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ABSTRACT

The total reaction cross sections for intermediate energy proton scattering on ^{40}Ca and ^{208}Pb are calculated within the Dirac-Eikonal formalism. Comparison with data indicate that the recently proposed impulse-approximation Dirac optical potential for nucleon-nucleus scattering, is not absorptive enough.

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In the last few years the Dirac equation used with a mixture of phenomenological scalar and vector interactions, has been shown to provide a greatly improved starting point for understanding intermediate energy proton-nucleus scattering[1]. Calculation based on an impulse-approximation optical potential gave excellent agreement with data on elastic scattering differential cross-section, spin polarization and spin rotation for systems such as 500 MeV $p_{pol} + {}^{16}O$ and ^{40}Ca.

Parallel to the above developments several attempts to derive the relativistic nucleon-nucleus optical potential have been made. These range from extending the familiar impulse approximation "$t\rho$" - type derivation to include explicitly scalar and vector components[3], to more ambitious plans starting from a relativistic many-body field theory of interacting nucleons and mesons. One such theory, which is extensively cited, is that of Walecka[4]. Though originally constructed to describe nuclear matter as a system of interacting nucleons and isoscalar scalar and vector mesons, it is also adequate for the description of spin saturated, isoscalar (closed-shell) nuclei such as ^{16}O and ^{40}Ca. The inclusion of the isovector π and ρ mesons in the theory was subsequently performed by Serot[5]. In most of the applications of the theory, special emphasis was placed on deriving the real part of the nucleon-nucleus optical potential (the single particle potential).

In a recent work Horowitz[6], calculated the relativistic imaginary potential to lowest order in nuclear matter for the exchange of σ, ω and π -mesons. Of course the relativistic "$t\rho$" potential refered to earlier does supply a well-defined imaginary potential, which is directly related to the scalar and the time component of the vector nuclear density. It would be important to check these potentials in a direct way.

An important observable quantity that is direcly related to the imaginary part of the optical potential is the total reaction cross section σ_R. Though obtainable from an optical model analysis of the elastic scattering data, it is, nevertheless, of value to calculate σ_R directly. Such a calculation would supply a further test of the adequacy of the theoretical imaginary potential and help analyzing its reactive content.

The purpose of the present Letter is to develop a theory of, and calculate σ_R within a Dirac description of the elastic scattering of nucleons of nuclei. We use the eikonal approximation in our discussion of the nucleon-nucleus elastic scattering amplitude. Such a Dirac-eikonal approximation has recently been put forward by Amado et al.(7) and Friar and Wallace(8). We present results for $p + {}^{40}Ca$ and $p + {}^{208}Pb$ at $10 < E_p < 1000$ MeV, and discuss the corresponding non-relativistic calculations of Di Giacomo et al.(9).

The Dirac equation that describesthe elastic scattering of a nucleon, treated as a Dirac particle, from a spin-saturated nucleus, is usually written in the form, using a time-independent description,

$$[\vec{\alpha}\cdot\vec{p} + \beta(m+V_s) + V_o]\Psi = E\Psi \qquad (1)$$

where it is assumed that the average, complex, nucleon-nucleus potential is a sum of a scalar component, V_s, and the fourth (time) component of a vector potential, V_o. The matrices α and β are Dirac's, and Ψ is the four-component vector wave-function.

Let us write V_s and V_o as

$$V_s = U_s - iW_s$$
$$V_o = U_o - iW_o \qquad (2)$$

The total reaction cross section, expressed directly in terms of W_s and W_o, can be deduced from Eq. (1), by using the usual Wronskian manupulation on Eq. (1). We find(10),

$$\sigma_R \equiv \frac{-\int_{S\to\infty}\vec{J}\cdot d\vec{A}}{v\gamma} = \frac{2}{\hbar v\gamma}\langle\Psi^{(+)}|\,W_o + \gamma_4 W_s\,|\Psi^{(+)}\rangle, \qquad (3)$$
$$\gamma_4 \equiv \beta \quad , \vec{\alpha} \equiv i\gamma_4\vec{\gamma}$$

where $\vec{J}$ is the hadronic current $i\bar{\Psi}\vec{\gamma}\Psi$ and $v\gamma = \frac{v}{\sqrt{1-(\frac{v}{c})^2}}$,

with v being the incident velocity. The integral $-\int_{S\to\infty}\vec{J}\cdot d\vec{A}$ is just the net inward flux due to absorption. We note that $\Psi^{(+)}$ is the exact solution of Eq. (1). Equation (3) is the relativistic generalization of the well-known non-relativistic expression.

Writing $\Psi^{(+)}$, in terms of its upper, component u_s, through

$$\Psi^{(+)} = \left(\frac{E+m}{2m}\right)^{1/2}\begin{pmatrix}1\\ \frac{1}{A}\vec{\sigma}\cdot\vec{p}\end{pmatrix}u_s \qquad (4)$$

$$A = E + m + V_s - V_o \qquad (5)$$

we may reexpress σ_R as

$$\sigma_R = -\frac{1}{m v\gamma}\int_{S\to\infty} dA\, \mathrm{Re}\,(u_s^{\dagger}\vec{\sigma}\cdot\hat{n}\,\vec{\sigma}\cdot\vec{p}\,u_s) \qquad (6)$$

Eq. (6) can be obtained directly from the integral $\int_{S\to\infty} \vec{J}\cdot d\vec{A}$

We calculate Eq. (6) using the eikonal approximation for u_s developed recently by Amado et al.[7] We find

$$\sigma_R = \chi_s^\dagger \left[\int d^2b \left(1 - \exp\left(\phi_c(b) - \phi_{SO}(b)\vec{\sigma}\cdot\vec{b}\times\hat{k}\right)\right)\right]\chi_s \qquad (7)$$

where $\phi_c(b)$ and $\phi_{SO}(b)$ are given by

$$\phi_c(b) = 2\,\mathrm{Re}\; t_c(b) \qquad (8)$$

$$\phi_{SO}(b) = 2\,\mathrm{Re}\; t_{SO}(b) \qquad (9)$$

The thickness functions $t_c(b)$ and $t_{SO}(b)$ were derived by Amado et al.[7]

$$t_c(b) = \frac{-i}{2(\hbar c)^2 k}\int_{-\infty}^{\infty} dz'\left(N^2 - F^2 + E^2 - m^2\right) \qquad (10)$$

$$t_{SO}(b) = \frac{-ib}{2}\int_{-\infty}^{\infty} dz'\,\frac{1}{N+F}\,\frac{1}{r}\frac{\partial}{\partial r}(N+F) \qquad (11)$$

where we have introduced the quantities N and F defined by

$$N \equiv m + V_s(b,z) \qquad (12)$$

$$F \equiv E - V_0(b,z) \qquad (13)$$

Using the usual spin algebra, we can reduce Eq. (7) to the final form

$$\sigma_R = 2\pi\int b\,db\; T(b) \qquad (14)$$

$$T(b) = 1 - e^{\phi_c(b)}\cosh\phi_{SO}(b) \qquad (15)$$

Eq. (14) expresses σ_R in terms of an impact parameter integral involving a relativistic transmission coefficient, T(b). It is clear that the exact form and details of T(b) would be irrelevant if the nucleon-nucleus scattering is dominated by a black disk-type absorption. In such a case T(b) would be representable as

$$T(b) = \theta(b - R_c) \qquad (16)$$

where $\theta(x)$ is the step function, and R_c is a characteristic absorption radius. If Eq. (16) is used, σ_R becomes the simple geometrical limit,

$$\sigma_R = \pi R_c^2 \qquad (17)$$

If the above were true, not too much physics would be extracted from σ_R. Luckily total reaction cross section data of proton-nucleus systems at intermediate energies exhibit major deviations from the black disk result Eq. (17). Nuclei become quite transparent to nucleons at intermediate energies[9], and the quantity that measures this nuclear transparency in details is given by T(b) of Eq. (15). Therefore detailed evaluation and discussion of T(b) and the resulting σ_R is clearly called for. This has been done using the conventional non-relativistic theory by Digiacomo, De Vries and Peng[9]. In the following we present our result for and discussion of σ_R within the Dirac-eikonal treatment presented above. The expression for σ_R we have used is a slightly modified version of Eqs. (14) and (15), to take into account the point Coulomb scattering effects.

We calculate σ_R for $p + {}^{40}Ca$ and $p + {}^{208}Pb$ in the energy range $10 < E_p < 1000$ MeV using for the complex V_s and V_o interactions, the impulse-approximation Dirac optical potential, derived by McNeil et al.[3] which has the form

$$\langle \vec{k}' | U_{oo} | \vec{k} \rangle = -\frac{4\pi i k}{m}\left[F_s(q=0)\,\rho_s(q) + \gamma_4 F_V(q=0)\,\rho_V(q)\right]$$

$$\equiv V_s(q) + V_o(q) \qquad (18)$$

where q is the momentum transfer.

In Eq. (18), F_s and F_V are the scalar and vector pieces of the Lorentz-invarinat N-N amplitude in the forward direction, respectively, and ρ_s and ρ_V are the scalar and vector form factors of the target nucleus.

We write $V_s(r) \equiv V_s(E)\,\hat{\rho}_s(r)$ and $V_o(r) \equiv V_o(E)\,\hat{\rho}_V(r)$, so that $V_s(E)$ and $V_o(E)$ correspond to the values of the potentials at a distance corresponding to a nuclear density of $0.17\ fm^{-3}$. The functions $\hat{\rho}_s(r)$ and $\hat{\rho}_V(r)$ specify the density shapes. The quantities $V_o(E)$ and $V_s(E)$ for $p + {}^{40}Ca$ were shown in Fig. 1 of McNeil et al.[3] as functions of the proton energies. We have used their results to construct the corresponding potential strengths for $p + {}^{208}Pb$.

For the density shape of ${}^{208}Pb$ we have used a Saxon-Wood form with parameters fixed in accordance with results obtained from electron scattering, which basically supplies ρ_V

for protons. We have however set $\hat{\rho}_s(r) = \hat{\rho}_V(r)$ for all r. The radius, R, and diffuseness, a, parameters for ${}^{208}Pb$, are[11]

$$R = 6.624\ fm \quad , \quad a = 0.549\ fm \quad .$$

The density shape of ${}^{40}Ca$ is usually parametrized as[11]

$$\rho_{^{40}Ca}(r) = \left(1 + \omega r^2/R^2\right)/\left[1 + \exp\{(r-R)/a\}\right] \qquad (19)$$

with $\omega = -0.1017$, $R = 3.669$ fm, $a = 0.584$ fm.

The results are presented in Figures 1 and 2. It is clear from the figures that the comparison of our σ_R in the energy range $100 < E < 1000$ MeV, where one expects our theory based on the impulse and eikonal approximation to be quite adequate, with the data shows only qualitative agreement. There is a clear indication that the impulse-approximation Dirac optical potential, whose main reactive contact is one-nucleon knockout, is not absorptive enough. The quality of our calculation coincides with those of DiGiacomo et al.[9].

Of course, at lower energies, nuclear medium effects (Pauli blocking, multiple scattering contribution, etc.), which were completely left out here, are certainly important. Thus it is pointless to dwell into a detailed discussion of our results in the energy range $10 < E < 100$ MeV.

In conclusion, we have calculated the total reaction cross sections for $p + {}^{40}Ca$ and $p + {}^{208}Pb$ in the energy range $10 < E_p < 1000$ MeV, using the Dirac-eikonal description and the first-order impulse approximation Dirac optical potential. Our results in the energy range $100 < E_p < 1000$ MeV, are below the existing experimental values, indicating that the impulse approximation Dirac optical potential results in too strong transparency.

We hope that further experimental work on would supply more precise data that would impose a stronger constraint on the theoretical description and consequently better our understanding of the physics of the proton-nucleus Dirac optical potential.

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Figure Caption

Figure 1. The total reaction cross section for p + ^{40}Ca. The data points were collected from Ref. 12. (See Text for details)

Figure 2. Same as above for p + ^{208}Pb

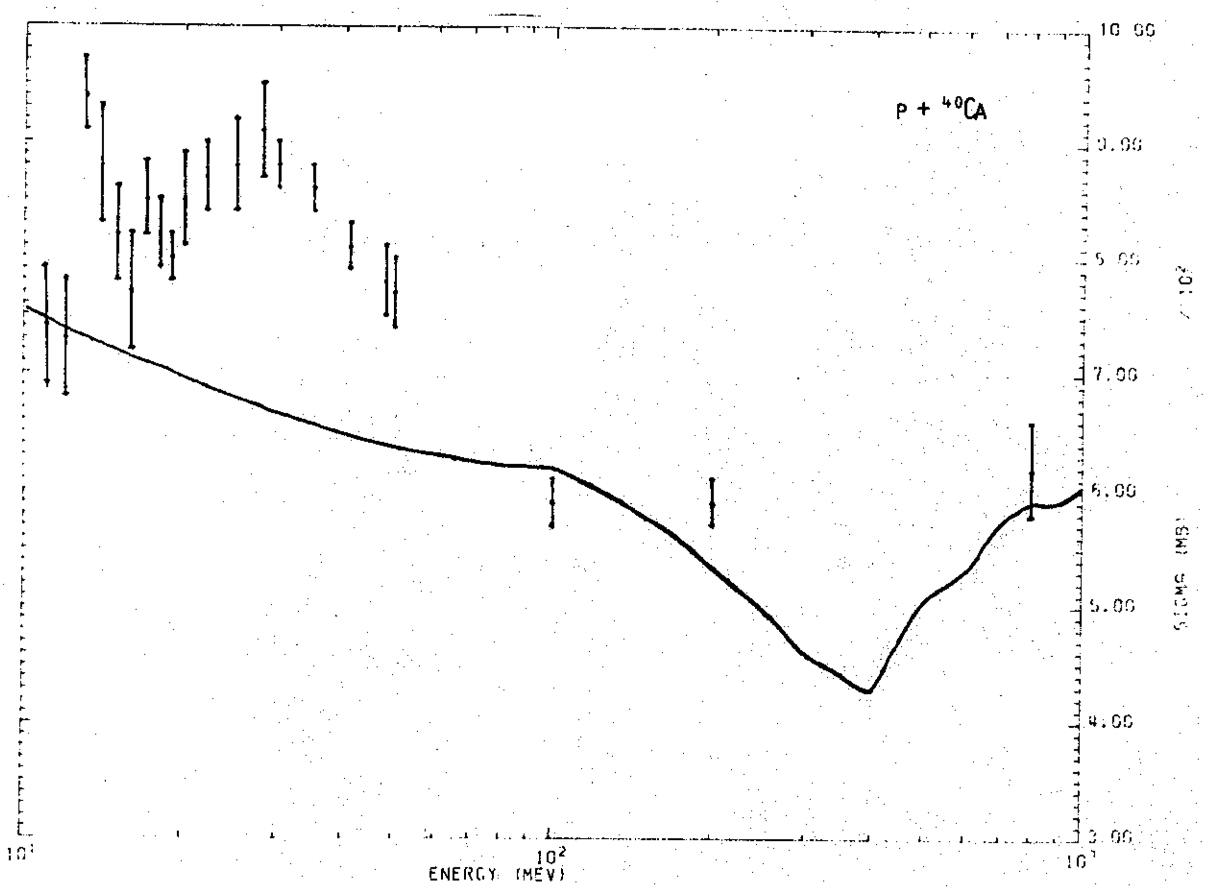

FIG. 1

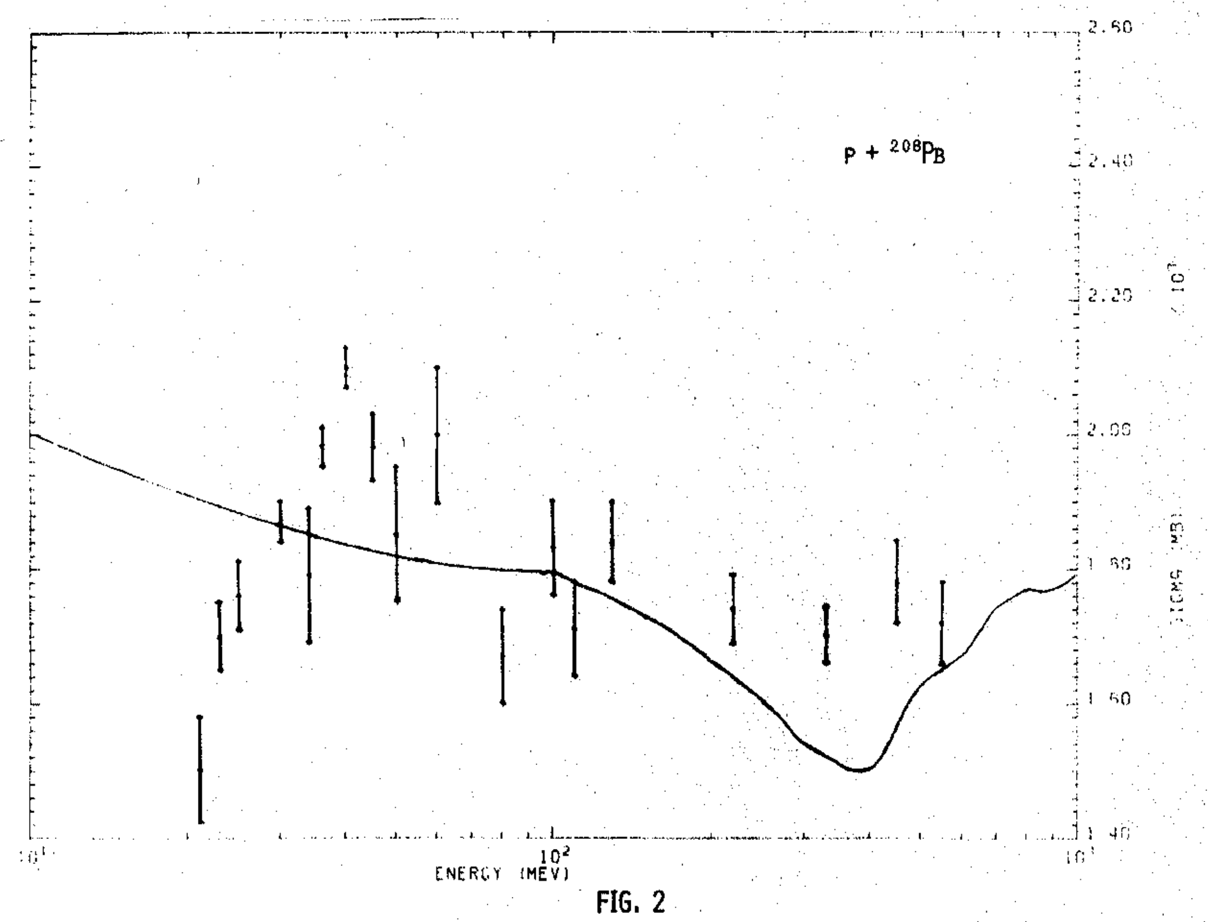

FIG. 2