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Pseudo-Scalar πN Coupling and Relativistic Proton-Nucleus Scattering

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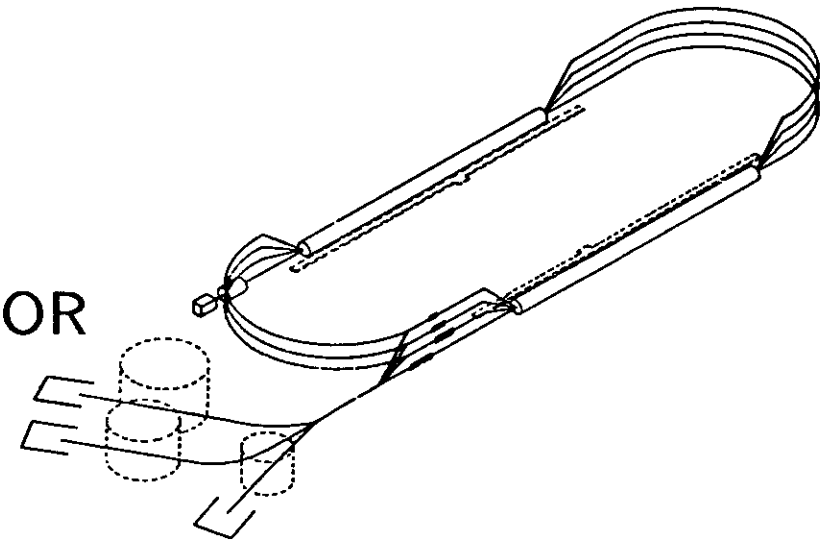

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Abstract

Relativistic p-^{40}Ca elastic scattering observables are calculated using relativistic NN amplitudes obtained from the solution of a two-body relativistic equation in which one particle is kept on its mass-shell. Results at 200 MeV are presented for two sets of NN amplitudes, one with pure pseudo-vector coupling for the pion and another with a 25% admixture of pseudo-scalar coupling. Both give a very good fit to the positive energy on-shell NN data. Differences between the predictions of these two models (which are shown to be due only to the differences in their corresponding negative energy amplitudes) provide a measure of the uncertainty in constructing Dirac optical potentials from NN amplitudes.

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It is well known that the relativistic impulse approximation(RIA) gives a good description of medium energy p-nucleus scattering observables[1]. In this approach the scattering of the proton is described by a Dirac equation with an optical potential U of the form

$$U_{RIA}^{(\rho',\rho)}(r) = \int d^3r' \;\; T^{(\rho'\,\rho_2',\rho\;\rho_2)}(r,r')\rho^{(\rho_2',\rho_2)}(r') \tag{1}$$

where the ρ superscripts (known as ρ-spin) are positive(negative) for nucleons in a positive(negative) energy state. This equation therefore expresses the optical potential as a folding of the NN T matrix describing scattering of two initial nucleons in ρ-spin states (ρ, ρ_2) to two final nucleons in ρ-spin states (ρ', ρ_2') by a nucleon density distribution ρ which depends on the ρ-spin of the initial and the final bound nucleon.

Previous work[2,3] has clearly established that the success of the RIA depends strongly on the $U^{(+,-)}$ and $U^{(-,+)}$ amplitudes, which in turn depend on knowledge of T matrix elements in which *at least one* particle in the initial or final state is in the negative energy state. (In this letter these amplitudes will be referred to collectively as "negative ρ-spin amplitudes "). These amplitudes cannot be measured directly , and some ansatz has to be made to extend the physically accessible positive energy amplitudes to the full Dirac space.

In the original calculations[1], the values of the negative ρ-spin amplitudes were inferred by expanding T in terms of five Fermi covariants, and fitting these to the on-shell $T^{(++,++)}$ data. However, this procedure is ambigious and sensitive to the choice of the five covariants[4]. For example the covariants $\gamma_1^5\gamma_2^5$ and $-(\gamma^5\; q.\gamma)_1(\gamma^5\; q.\gamma.)_2/4m^2$ give identical results in the $(++,++)$ sector, but their extrapolations to the negative ρ-spin sectors are different, resulting in generally poor fits at low energy(200 MeV) if $\gamma_1^5\gamma_2^5$ terms are included. This problem led Tjon and Wallace[5] to adopt a theoretical model of NN interaction as a basis for predicting all $T^{(\rho'\,\rho_2',\rho\;\rho_2)}$ matrix elements in Eq(1). Use of a dynamical model which describes the NN observables in a qualitative way over the 0 to 1000 MeV range was thought to be the best way to minimize the ambiguity in prediction of the optical potential. The optical potential based on a complete set of amplitudes (referenced to as IA2[6]) produces good agreement with experimental results over a wide range of projectile energies[3] from 200 to 800 MeV.

In view of the importance of the negative ρ-spin sectors to the success of the RIA, and because these amplitudes cannot be directly determined by data, it is important to see whether different relativistic dynamical models for T will work as well, and to investigate the sensitivity of RIA results to realistic variations of negative ρ-spin amplitudes. We have studied this question in detail, and in this letter we present a brief summary of our results. A more complete discussion will be published elsewhere.

To study the sensitivities of the p-nucleus scattering observables to realistic variations in the negative ρ-spin sectors we used relativistic NN amplitudes obtained from the solution of the relativistic equation in which one particle is on-shell[7]. To ensure that the resulting amplitudes satisfy the Pauli principle, the OBE kernels used in this calculation were explictly antisymmetrized[8,9]. Hence the 4 classes of amplitudes $T^{(+-,++)}$,$T^{(-+,++)}$, $T^{(++,+-)}$ and $T^{(++,-+)}$ can all be obtained through antisymmetry, or time reversal invariance, from $T^{(+-,++)}$ which we will referred to simply as $T^{(-,+)}$, and the amplitudes $T^{(+-,+-)}$,$T^{(+-,-+)}$,$T^{(-+,+-)}$ and $T^{(-+,-+)}$ can similarly be obtained from $T^{(+-,+-)}$, referred to as $T^{(-,-)}$. The amplitudes $T^{(--,\rho\rho_2)}$ and $T^{(\rho'\rho_2',--)}$ are all taken to be zero. Finally, the πN coupling used in these solutions is a mixed coupling of the form

$$\lambda\gamma^5 + (1-\lambda)\frac{\gamma.q\gamma^5}{2m}.$$

The parameter λ varies the mix of pseudo-scalar and pseudo-vector coupling, and is defined so that the on-shell amplitude is independent of λ. When λ is unity the coupling is purely pseudo-scalar and when it is zero the coupling becomes pure pseudo-vector.

Two OBE models have been found which fit the NN data equally well, but which have significantly different $T^{(+,-)}$ amplitudes[9]. In model 1, only the four mesons π,σ,ω and ρ are used. This is the minimal number needed to represent the long, medium and short range nuclear forces, and a very good fit to the positive energy NN amplitudes is obtained when the parameter λ has the value 0.25 which is 25% pseudo-scalar and 75% pseudo-vector. In another OBE model, model 2, the πN coupling is constrained to be pure pseudo-vector($\lambda = 0$) consistent with pair suppression and chiral symmetry. In order to fit the NN data equally well, two extra mesons, δ and η, must be included. (The δ meson is needed to get the correct splitting between $^1S_0$ and $^3S_1$ central terms, which emerges

automatically when $\lambda = 0.25$.) These two models allow us to explore the sensitivity to the amount of pseudo-scalar coupling one may use and still obtain a good fit to the NN observables. They both differ significantly from the model used by Tjon and Wallace.

The results for the polarized p-^{40}Ca elastic scattering at 200 MeV obtained from the two models are shown in Fig.1. Calculations are based on the IA2 formalism of reference 6. Although both models give a reasonable description for the p-nucleus observables, it can be seen that the mixed coupling model gives superior results over the pure pseudo-vector coupling case. However, since the integral in (1) has only been evaluated in the $t\rho$ approximation (in which the T-matrix is evaluated on-shell and factored out of the integral) and other effects such as Pauli blocking and vacuum polarization have not been included, it cannot be concluded that the mixed coupling case will continue to give the best results after these effects are taken into account.

We would like to emphasize that the relativistic NN amplitudes used were the results of dynamical calculations based on a relativistic equation, and do not have any adjustable parameters. Calculations have also been performed at other energies and the predictions agree with the data as well as in the case of 200 MeV.

In order to isolate the model dependence arising from negative-energy components of T, we compare models 1 and 2 above with a calculation of Tjon and Wallace[5] in Fig.2. In this case we standardize the comparisons by replacing the $T^{(++,++)}$ amplitudes in each case by the on-shell amplitudes determined by Arndt et al[11]. Note that the differences between models 1 and 2 are substantially unchanged, even though the depth of the oscillation in A_y has increased somewhat. This shows that (i) the differences between models 1 and 2 are not due to any differences in the $T^{(++,++)}$ amplitudes, and that (ii) even though models 1 and 2 give a very good fit to the NN data, there is still some overall sensitivity to using the Arndt $T^{(++,++)}$ amplitudes as shown by the systematic differences between the results of Fig.1 and Fig.2. The differences between the the two pseudo-vector cases (model 2 and the Tjon-Wallace case) are due solely to model dependence arising from the negative ρ-spin sectors of the T-matrix in Eq(1). The Tjon-Wallace analysis uses a Blankenbecler-Sugar reduction of the Bethe-Salpeter equation and was solved with coupled NN and $N\Delta$ channels[12]. We have checked that the differences shown in Fig.2. are *not* due to additional

$(- -)$ channels in which *both* of the initial or final particles have negative ρ-spin, which are included in the Blankenbecler-Sugar equation but not present in the equation of references 7 and 9.

In summary, we emphasize that although the p-nucleus observables cannot be uniquely predicted by the on-shell NN amplitudes, the use of meson exchange dynamics subtantially restricts the ambiguity. Differences in the predictions of models 1 and 2, both of which fit the on-shell NN data very well, are due to the differences in their corresponding $T^{(+,-)}$ amplitudes, which cannot be uniquely determined by the on-shell data. The model dependence is significant but still smaller than the sizes of the pair contributions themselves. These results are thought to provide a reasonable measure of the uncertainty in predicting the Dirac optical potential from NN amplitudes, which we expect to be largest at lower energies.

Finally, it is amusing that the simpler model 1, with the exchange of only four mesons and a 25% admixture of γ^5 coupling for the pion, fits the observables as well as it does. This result suggests either that some degree of pair non-supression on the Born level may be allowed, or that the σ counter terms required to control the γ^5 part of the pion coupling may already be included as part of the phenomenological σ exchange potential used in the NN models. In view of the success here, it may be worth examining the results of such mixed coupling models in other reactions, such as electromagnetic processes or processes involving pion production or absorption.

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Figure Captions

Fig.1. Predictions for p-^{40}Ca observables for the $\lambda = 0.25$ model 1 (solid line) and $\lambda = 0$ model 2 (dashed line) described in the text. The stars are data from reference 10.

Fig.2. Results for the p-^{40}Ca observables with theoretical $T^{(++,++)}$ amplitudes replaced by the Arndt amplitudes, and theoretical amplitudes in other ρ-spin sectors left unchanged. Model 1 (solid line), model 2 (dashed line) and the calculation by Tjon and Wallace (dotted line) are shown. The data are as in Fig.1.

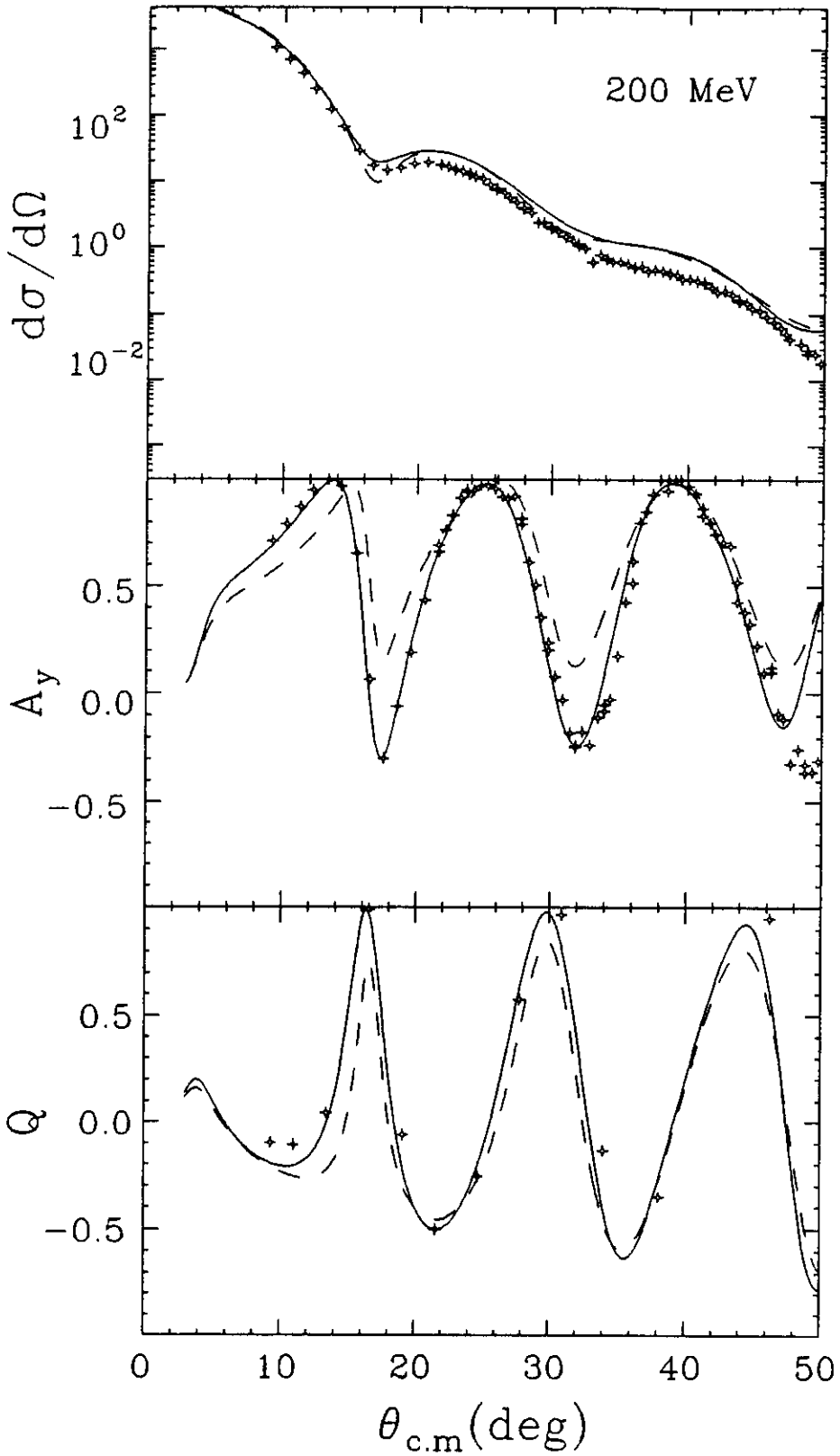
200 MeV
10^2
10^0
10^{-2}
$d\sigma/d\Omega$
0.5
0.0
−0.5
A_y
0.5
0.0
−0.5
Q
0
10
20
30
40
50
$\theta_{c.m}$(deg)

Figure 1

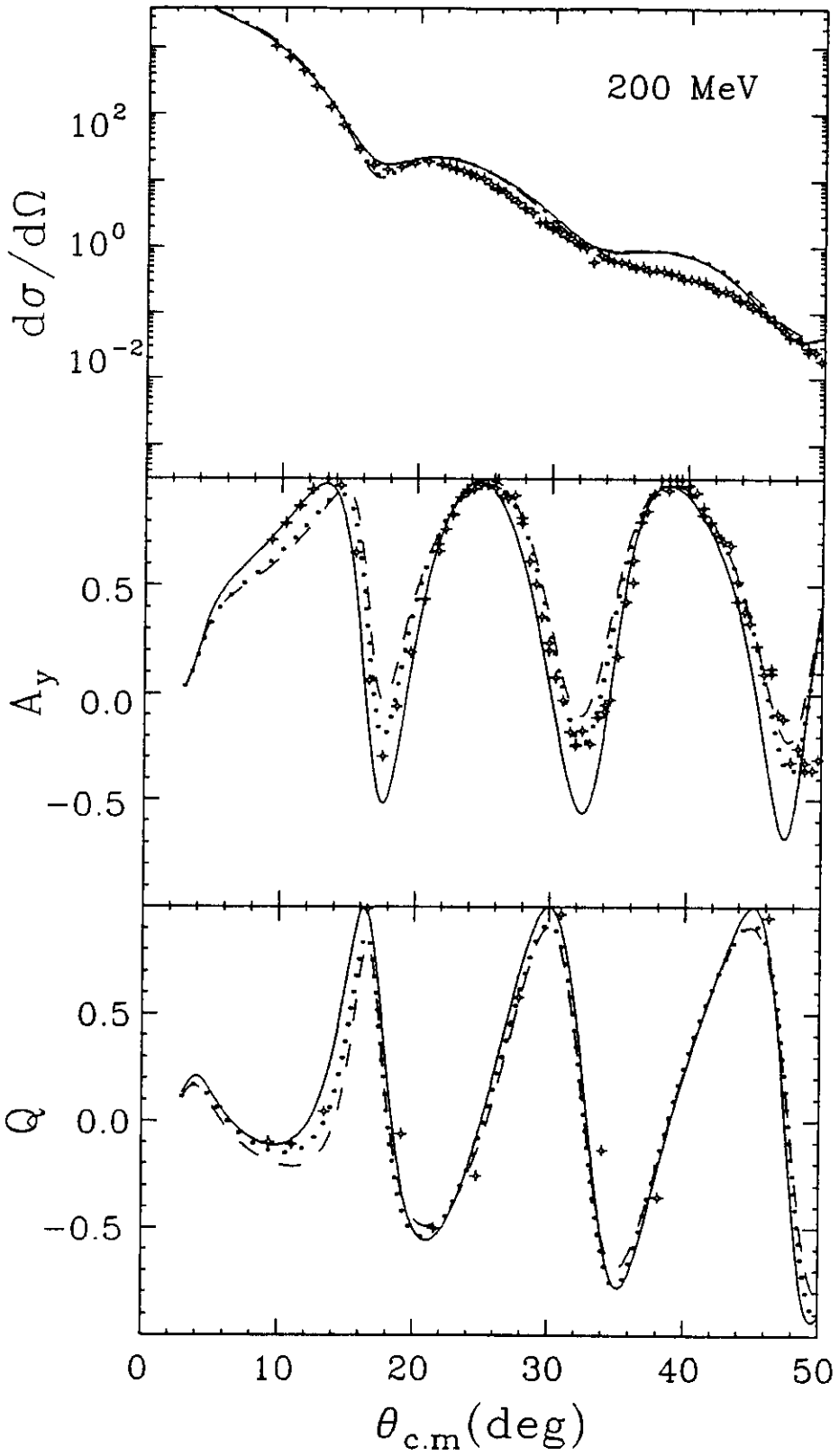
200 MeV
10^2
10^0
10^{-2}
$d\sigma/d\Omega$
0.5
0.0
−0.5
A_y
0.5
0.0
−0.5
Q
0
10
20
30
40
50
$\theta_{c.m}$(deg)

Figure 2