burleson
Department of Physics, New Mexico State University, Las Cruces, New Mexico 88003

and

S. Hama
Department of Physics, Florida State University, Tallahassee, Florida 32306
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We present results of calculations which suggest that several of the spin observables for elastic scattering of 500-MeV polarized protons from a polarized ^{13}C target are sensitive to relativistic aspects of nuclear structure.

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Over the last few years our theoretical understanding of the intermediate-energy proton+nucleus (pA) elastic-scattering process has improved considerably as a result of Dirac phenomenology[1] and the development of the relativistic impulse approximation (RIA)[2]; the recently obtained quantitative agreement between experimental and theoretical analyzing power (A_y) and spin-rotation (Q) observables stands in marked contrast to the previous failure of nonrelativistic (NR) multiple-scattering approaches.[3]

A characteristic feature of the relativistic models is the large scalar and timelike vector potentials of the pA interaction. One consequence of such potentials is that virtual, negative-energy *projectile* states contribute significantly to the pA scattering process[4,5]; it is their inclusion in the relativistic models that leads, in large part, to the good agreement with A_y and Q data at 500 MeV.

Relativistic nuclear-structure models[6-8] also contain strong scalar (U_S) and vector (U_V) binding potentials. In relativistic Hartree models[8] these potentials enhance the strength of the lower component of the nuclear wave function compared to that in the weak-binding or NR limit (i.e., $U_S = U_V = 0$). Proof of the existence or nonexistence of relativistic corrections to nuclear wave functions is not easy. Theoretically, the lower-component enhancement, predicted in relativistic Hartree models,[8] may be quenched when exchange, correlation, three-vector currents (for nonspherical targets),[9] and meson-loop corrections are included.[10] Experimentally, magnetic elastic electron scattering from odd targets,[11] $^{12}\text{C}(e,e')(12.7\ \text{MeV}\ 1^+\ T=0)$ magnetic transition form factors,[12] and the $P - A_y$ spin difference for $^{12}\text{C}(p,p')(12.7\ \text{MeV}\ 1^+\ T=0)$[13] may provide some insight concerning relativistic effects in the target wave function. The results of these investigations are, so far, indecisive.

In this Letter we propose an alternative method. We show that several of the calculated spin observables in intermediate-energy *pA elastic scattering from polarized odd nuclear targets* are sensitive (in both shape and magnitude) to realistic enhancements of the lower component of the target wave function. It is important to address this sensitivity since polarized nuclear targets are currently being developed for such experiments.[14-16] The choice of a $^{13}\text{C}_{\text{pol}}$ target in this study was motivated by previous developments in polarized-target technology.[14,15]

The 500-MeV $p_{\text{pol}} + {}^{13}\text{C}_{\text{pol}}$ elastic-scattering observables were calculated with the RIA optical potential[2,5] given by

$$U^{\text{opt}}_{\mu,\mu'} = \sum_{i=1}^{A} \langle 0_{\mu'} | t_i | 0_{\mu} \rangle, \tag{1}$$

where t_i is the nucleon-nucleon (NN) interaction operator,[2]

$$t_i = F_S + F_P \gamma_0^5 \gamma_1^5 + F_V \gamma_0^\mu \gamma_{1\mu} + F_A \gamma_0^5 \gamma_0^\mu \gamma_1^5 \gamma_{1\mu} + F_T \sigma_0^{\mu\nu} \sigma_{1\mu\nu}. \tag{2}$$

Projectile and target nucleon are denoted by (0,1), respectively. In Eq. (1) the quantum numbers μ and μ' refer to the initial and final total angular momentum projection for the target (equal to $\pm\frac{1}{2}$ for ^{13}C), and $|0_\mu\rangle$ is the antisymmetrized target wave function given by

$$|0_\mu\rangle = (1/\sqrt{A!}) \mathrm{Det} \prod_{i=1}^{A} u_{\{\alpha\}}(\mathbf{r}_i), \tag{3a}$$

where $u_{\{\alpha\}}$ is expressed as

$$u_{nlj\mu}(\mathbf{r}) = \begin{bmatrix} \phi_{nlj}(r) \\ -i\boldsymbol{\sigma}\cdot\hat{\mathbf{r}}\lambda_{nlj}(r) \end{bmatrix} Y_{lj}^{\mu}(\hat{\mathbf{r}}). \tag{3b}$$

With this independent-particle form for the target wave function, the optical potential can be separated into a core part ($1s_{1/2}$ and $1p_{3/2}$ orbitals) plus a contribution from the $1p_{1/2}$ neutron. More sophisticated relativistic target wave functions are currently unavailable but can be readily included in Eq. (1) in the future.

At this time, a full numerical solution of the relativistic proton+odd nucleus elastic-scattering problem is not available.[17] Therefore, the $p+{}^{13}$C elastic-scattering amplitude,

$$f_{m_s'\mu';m_s\mu}(\mathbf{k},\mathbf{k}') = f^{\mathrm{core}}_{m_s';m_s}(\mathbf{k},\mathbf{k}')\delta_{\mu\mu'} + f^{\mathrm{sp}}_{m_s'\mu';m_s\mu}(\mathbf{k},\mathbf{k}'), \tag{4a}$$

was approximated by the assumption of the RIA $p+{}^{12}$C scattering amplitude for f^{core} (as obtained in Ref. 5) and use of the relativistic plane-wave Born approximation for f^{sp}, where

$$f^{\mathrm{sp}}_{m_s'\mu';m_s\mu}(\mathbf{k},\mathbf{k}') \simeq -[m/2\pi(\hbar c)^2]\bar{u}_{s'}(\mathbf{k}') \int d^3r\, e^{-i\mathbf{k}'\cdot\mathbf{r}} U^{\mathrm{sp}}_{\mu,\mu'}(\mathbf{r}) e^{i\mathbf{k}\cdot\mathbf{r}} u_s(\mathbf{k}). \tag{4b}$$

U^{sp} is the odd-nucleon portion of the RIA optical potential, and $u_s(\mathbf{k})$ denotes a projectile spinor. Distortion effects and virtual projectile pair-production processes were therefore included for the core nucleons but not for the $1p_{1/2}$ neutron. The results of such calculations should indicate which spin observables are most sensitive to the lower component of the target wave function; this sensitivity is expected to remain, for the most part, when all distortion effects are included.[18]

The relativistic target wave functions used are those of Horowitz and Serot.[8] The NN interaction was derived from the SP82 phase-shift solution of Arndt *et al.*[19] For comparison, other calculations were made in which the lower component of the $1p_{1/2}$ neutron wave function was set to the weak-binding, NR limit, using the Dirac-equation result,

$$\lambda_{1p_{1/2}}(r) = \frac{\hbar c}{E+m}\left[\frac{d}{dr} - \frac{\langle \boldsymbol{\sigma}\cdot\mathbf{l}\rangle}{r}\right]\phi_{1p_{1/2}}(r), \tag{5}$$

where $\phi_{1p_{1/2}}(r)$ was again taken from Ref. 8.

The solid curves in Figs. 1–3 correspond to results of calculations with $\lambda_{1p_{1/2}}(r)$ from Ref. 8, and the dashed curves represent results obtained with Eq. (5). As seen in Fig. 1 the sensitivity of unpolarized-target observables $d\sigma/d\Omega(\theta)$, $P(\theta)$ [or $A_y(\theta)$], and D_{LOSO} [essentially $-Q(\theta)$ at small momentum transfer] to $\lambda_{1p_{1/2}}$ is slight. Cross-section and analyzing-power data[20] at 547 MeV are in reasonable agreement with

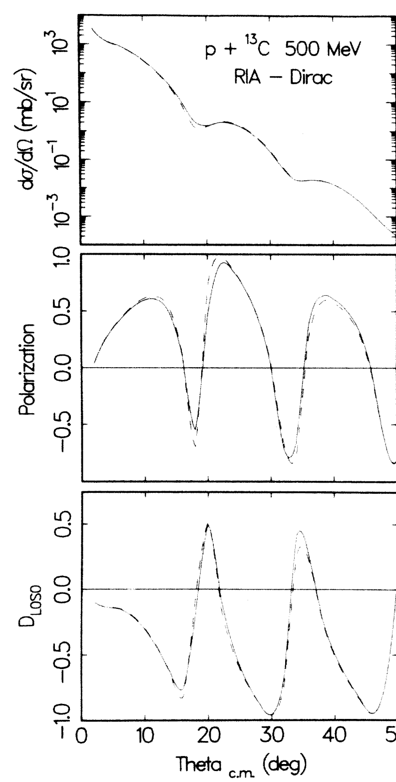

FIG. 1. Results of RIA calculations for 500-MeV $p_{\mathrm{pol}}+{}^{13}$C (unpolarized target) elastic-scattering observables using relativistic $\lambda_{1p_{1/2}}$ (solid curves) of Ref. 8 and NR $\lambda_{1p_{1/2}}$ (dashed curves) using Eq. (5) as discussed in the text.

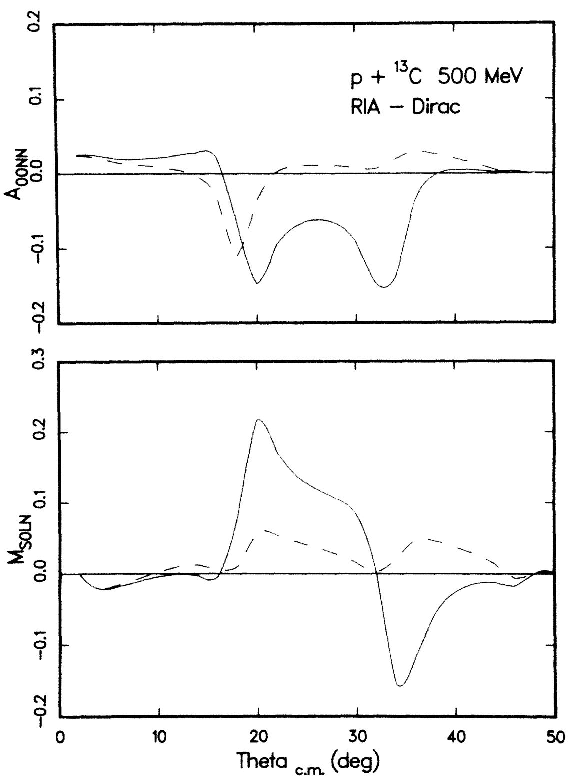

FIG. 2. Same as Fig. 1 except $\hat{\mathbf{n}}$-type polarized-target observables. Note the expanded vertical scale.

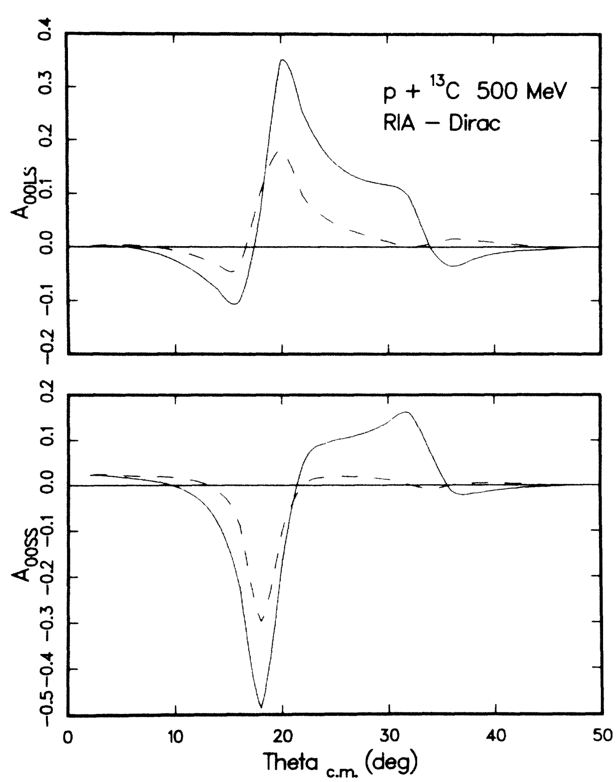

FIG. 3. Same as Fig. 1 except $\hat{\mathbf{s}}$-type polarized-target observables. Note the expanded vertical scale.

these predictions. The notation for spin observables is that of Bystricky, Lehar, and Winternitz[21]; $\hat{\mathbf{n}}$, $\hat{\mathbf{l}}$, and $\hat{\mathbf{s}}$ lie along the directions $(\mathbf{k}\times\mathbf{k}')$, $(\mathbf{k}+\mathbf{k}')$, and $(\mathbf{k}'-\mathbf{k})$, respectively.

The sensitivity of unpolarized-target observables to $\lambda_{1p_{1/2}}$ in those angular regions corresponding to diffractive minima in the cross section cannot be used to investigate relativistic nuclear structure effects since this requires an accurate theoretical description of the core portion of the $p+{}^{13}\mathrm{C}$ scattering amplitude. Uncertainties in the NN interaction, core wave function, correlation effects, target deformation, and multistep processes, etc., make conclusions drawn from such comparisons ambiguous.

The observables A_{00NN} and M_{S0LN} ($\hat{\mathbf{n}}$-type polarized-target) as well as observables A_{00LS} and A_{00SS} ($\hat{\mathbf{s}}$-type polarized target) display (Figs. 2 and 3) sensitivity to $\lambda_{1p_{1/2}}$ throughout the angular region between the first diffractive minimum and maximum in the cross section. The $\hat{\mathbf{l}}$-type polarized-target observables show little sensitivity to $\lambda_{1p_{1/2}}$. The $\hat{\mathbf{n}}$- and $\hat{\mathbf{s}}$-type spin observables are dominated by the spacelike vector and pseudoscalar interactions, respectively.[22] These interactions couple the upper and lower components and cause these observables to be roughly proportional to $\lambda_{1p_{1/2}}$ without significant suppression by the core and $\phi_{1p_{1/2}}(r)$ contributions.

The spin observables in Figs. 2 and 3 are small in overall magnitude since the interaction of the projectile with only one of the thirteen target nucleons contributes. It is important to note, however, that the changes in these observables are roughly proportional to the assumed changes in $\lambda_{1p_{1/2}}$ and that the errors in the data are expected to be ≤ 0.01 for the A_{00ij}.[14] We also point out that the $\hat{\mathbf{n}}$- and $\hat{\mathbf{s}}$-type observables, unlike the polarized-target observables, are not overly dependent on the theoretical description of the scattering amplitude from the core.

In summary, on the basis of the RIA calculations discussed here, we find that the following $p_{\mathrm{pol}}+{}^{13}\mathrm{C}_{\mathrm{pol}}$ elastic-scattering observables are proportionally sensitive to the magnitude of the lower component of the odd-nucleon relativistic wave function:

$$A_{00LS}\simeq -K_{L00S}\simeq M_{N0LS}\simeq -M_{L0NS},$$

$$A_{00SS}\simeq K_{S00S},\quad M_{S0LN}\simeq -M_{L0SN},$$

and

$$A_{00NN}\simeq K_{N00N}.$$

The approximate equalities indicate qualitative similarities between observables. An experiment to measure

$p_{pol} + {}^{13}C_{pol}$ elastic-scattering spin observables at intermediate energies is being planned at the Clinton P. Anderson Meson Physics Facility.[14] The experimental advantages of forward-single proton-nucleus elastic scattering are obvious. More realistic predictions of the polarized-target spin observables will require considerable effort. An effort is currently under way to carry out a full distorted-wave calculation including more realistic target wave functions and improved *NN* interactions and will be reported when completed. Also required as part of this investigation is the development of a nonrelativistic calculation of $p_{pol} + {}^{13}C_{pol}$ elastic scattering.

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[17]A coupled-channels Dirac computer code is currently being developed by one of us (R.L.M.) for application to odd-*A* targets.

[18]Preliminary calculations using $p + {}^{12}C$ relativistic distorted waves in Eq. (4b) indicate that the sensitivities for $\hat{\mathbf{n}}$-type polarized-target spin observables (Fig. 2) are reduced by about $\frac{1}{2}$ while the sensitivities of $\hat{\mathbf{s}}$-type observables (Fig. 3) are only slightly reduced.

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