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MICROSCOPIC RELATIVISTIC DESCRIPTION OF $p-208\text{Pb}$ ELASTIC SCATTERING*

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ABSTRACT

Relativistic optical potentials are calculated for $p-208\text{Pb}$ elastic scattering at 200 and 400 MeV by folding a model for the NN t matrix with Hartree densities. Use of pseudovector π - N coupling in t (at 200 MeV) and including Pauli blocking corrections gives good agreement with TRIUMF data. The role of medium corrections in relativistic versus nonrelativistic approaches is discussed.

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A number of relativistic approaches to nuclear physics all suggest the optical potential or self energy for a nucleon involves large attractive Lorentz scalar and repulsive vector contributions. Relativistic mean field calculations¹ relate these potentials to large sigma (scalar) and omega (vector) meson fields and provide a good description of ground state charge densities. Dirac optical model fits to elastic proton scattering² also use strong potentials to reproduce analyzing power data. Finally, relativistic impulse approximation (RIA) calculations³ find strong potentials coming from large scalar and vector pieces of a Lorentz invariant representation of the NN amplitudes. These RIA calculations provide an excellent description of elastic scattering at 500 MeV and above.

In this paper, microscopic relativistic optical potentials are calculated for $p-208\text{Pb}$ elastic scattering at 200 and 400 MeV. These calculations contain important physics beyond the original RIA.

First, medium modifications from Pauli blocking are included using nuclear matter calculations in a local density approximation. Nonrelativistic work has suggested that these may be important even at relatively high energies.

Second, the original RIA representation of the NN amplitudes involve ambiguities which become increasingly serious as the energy is decreased. To resolve these ambiguities, a simple direct plus exchange model of the NN amplitudes⁴ is employed which allows the use of a pseudovector (A_7) rather than the simple γ_5 of the original RIA) π - N coupling. This is important because the exchange of a π can make sizeable contributions to the scalar and vector amplitudes and hence potentials.

After describing the formalism of our calculations, we show results which accurately reproduce the analyzing power for $p-208\text{Pb}$ elastic scattering. Next, the importance of medium modifications and amplitude ambiguities is discussed as a function of energy. Finally, these calculations are compared to the relativistic results of Tjon and Wallace⁵ (who examine the amplitude ambiguities but don't include Pauli blocking) and the nonrelativistic Paris G matrix results of Rikus and von Geramb.⁶

To construct an optical potential in a relativistic " t_ρ " approximation, one makes important assumptions regarding the "off-shell" behavior of the NN amplitudes.⁷ One chooses the form of an operator $\hat{F}$ whose free Dirac spinor matrix elements are equated to NN data. The standard representation of $\hat{F}$ is⁸

$\hat{F} = \sum_i F_i(q, E) \lambda_i^{(1)} \lambda_i^{(2)}$		
i	λ_i	
s (Scalar)		1
v (Vector)		γ_μ
p (Pseudoscalar)		γ_5
a (Axial-Vector)		$\gamma_5 \gamma_\mu$
t (Tensor)		$\sigma_{\mu\nu}$

(1)

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Here, $\lambda_i^{(1)}$ is a Dirac matrix in the spinor space of particle one and the Lorentz invariant amplitudes F_i are functions of energy E and momentum transfer q . Taking the free spinor matrix elements of eq. (1) one can derive a 5×5 nonsingular matrix relating the F_i to the five conventional Wolfenstein amplitudes.⁸ We emphasize, only the free spinor matrix elements of eq. (1) are determined by the NN data while the full “off-shell” operator is needed to construct an optical potential.

To resolve ambiguities in $\hat{F}$ a simple model was developed which includes the direct and exchange first Born terms from a number of “mesons”.⁴ This model divides the Lorentz invariant amplitudes into direct i^D and exchange i^X contributions.

$$F_i = i_i^D(q) + i_i^X(q). \quad (2)$$

Here, the exchange momentum transfer Q is for scattering angle $\pi - \theta$. The exchange parts of the scalar and vector invariants i_i^X , i_i^X have large contributions from π exchange. As discussed in [4,9], it is important to evaluate these with a pseudovector ($\vec{A}\gamma_5$) invariant in place of the pseudoscalar (γ_5) one in eq. (1). This serves to decrease the effects of i_i^X and i_i^X substantially at low energies.

The optical potential $U_{\text{opt}} = U_s + \gamma_0 U_v$ is calculated by folding F_i with ρ and making a local density approximation for the exchange term.

$$U_i(r) = -4\pi p_i/m \int d^3s \left\{ i_i^D(s) \rho_i(\vec{r} + \vec{s}) + i_i^X(s) \rho_i(\vec{r} + \frac{1}{2}\vec{s}) \rho_{\text{eff}}(k_F s) \right\} \quad (3)$$

Here, p is the projectile momentum, $j_0(p)$ a plane wave approximation to the projectile wavefunction and the off-diagonal density matrix is approximated by its nuclear matter value $\rho_{\text{eff}}(ks) = 3/(sk)^3 \{ \sin(sk) - sk \cos(sk) \}$. This is at the local Fermi momentum k_F deduced from $\rho_0(\vec{r} + \frac{1}{2}\vec{s})$.¹⁰ The baryon ρ_0 and scalar ρ_s densities are taken from mean field calculations and have not been varied.¹ Finally, i_i^X and i_i^D are Fourier transforms of i_i^X and i_i^D .

It remains to include medium modifications from Pauli blocking. Nuclear matter calculations of the lowest order relativistic Brueckner optical potential have been performed both with and without the Pauli operator. These calculations use the HEA,¹¹ one boson exchange potential and will be described in a later work (they do not include binding energy corrections). From the ratio of the two nuclear matter calculations we define Pauli blocking correction factors a_i which can be applied to the finite nucleus optical potential in a local density approximation.

$$U_i \Leftarrow \{1 - a_i(E) [\rho_0(r)/\rho_0]^2\} U_i(r) \quad (4)$$

Here, $\rho_0 = 0.19 \text{ fm}^{-3}$ and the assumed k_F^2 density dependence is based on simple phase space arguments. At $E = 200$ and 400 MeV the nuclear matter calculations

give for the a_i

	Scalar		Vector	
	Real	Imag.	Real	Imag.
Energy				
200 MeV	-0.01	0.10	0.06	0.21
400	-0.04	0.06	-0.01	0.09

(5)

The calculations can be summarized as follows. Ref. [4] is used for the t matrix which is folded with the mean field densities of Ref. [1] and then multiplied by the Pauli blocking corrections of eq. (4) and (5).

The real part of U_i for ^{208}Pb at 200 MeV is about -400 MeV in the interior while $\text{Re}U_v$ is about 300 MeV . From the relativistic U_{opt} a Schrödinger-like equivalent potential can be calculated.² This is shown in Fig. 1. Compared to the nonrelativistic Paris G matrix calculation of Ref. [6], we have a non-Wood-Saxon shape for the central and a much stronger real spin-orbit potential.

The analyzing power at 200 MeV is shown in Fig. (2a) for a calculation with pseudovector amplitudes and Pauli blocking. The agreement with TRUMF data¹² is very good. If Pauli blocking is omitted or pseudoscalar amplitudes are used, the curve is much worse (not shown, see Ref. [9]). In contrast, the nonrelativistic calculation of Ref. [6] is seen to underestimate the depth of the analyzing power minima. Pseudovector amplitudes and Pauli blocking also serve to reduce both the magnitude and oscillation structure in the differential cross section leading to good agreement with data (the reaction cross section is $\sigma_R = 1.77 \text{ Barns}$). However, there seems to be no characteristic relativistic signature in the cross section.

The analyzing power at 400 MeV is shown in Fig. (2b). At this energy there is almost no difference between pseudovector and pseudoscalar amplitudes. With Pauli blocking, the agreement with data is very good. If Pauli blocking is omitted (dotted curve) there is only a slight but noticeable change in A_y . This dotted curve agrees well with the original RLA calculations in Ref. [13]. In contrast, a nonrelativistic KMT calculation by Ray and Hoffman¹³ is very bad. Comparing this to the Rikun and von Geramb calculation⁶ which (among other differences) includes medium modifications, one sees very much larger nonrelativistic Pauli blocking effects. Although the Rikun and von Geramb calculation is not too bad, one still sees the characteristic relativistic signature in the forward angle A_y which was seen in ^{40}Ca at 500 MeV .^{3,13}

Tjon and Wallace have also investigated ambiguities in the relativistic amplitudes with elaborate one-boson-exchange calculations of the full “off-shell” structure on the NN t matrix.⁵ They essentially agree with our much simpler pseudovector amplitudes and our results for the spin observables in ^{40}Ca at 200 MeV . However, they do not include Pauli blocking and this may explain their over estimation of the C_a cross section.

In conclusion, microscopic relativistic optical potentials have been calculated for p - ^{208}Pb elastic scattering at 200 and 400 MeV . These calculations go beyond

the simple RIA by resolving ambiguities in the relativistic NN amplitudes and including Pauli blocking corrections.

At 200 MeV, both Pauli blocking and the use of pseudovector NN amplitudes are important in obtaining a very good description of TRIUMF data. While at 400 MeV there is almost no difference between pseudoscalar and pseudovector amplitudes. Furthermore, at this energy, Pauli blocking corrections are much smaller than in nonrelativistic calculations.

These calculations and similar ones for ^{16}O , $^{40,48}\text{Ca}$ and ^{90}Zr quantitatively reproduce all measured elastic spin observables (both A_y and spin rotation function Q) at energies near 200 MeV. It remains to be seen how unique this good description is. Further nonrelativistic work to compare with this relativistic approach would be very useful as would measurements of Q for Pb (since there may be larger differences among calculations for Pb than Ca).

Tables of the observables and relativistic optical potentials for closed shell nuclei are available from the authors. Also available is a documented relativistic mean field computer code which produced the Hartree target densities used.¹

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FIGURE CAPTIONS

Figure 1a:

Schödinger equivalent central potential for ^{208}Pb at 200 MeV. The real part is the heavy solid curve while the imaginary part is dashed. The n.r. curves are the nonrelativistic results of reference [6].

Figure 1b:

Schrödinger equivalent spin-orbit potential. See caption to Figure 1b (the real part is negative at small r while reference [6] is positive).

Figure 2a:

Analyzing power in ^{208}Pb at 200 MeV (solid curve). The dotted curve is the nonrelativistic result of reference [6] and the TRIUMF data is from reference [12].

Figure 2b:

Analyzing power in ^{208}Pb at 400 MeV. The solid curve includes Pauli blocking while the dotted curve does not. The nonrelativistic calculation with medium modifications⁶ is dashed, while the dot dashed curve is the KMT impulse result of reference [13]. The TRIUMF data is from reference [14].

FIGURE 1a

FIGURE 1b

FIGURE 2a

FIGURE 2b