terferometers are subject to other errors that must be overcome in the design of experiments.[9,10] Nevertheless, the smallness of the shifts in mirror positions likely to be produced by gravitational waves[6] makes the ultimate quantum limits on their measurability a matter of practical concern.

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Pion Prouction, Nuclear Dirac Phenomenology, and the πNN Vertex

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The amplitude for the (p,π^+) reaction is calculated in a relativistic one-nucleon model with use of a distorted-wave Born-approximation approach. The nucleon continuum and bound-state wave functions are solutions of Dirac equations with appropriate vector and scalar nuclear potentials. Calculations with the pseudovector πNN coupling, which satisfies the constraints of partial conservation of axial-vector current, are in much better agreement with the data than calculations with the simple pseudoscalar coupling.

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The hope that (p, π^+) reactions leading to discrete final states of residual nuclei will become a major spectroscopic probe of nuclear wave functions at high momenta has been continually frustrated by the lack of a consistent theoretical understanding of the reaction mechanism. Two leading models[1] have been proposed for the process, the one-nucleon model (ONM) and the two-nucleon model (TNM). In the ONM, the incident proton first scatters from the target nucleus and then emits a (off shell) pion. The latter rescatters onto its mass shell while the neutron is captured into a nuclear orbit. In the TNM, the pion is produced in a collision involving the incident proton and one of the target nucleons, whereby the large momentum transfer is shared among three nuclear wave functions. Both models have had a modest degree of success but neither has been able to provide a fully satisfactory picture of the reaction mechanism. This is particularly evidenced by the lack of a reasonable interpretation of the analyzing-power data.

The ONM has attracted much attention, perhaps because of its simplicity and the fact that it has some resemblance to stripping reactions which have played an important role in nuclear spectroscopy. Most of the theoretical effort has been concentrated on a nonrelativistic distorted-wave Born-approximation (DWBA) treatment of the reaction.[1] A major problem for these calculations has been an ambiguity which is associated with difficulties in nonrelativistic reductions of the relativistic πNN vertex. For example, recent extensive calculations by Tsangarides[2] have shown that whereas the "Galilean invariant" form gives better account of cross sections, it predicts analyzing powers of a sign opposite to that of the data. On the other hand, the "static" form appears to predict the correct sign for the analyzing powers but often fails to reproduce the shape of the cross sections. As has been the case with earlier work, extreme sensitivity to

pion distortion, and to a lesser extent proton distortion, is a persistent feature of these calculations.

A relativistic approach has the advantage of avoiding the ambiguity present in the nonrelativistic πNN vertex. Moreover, such calculations treat explicitly the contributions from lower components of the nuclear wave functions. Plane-wave Born-approximation calculations within this framework have been carried out recently.[3,4] A preliminary attempt at including distortion effects was undertaken,[5] but this was only done in a very approximate fashion.

In this Letter we report a new relativistic DWBA calculation of the (p, π^+) reaction, in which distortion effects in the incident and the outgoing channels are treated properly. The results are in good agreement with experiment for closed-shell targets. We report the first reasonable agreement between theory and experiment for the analyzing power in (p, π^+) reactions, and confirm its apparent final-state independence. The results clearly favor the use of the pseudovector form of the πNN vertex over the simple pseudoscalar (γ_5) form.

The DWBA for the (p, π^+) reaction t matrix may be written as[4]

$$T = i\sqrt{2}\int d^3r\, \bar{\psi}_b(\vec{r})\,\Gamma\,\varphi_\pi^{*(-)}(\vec{r})\,\psi_i^{(+)}(\vec{r}), \qquad (1)$$

where ψ_b and ψ_i are Dirac spinors for the final-state bound neutron and the incident proton, respectively. The φ_π describes the outgoing pion and Γ is the πNN vertex operator:

$$\Gamma = \begin{cases} g\gamma_5 & \text{pseudoscalar (PS)} \\ (g/2M)\gamma_\mu\gamma_5\partial_{\pi}{}^{\mu} & \text{pseudovector (PV)}, \end{cases} \qquad (2)$$

where g is the physical coupling constant and M is the nucleon mass. For simplicity, expression (1) is written for the case of a target nucleus with spin and isospin both equal to zero.

The large and small components of the bound-state wave function ψ_b are generated by solving the appropriate Dirac equation using a combination of vector and scalar nuclear potentials. These potentials, which arise from the exchange of scalar and vector mesons, can be obtained from self-consistent calculations,[6,7] where they are found to follow approximately the nuclear shape. For consistency, we take the shapes of these potentials to be the same as those determined from consideration of the incident proton distorted waves as will be discussed below. The depths V_s and V_v of the scalar and vector potentials are chosen such that (i) the ratio V_v/V_s is fixed at -0.81, as suggested[8] by Walecka's[9] mean-field theory for nuclear matter, and (ii) the resulting single-particle bound state has the correct binding energy.

The incident proton distorted waves ψ_i are generated from solutions of the Dirac equation with complex vector and scalar potentials which have Woods-Saxon shapes. The parameters of these potentials are determined from fits to the proton elastic scattering cross section and analyzing power data using the automatic search code RUNT.[10] This approach has been quite successful in fitting proton-nucleus elastic scattering data at intermediate energies.[8,10,11]

The pion distorted waves are generated from the pion-nucleus optical potentials of Stricker, McManus, and Carr (SMC).[12] These potentials give a good account of pionic atom data and fit well the pion elastic scattering data in the range of pion energies up to 50 MeV. Our computer code can presently handle only the SMC potentials. We have, therefore, not tested the sensitivity of our calculations to the variety of pion potentials available. However, we note in this regard that our results were found to be rather insensitive to small variations in the parameters of the SMC potentials.

The DWBA calculations were performed with use of both the PS and PV vertex operators of Eq. (2). As pointed out by Friar,[13] the equivalence between these two forms is broken by the scalar interactions of the nucleons. Noble[14] has also shown that if the PS coupling amplitude is calculated in the $\sigma+\omega$ model, which satisfies the requirement of partial conservation of axial-vector current (PCAC),[15] the equivalence is largely restored. In our present calculations we use the simple γ_5 PD vertex and hence expect the equivalence to be broken. In fact, because of the differences between initial and final (bound) state interactions, the vector potentials also contribute to this breaking. It is therefore not surprising to see important differences between the PS and PV coupling predictions.

Figure 1 shows the results of our calculations for the reaction ^{40}Ca$(p, \pi^+)^{41}$Ca(g.s.) at an incident proton energy of 160 MeV. The data points are those of Pile *et al.*[16] The neutron is assumed to be captured in a $1f_{7/2}$ orbit with a spectroscopic factor of 1 [recent compilations[17] based on (d, p) reactions give values in the range 0.75–0.93]. The solid curve is obtained with the PV vertex and the dashed curve with the PS one. The former is in much better accord with the data. The

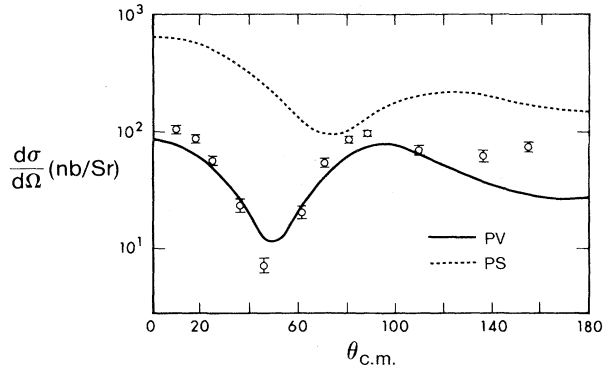

FIG. 1. Cross sections for the reaction $^{40}Ca(p, \pi^+)^{41}Ca(g.s.)$ at incident proton kinetic energy of 160 MeV. The curves show the results of our present calculations with pseudovector coupling (solid curve) and pseudoscalar coupling (dashed curve).

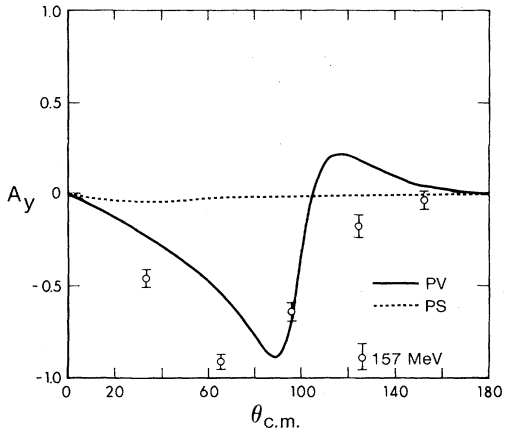

FIG. 2. The analyzing power A_y for the reaction $^{16}O(p_{pol}, \pi^+)^{17}O(g.s.)$ at incident proton kinetic energy of 160 MeV. The curves show the results of our present calculations with pseudovector coupling (solid curve) and pseudoscalar coupling (dashed curve).

angular distribution predicted with PS coupling has a minimum that is shifted by ~30° with respect to the data. In addition, the magnitude of the cross section is nearly an order of magnitude higher than the data at forward angles. Calculations for this reaction at other bombarding energies (up to $T_p = 185$ MeV) show the same good agreement with observed cross sections when one uses a PV vertex operator. The apparent failure of the simple PS coupling could not be remedied by reasonable changes in the bound-state geometries or by using different proton optical potential parameters (which still fit the elastic scattering data).

Similar good agreement with the data is obtained for the reaction $^{16}O(p, \pi^+)^{17}O(g.s.)$, at proton energies of 160 and 185 MeV. For reactions on ^{12}C, our calculations reproduce the shapes of the angular distributions[18,19] but generally underestimate the cross section magnitudes. Miller[20] has shown that configuration mixing is important for the states in question, especially at high momentum transfer. Our pure single-particle description, therefore, may not be adequate for these states.

The differences observed in the predictions of PV and PS forms for the cross sections also show in the analyzing-power calculations. This is illustrated by the comparisons in Fig. 2. The data are those of Sjoreen *et al.*[21] Here again it is evident that the PV coupling is in qualitative agreement with the data, while the PS coupling predicts very little analyzing power at this energy. These features could not be reversed by reasonable adjustments in the ground-state geometrical parameters. While the analyzing powers are found to be more sensitive to proton distortion than the cross sections, use of a different set of optical-model parameters does not change the above conclusion concerning the superiority of PV coupling calculations. Similar calculations (with PV coupling) for the analyzing power in the reaction $^{12}C(p, \pi^+)^{13}C$ are in good agreement with the data[18,19] for proton bombarding energies of 159 and 200 MeV. This is true for both the ground and first excited states in ^{13}C. The data show the analyzing powers for these two states to be similar and our calculations do indeed predict this apparent state independence.

In conclusion we find that a relativistic DWBA one-nucleon model for (p, π^+) reactions leads to consistently encouraging results. When the nuclear final state is dominantly a pure single-particle state the observed cross sections are well reproduced by our calculations if the pseudovector coupling vertex is used. The analyzing powers resulting from these calculations are also in good agreement with experiment. In particular, the observed state independence of the analyzing power is correctly predicted by our calculations. Invariably the simple pseudoscalar (γ_5) coupling leads to results that are inferior to those obtained with the pseudovector coupling. This points out the importance of compliance with the restriction of PCAC in (p, π^+) reaction calculations.

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Measurement of Subshell Photoionization Cross Sections of Ba near the 4*d* Threshold

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Measurements of 4*d*, 5*p*, and 5*s* subshell cross sections have been performed on polycrystalline Ba. These results essentially confirm many-body atomic calculations including the resonant enhancement of photoemission from the outer shells at the 4*d* threshold. Evidence is also presented for a two-electron discrete excited state about 20 eV above the 4*d* threshold.

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We present here measurements of the angle-integrated 5*p*, 5*s*, and 4*d* subshell photoionization cross sections for polycrystalline Ba around and above the 4*d* threshold. Soft-x-ray–induced photoemission in Ba is dominated by many-electron interactions: A broad 4*d* resonance is accompanied by outer-shell photoexcitation resonances near the threshold which cannot be explained in the framework of a one-electron model.

The energy of soft x rays absorbed in a solid or gas is converted principally into photoelectron energy. The kinetic energy of outgoing photoelectrons provides information about the initial and final states of the atomic excitation responsible for the absorption. The experiment described here employs an electron energy analyzer in conjunction with a tunable soft x-ray source, so that we are thus able to determine the partition of the absorption into several types of excitations. Previous experiments on similar systems have measured only total cross section—the total attenuation of a photon beam through a thin film or gas sample.

Measurements of subshell cross sections in the solid state is experimentally much simpler than in the gas phase (although interpretation of the

