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Analysis of Relativistic Optical Potential for Medium-Energy Protons

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The influence of the parameters of the relativistic optical potential on the nucleon scattering properties, such as cross sections, angular distributions and spin observables etc., is studied based on a set of global Dirac phenomenological optical potential. It is shown that, in contrast with the case at low energies, the total scattering cross sections vary slowly with the energy and depend weakly on the potentials at E_p < 300 MeV. The differential cross sections and spin observables depend not only on the volume integrals of the optical potentials, but also on their strengths and shapes. The applicability of the relativistic microscopic optical potential based on the Walecka model in the medium energy region is also discussed in this paper.

1. INTRODUCTION

Nucleon-nucleus scattering is one of important subjects in present nuclear physics studies in the medium energy region. Raising incident particle energy, the nonrelativistic optical model built in low energy area cannot adequately describe the experimental data of nucleon-nucleus elastic scatterings, especially the spin observables. During the past decade, the relativistic method has been used to investigate nucleon-nucleus scatterings with great success. These methods mainly include the relativistic impulse approximation (RIA) [1], the relativistic phenomenological optical model (RPOM)

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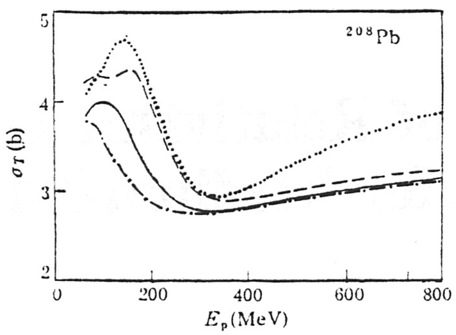

Fig. 1
Total cross section versus energies for P-^{208}Pb scatterings. The solid line denotes the result obtained by the RPOP [8], the dashed and dot-dashed lines represent the results calculated by multiplying the central potential by a factor $b = 2$ and $b = 0.5$, respectively, the dotted line denotes the result obtained by the Walecka model [5].

[2], the Walecka model (QHD) [3] and the Dirac-Brueckner-Hartree-F ock (DBHF) [4] method, etc. In the relativistic description, the mean field of a nucleon in nuclear medium results from a cancellation between the large Lorentz scalar and vector potentials and the Arithmetic sum of the scalar and vector potentials provides a strong spin-orbit potential, so it can describe the medium-energy nucleon-nucleus scatterings quite well, especially for the spin observables. The simplest model in the description of the large scalar and vector potentials of a nucleon in nuclear medium is the Walecka's σ-ω model, which starts from an effective Lagrangian including nucleon, σ and ω mesons. The coupling constants between the nucleon and mesons, g_σ and g_ω, are determined by the properties of the nuclear matter saturation. The relativistic microscopic optical potential (RMOP) obtained by the Walecka model in the Hartree-Fock (HF) approximation could describe qualitatively the elastic nucleon-nucleus scattering experimental data for incident proton energies below 300 MeV [5]. Starting from bare nucleon-nucleon interaction, the fundamental method is that the self-energy of a nucleon in the nuclear medium is derived from the DBHF in relativistic many-body theory, which could reproduce a large body of elastic nucleon-nucleus scattering data over a wide range of projectile energies [6,7]. In the description of the relativistic phenomenological optical potential (RPOP) based on Lorentz scalar-vector potentials, its parameters are adjusted to reproduce the experimental data. Recently, by fitting systematically the experimental data of the differential cross section and spin observables Hama *et al.* obtain a set of parameters of the relativistic phenomenological optical potentials for medium heavy nuclei at proton energies ranging from 65 MeV to 1040 MeV. The RPOP provides a powerful tool in the study of the relativistic nuclear reaction in the medium energy region. It can reproduce experimental data quite well over a wide energy range. In this paper, we employ the RPOP to analyze the influence of its parameters on the scattering calculation and to investigate the applicability of the relativistic optical potential obtained from the microscopic theory.

At present time, although the RMOP and RPOP have been widely studied, a systematic study and analysis of the influence of the optical potential parameters on differential cross sections and spin observables of the nucleon-nucleus elastic scatterings in the medium energy region are still lack. Because of simplicity of Walecka model, it has been extensively used to describe the nucleon-nucleus interaction in nucleus-nucleus collisions at high energies [9]. So it is necessary to discuss the applicability of the microscopic optical potential based on the Walecka model at medium and high energies. Starting from the RPOP, the influence of various parameters of the optical potential on the

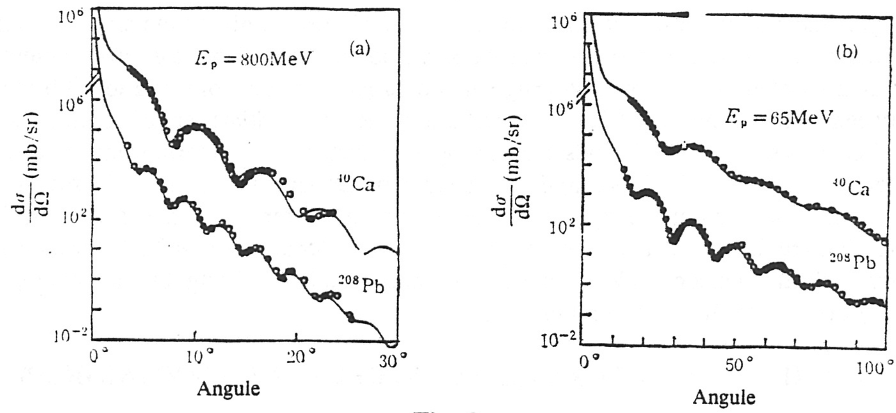

Fig. 2
Angular distributions for P-^{40}Ca and P-^{208}Pb scatterings. The solid line denotes the results given by the RPOP. (a) for the incident proton energy E_p = 800 MeV; (b) for the incident proton energy E_p = 65 MeV.

cross section and spin observables at different energies is discussed and a comparison of the microscopic optical potential based on Walecka model with the phenomenological potential is made. Thus, we showed the suitability of the Walecka model in different energy regions.

2. THE DIRAC OPTICAL POTENTIAL

In Lorentz scalar and vector optical potential model, the Dirac equation of a nucleon in nuclear medium can be expressed as

$$[\boldsymbol{\alpha} \cdot \boldsymbol{p} + \gamma_0(M + U_s(r)) + U_0(r) + V_c(r)]\Psi(\boldsymbol{r}) = E\Psi(\boldsymbol{r}), \tag{1}$$

where U_s and U_0 are the scalar and vector potentials of a nucleon in nuclear medium, respectively. They are complex and depend on the incident energy and target mass number. V_c is the Coulomb potential between a proton and the nucleus. By eliminating the small component of the wave function, one can get the second order Dirac equation, i.e., equivalent Schrödinger equation

$$\left[\frac{\boldsymbol{p}^2}{2E} + U_{eff}(r) + V_c(r) + U_{so}(r)\,\boldsymbol{\sigma} \cdot \boldsymbol{L}\right] \varphi(\boldsymbol{r}) = \frac{E^2 - M^2}{2E}\varphi(\boldsymbol{r}), \tag{2}$$

where U_{eff} and U_{so} are the Schrödinger equivalent central and spin-orbit potentials, respectively,

$$U_{eff}(r) = U_o + \frac{1}{2E}[U_s(2M + U_s) - (U_o + V_c)^2] + U_D(r),$$

$$U_D(r) = \frac{1}{2E}\left[-\frac{1}{2r^2D(r)}\frac{\mathrm{d}}{\mathrm{d}r}\left(r^2\frac{\mathrm{d}D(r)}{\mathrm{d}r}\right) + \frac{3}{4D^2(r)}\left(\frac{\mathrm{d}D}{\mathrm{d}r}\right)^2\right],$$

$$U_{so}(r) = -\frac{1}{2ErD(r)}\frac{\mathrm{d}D(r)}{\mathrm{d}r},$$

$$D(r) = M + E + U_s(r) - U_o(r) - V_c(r). \tag{3}$$

$U_D(r)$ is the Darwin term, which is small and contributes mainly on the nuclear surface. Hama *et al.* present a set of parameters of the relativistic phenomenological optical model potential (RPOMP) by fitting a set of elastic proton scattering data on targets ranging from ^{40}Ca to ^{208}Pb at incident energies between 65 MeV and 1042 MeV. The scalar and vector potentials, are of volume distribution and can be chosen as symmetrical Woods-Saxon shapes. A surface peaked term is introduced in the imaginary potential at low energies its strength decreases exponentially as the energy increases. The depth of the potential is function of energy, but the geometric parameters, i.e., the radius and diffuseness of the potential, are functions of both energy and target mass number. The RPOP reproduces not only a large body of elastic nucleon-nucleus experimental data used in the fitting, but the other experimental data. Therefore the RPOP has a good universality.

3. PARAMETERS OF THE RELATIVISTIC OPTICAL POTENTIAL (ROP)

In order to discuss the influence of the parameters of the ROP on nucleon-nucleus scatterings in the medium energy range, we choose the first set of parameters of the RPOP obtained by Hama *et al.* [8]. The partial wave method is adopted in the calculations of nucleon-nucleus scatterings at the medium energy range, and more than sixty partial waves are included in the calculations. It turns out that higher precision is required in numerical calculations. Fixing the momentum transfer $q < 3\ \text{fm}^{-1}$, the results obtained by our program coincide with those by Hama *et al.* This guarantees the correct results in the calculations.

The RPOP has been used to discuss the influence of the strength of the potential on the total scattering cross section. The change of the strength of the potential is performed by multiplying the Schrödinger equivalent potential by a factor b. Figure 1 shows that the total cross sections for proton-^{208}Pb scatterings vary with the energies. The solid line in Fig. 1 denotes the result calculated by the RPOP, the dashed and the dot-dashed lines represent the results of changing the strengths of the real part of the central potential by $b = 2$ and $b = 0.5$, respectively. It is well known that the nucleon scattering total cross section is sensitive to the strength of the optical potential at low energies. From Fig. 1 one can see that the total cross section varies with the strength of the potential for incident proton energies below 200 MeV. In contrast to the low energy case, the influence of strength on the total cross section becomes small at $E_p > 200$ MeV and the total cross section varies slowly with the energy. Therefore, the value of the total cross section does not provides more information about the nucleon-nucleus interaction in the study of high energy scatterings. In order to study the influence of the potential parameters on the angular distribution and spin observables, the proton scatterings from ^{40}Ca and ^{208}Pb are discussed at incident energies $E_p = 65$ MeV and $E_p = 800$ MeV, respectively. Because the scattering results are not sensitive to the change of the optical potential parameters at high energy cases, we take $b = 2$ and 0.5 at $E_p = 800$ MeV, and $b = 1.2$ and 0.8 at $E_p = 65$ MeV, respectively. Figure 2 shows the comparison of the differential cross sections calculated by the RPOP with the experimental data, from [10, 11]. At the two energy cases, the influences of the changed strengths of the real and imaginary parts in the Schrödinger equivalent central potential on the angular distribution are given in Fig. 3, respectively. From Fig. 3 one can see that the change of the potential strength affects weakly on the forward peak value. At high energies, the values of the cross section fall rapidly as the angle increases, so the potential strength affects weakly on the total cross sections. As the angle increases, the influence of the strength of the potential on the differential cross section increases, the greater the strength of the real part of the central potential is, the greater the cross section is. The real part of the central potential is repulsive at high energies. The cross section is still proportional to the strength. At lower energies, the variation of the strength of the real part of the central potential also changes the phase of the oscillation of the differential cross section. The phase

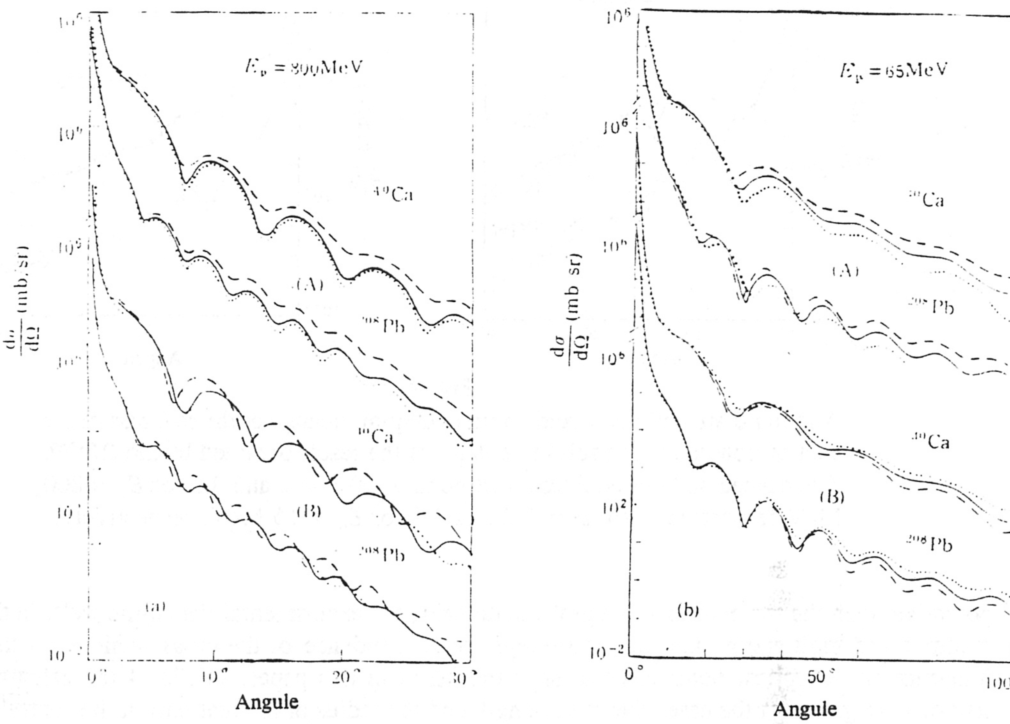

Fig. 3

Angular distributions for P-^{40}Ca and P-^{208}Pb scatterings. The solid line denotes the result obtained by the RPOP. The dashed and dotted lines correspond to (a) b = 2 and 0.5 for E_p = 800 MeV respectively; (b) b = 1.2 and 0.8 for E_p = 65 MeV, respectively; (A) changes the strength of the real part of the central potential; (B) changes the strength of the imaginary part of the central potential.

moves to the small angle as the strength increases. But, at high energies, even if the strength is doubled, the phase of the oscillation still changes weakly. The influence of the changed strength of the imaginary part of the central potential on the scattering results is less than that of the real part. At E_p = 65 MeV, when the strength of the imaginary part of the central potential is increased, the cross sections decreases, the ratio of the peak to valley values in the differential cross section becomes larger and the phase changes weakly. At E_p = 800 MeV, the situation becomes different, the strength of the imaginary part of the central potential changes mainly the phase of the diffractive picture, the phase shifts toward small angles and the cross section increases as the strength increases. As the strength of the real part of the spin-orbit potential increases, the differential cross section increases slowly. The spin-obit potential has little effect on the differently cross section, but the spin observables. The tendencies are the same at high and low energy cases. The influence of the imaginary part of the spin orbit potential is small, especially, it can be neglected at low energies. Spin observables, such as analyzing power (P) and spin rotation function (Q), are very sensitive to the change of the parameters of the optical potential, which provides the maximum constraint for the optical potential. The phase variations with the angle for the spin observables consist with that of the differential cross sections.

The parameters of the optical potential are not unique at low energies. The scattering cross section is mainly determined by the volume integral of the optical potentials. Different optical

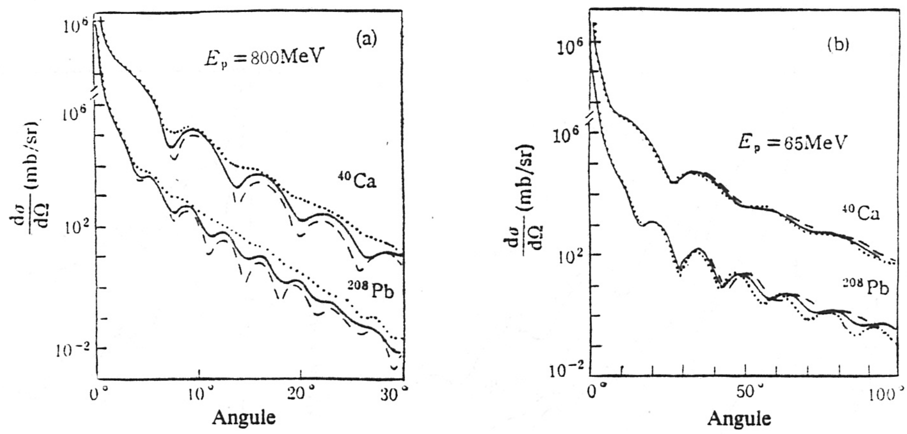

Fig. 4

Angular distributions. Fixed volume integral, change of the real part of the central potential. The solid line denotes the result obtained by the RPOP. The dashed and dotted lines correspond to (a) b = 2 and 0.5 for E_p = 800 MeV respectively; (b) b = 1.2 and 0.8 for E_p = 65 MeV, respectively.

potentials with the same volume integral can describe the experimental data quite well. In the case of medium and high energy nucleon scatterings, the dependence of the cross sections on the volume integrals of the optical potentials has been discussed in this paper. In Fig. 4 the calculated cross sections are given for the cases that the strength and the radius of the real part of the central potential are changed while the volume integrals of the potential are fixed. At E_p = 65 MeV, the differential cross section depends mainly on the volume integral of the potential and changes very little for these cases. However, the change of the calculated differential cross section is still large for different potential parameters, even if the volume integral is fixed at E_p = 800 MeV. Especially, the spin observables the strongly depend on the shape of the potential. Therefore, in order to describe scattering experimental data well, more constraints have to be made on the parameters of the optical potential, at higher energies.

4. WALECKA MODEL

In the Walecka model, the interaction between two nucleons is through exchanging isoscalar mesons and the effective coupling constants g_σ and g_ω are adjusted to reproduce the properties of the nuclear matter saturation. In the lower order approximation, we let only the Hartree-Fock self-energy of a nucleon in nuclear medium represent the real part of the nucleon-nucleus optical potential and calculate the imaginary part to the fourth order of the meson exchange diagrams. For finite nuclei, the local density approximation is adopted to obtain the relativistic microscopic optical potential [3].

In order to discuss the applicability of the RMOP based on the Walecka model in the medium energy region, a comparison of the microscopic optical potential with the phenomenological potential has been made. Figure 1 also shows that the total cross section calculated by the relativistic microscopic potential based on the Walecka model varies with energies for the proton-^{208}Pb scatterings. The strengths (r = 0) of the scalar and vector potentials for ^{40}Ca against energies are given in Fig. 5. The change of the real parts of the scalar and vector potentials in the σ-ω model with energies comes from a small Fock term. Their strengths decrease slowly by a fens tens of MeV from 65 MeV to 1000 MeV as the energy increases. However, the strength of the real part of the phenomenological potential

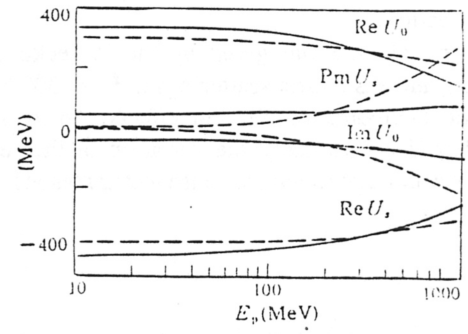

Fig. 5
The strengths of the scalar and vector potentials ($r = 0$) vary with energies. The solid and dashed lines represent the results obtained by the RPOP and the Walecka model, respectively.

falls rapidly. It changes about 200 MeV in this energy range. In contrast to the real part, the strengths of the imaginary parts of the scalar and vector potentials in the σ-ω model raise quickly as the energy increases, but the change of the phenomenological potential is quite small. From Eq. (3), one can see that the Schrödinger equivalent central potential results from a cancellation between the scalar and vector potentials. At low energies, it is determined mainly by their arithmetic sum, though the strength of the scalar and vector potentials of the phenomenological potential is larger at low energies, their arithmetic sum is similar to that in the Walecka model, so the Schrödinger equivalent potentials obtained by both models are practically the same. At high energies, the strength of the central potential depends strongly on the vector potential and weakly on the scalar potential. Because the σ-ω model provides a too strong vector potential, the strength of the Schrödinger equivalent central potential increase quickly as the energy increases. Therefore, its deviation from the phenomenon topical potential is bigger. The spin-orbit potential is determined by the arithmetic sum of the scalar and vector potentials (U_s-U_0). A stronger spin orbit potential is given by the phenomenological potential at low energies, its real part is negative and decreases slowly as the energy increases. Because the strengths of the scalar and vector potentials in microscopic potential are too large at high energies, the real and imaginary parts of the spin-orbit potential given by them are too strong.

5. SUMMARY

An analysis of the parameters of the relativistic phenomenological optical potential for medium energy protons shows the situation to be different from that at low energies. At $E_p > 300$ MeV the total cross section varies slowly with the energy and weakly depends on the potentials, meanwhile the differential cross sections and the spin observables depend not only on the volume integral of the optical potentials, but also on their strengths and shapes. The central potential plays a principal role for the differential cross section. The influence of the imaginary part of the central potential on the cross section increases as the energy increases. The real part changes the phase of the diffractive picture of the differential cross section at low energies. While at high energies, it changes mainly the value of the cross section. The stronger the potential is, the greater the cross section is. The phase changes are very small. For the imaginary part of the central potential it is different. At lower energies if the strength increases the ratio between the peak and valley values of the differential cross section increases. At high energies its influence on the phase becomes greater. The spin-orbit potential affect weakly on the differential cross section and affect mainly on the spin observables. The spin observables are the most sensitive experimental measurable quantity, changing of any optical potential parameters can induce the change of its value, but, the oscillation phase of the spin observables is related to that of the differential cross section.

The microscopic optical potential given by the Walecka σ-ω model can give a qualitative description of the nucleon-nucleus elastic scatterings at $E_p < 300$ MeV. However, a simple σ-ω model do not describe well the nucleonic correlation effects, especially the energy-dependence of the potential. In order to describe reasonably the variation of the self-energy of a nucleon in nuclear medium with energy, it is necessary to introduce isovector mesons and consider high order correlation effects in this model.

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