

Role of the nuclear surface on the reaction cross section for deformed nuclei

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Abstract-The reaction cross section for proton scattering from ^{12}C , ^{20}Ne , ^{40}Ca , ^{54}Fe and ^{208}Pb at 800 MeV is calculated according to Glauber theory. The density of the target is considered in Symmetrized Fermi form. The deformation of the target nucleus and the finite range of the nucleon-nucleon amplitude are considered. The calculations are done for modified Glauber model I (*i.e.* taking into account Coulomb field) and modified Glauber model II (*i.e.* taking into account Coulomb and nuclear fields). The results of considering deformation and finite range are quite near to the available experimental values.

Key words: *proton-nucleus scattering, reaction cross section, Glauber optical model.*

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1. Introduction:

The reaction cross section, σ_R , is one of the most inclusive information about the interaction of a projectile with a target and of fundamental importance in the full understanding of a nuclear system [1]. Values of σ_R largely determine the imaginary part of the optical potential for heavy nuclei and therefore represent a strong constraint on the optical potential which also represent a fundamental quantity in nuclear studies. Interaction cross section measurements at high energies have been used to estimate the extent of matter densities of exotic nuclei produced in fragmentation reactions [2,3]. Attempts have been made to extract the same information from reaction cross section measurements at lower energies [4-10]. Also, the nuclear reaction cross section is very useful for extracting fundamental information about the nuclear size and the density distributions of neutrons and protons in the nucleus. It also finds applications in various fields of research including shielding against heavy ions originating from, for example, space radiation and also against radiobiological effects resulting from clinical exposure. Also, it has applications in medicine, cosmic ray propagation, detector simulate on in particle and high energy physics, astrophysics, etc. [11,12].

Many attempts have been made to describe the reaction cross section in terms of the so-called optical limit to the Glauber model for proton-nucleus and nucleus-nucleus collisions [13-22]. In the simple Glauber approach, it's assumed that the flux attenuation of the elastic channel occurs by means of the classical straight line

trajectory. The scope of the Glauber model was extended to lower energies by modifying the Glauber model to account for the Coulomb distortion of the trajectory. It's the so-called modified Glauber model I. Within the framework of modified Glauber model I, Abul-Magd *et al* [23] have calculated the total reaction cross section for both proton-nucleus and nucleus-nucleus scattering. Their formula satisfied a satisfactory description to the experimental data at energies up to 100 MeV. They referred to the discrepancy, through the low energy range, as due to the physical effects which were not included in their calculation such as the internal Fermi-motion of the nucleons in the nuclei and the Pauli-blocking effects. Within the same framework, Alvi has introduced an analytical expression for proton-nucleus total reaction cross section using an approximate form of the Helm model form factor for the distributions of nucleons within nuclei [24]. It agrees well with the experimental data. The modified Glauber model I has been modified to take into account the deflection effect on the trajectory due to the nuclear potential effect. This formalism is referred to as the modified Glauber model II [25-27].

Most of the previous analyses using Glauber's theory have assumed Gaussian form for the density distribution functions. This leads to a considerable simplification in the calculations of the nuclear transparency function. While the Gaussian function may provide a reasonable description for the density distribution of light nuclei, certainly it will be invalid for intermediate and heavy mass nuclei. Lukyanov *et al* [28] have introduced the Symmetrized-Fermi function as an even analytical function valid for intermediate and heavy nuclei *i.e.* it resembles a Gaussian function for light nuclei while for heavier ones it goes over to the Fermi distribution. Symmetrized-Fermi function was successful in describing the elastic and inelastic angular distributions and the reaction cross section for heavy ion collisions [29-34]. In [35], it was a try to make use of the Symmetrized-Fermi function to introduce the Woods-Saxon optical potential and thus the elastic and inelastic angular distributions for proton-nucleus scattering.

In the present work, using microscopic Glauber optical model, we are going to compute the total reaction cross section for proton-nucleus scattering. The target nuclei are considered to be permanently deformed, axially, symmetric rotating. We will execute the integrations on the angles of the symmetry axis analytically using the same steps proceeded by Fäldt and Glauber [36]. The nuclear density function has only a quadrupole deformation. In addition, the Symmetrized-Fermi function is used to derive the optical thickness which is embedded in the eikonal phase shift in case of either zero or finite ranges. We study the influence of Coulomb and nuclear effects in modified Glauber models I and II. The reaction cross section is calculated for P-¹²C, ²⁰Ne, ⁴⁰Ca, ⁵⁴Fe and ²⁰⁸Pb at 800 MeV. We have compared the results in case of deformed nuclei with that in case of spherical nuclei.

2. Formalism:

Within the context of the diffractive collision theory, it's assumed that the deformed nucleus is initially in its rotational ground state, a state in which the symmetry axis Ω_p has the isotropic wave function $Y_0^0(\Omega_p) = (4\pi)^{-1/2}$ and goes to a final rotational state with wave function $Y_L^M(\Omega_p)$. So, in our calculations, we should be aware that the phase shift function depends on the instantaneous orientation Ω_p of

the symmetry axis of the nucleus as well as on the impact vector \mathbf{b} of the incident nucleon [36]. The corresponding reaction cross section for proton-nucleus scattering averaged over all orientations of the symmetry axis which is associated with non-rotational transitions is thus:

$$\sigma_R = \int d^2b \int \{1 - \exp[-\chi(\mathbf{b}, \Omega_p)]\} \frac{d\Omega_p}{4\pi} \quad (1)$$

where the imaginary part of the eikonal phase shift can be represented as:

$$\chi(\mathbf{b}, \Omega_p) = \bar{\sigma}_{NN} \int t(\mathbf{s}, \Omega_p) f(\mathbf{s}, \mathbf{b}) d^2s \quad (2)$$

And the nucleon-nucleon range function $f(b)$ can be used in the Gaussian form:

$$f(b) = \frac{1}{\pi r_0^2} \exp(-b^2/r_0^2) \quad (3)$$

where r_0 is the range parameter. Carrying out the integration over angles will leads to the form:

$$\chi(b, \Omega_p) = \bar{\sigma}_{NN} \int_0^\infty t(s, \Omega_p) F(s, b) s ds \quad (4)$$

where:

$$F(s, b) = \frac{2}{r_0^2} \exp[-(s^2 + b^2)/r_0^2] I_0(2sb/r_0^2) \quad (5)$$

and the average NN cross section $\bar{\sigma}_{NN}$ averaged over neutron and proton numbers is given by:

$$\bar{\sigma}_{NN} = \frac{Z_T}{A_T} \sigma_{pp} + \frac{N_T}{A_T} \sigma_{np} \quad (6)$$

where σ_{pp} and σ_{np} are the proton-proton and neutron-proton cross section respectively. They have the forms:

$$\sigma_{pp} = 13.73 - 15.04/\bar{\beta} + 8.76/\bar{\beta}^2 + 68.67\bar{\beta}^4 \quad (7)$$

and

$$\sigma_{np} = -70.67 - 18.18/\bar{\beta} + 25.26/\bar{\beta}^2 + 113.85\bar{\beta} \quad (8)$$

Here $\bar{\beta}$ is the ration between projectile velocity to light velocity, which can be written in the form [17]:

$$\bar{\beta} = \sqrt{1 - \frac{1}{\gamma^2}}, \quad \bar{\gamma} = \frac{E_L}{931.5} + 1.0 \quad (9)$$

and E_L represents the incident energy in the laboratory frame.

The optical thickness function of the nucleus can be defined as:

$$t(\mathbf{s}, \Omega_p) = \int_{-\infty}^{\infty} \rho(\mathbf{s} + \hat{k}z, \Omega_p) dz \quad (10)$$

Here, the vector \hat{k} is a unit vector in the direction of the incident momentum \mathbf{k} . The nuclear density distribution function has the form of Symmetrized-Fermi function:

$$\rho(r) = \rho(0) \left\{ \frac{1}{1 + \exp\{[r - R(\Theta)]/a\}} - \frac{1}{1 + \exp\{[r + R(\Theta)]/a\}} \right\} \quad (11)$$

with

$$R(\Theta) = c \left\{ 1 + \sum_L \beta_L Y_L^0(\Theta) \right\} \quad (12)$$

where the sum runs only over even values of L . If we take into consideration the quadrupole deformation only (*i.e.* $L = 2$) and expand the nuclear density functions in powers of the deformation parameter β_2 , so it can be written in the form:

$$\rho(r) = \rho_0(r) + \rho_2(r) P_2(\cos \Theta) \quad (13)$$

To separate the dependences on the orientation angles in the expression of the thickness function, we can make use of the addition theorem for spherical harmonics:

$$P_2(\cos \Theta) = \frac{4\pi}{5} \sum_{M=-2}^2 Y_2^{M*}(\Omega) Y_2^M(\Omega_p) \quad (14)$$

In this expression, $\Omega = (\theta_r, \phi_s)$ represents the angular coordinates of the vector $\mathbf{r} = (\mathbf{s}, z)$ in the laboratory system, $\Omega_p = (\theta_p, \phi_p)$ represents the coordinates of the symmetry axis in the same system and Θ is the angle between \mathbf{r} and the symmetry axis Ω_p . It should be noted that the vectors, like \mathbf{b} , lies in the impact plane and the integration will be extended in that plane, then:

$$\rho(r) = \rho_0(r) + \frac{4\pi}{5} \rho_2(r) \sum_{M=-2}^2 Y_2^{M*}(\Omega) Y_2^M(\Omega_p) \quad (15)$$

There is no loss of generality involved in setting $\phi_s = 0$ [36] and we shall do that in the work that follows:

$$\rho(r) = \rho_0(r) + \frac{\sqrt{4\pi}}{5} \rho_2(r) \left\{ Y_2^0(\theta_r, 0) \left[\frac{\sqrt{5}}{2} (3\mu^2 - 1) \right] + Y_2^2(\theta_r, 0) \left[\sqrt{\frac{15}{2}} (1 - \mu^2) \cos \phi_p \right] \right\} \quad (16)$$

where $\mu = \cos \phi_p$.

Now, to carry out the integration over straight line paths through the instantaneous configuration of the nucleus, we write:

$$t(s, \Omega_p) = t_{00}(s) + t_{20}(s) \left[\frac{\sqrt{5}}{2} (3\mu^2 - 1) \right] + t_{22}(s) \left[\sqrt{\frac{15}{2}} (1 - \mu^2) \cos \phi_p \right] \quad (17)$$

where $t_{00}(s)$, $t_{20}(s)$ and $t_{22}(s)$ are the partial wave thickness functions and they can be defined as:

$$t_{ij}(s) = \frac{\sqrt{4\pi}}{2i+1} \int_{-\infty}^{\infty} \rho_i(\sqrt{s^2 + z^2}) Y_i^j(\theta_r, 0) dz \quad (18)$$

where the partial wave nuclear density distribution functions:

$$\rho_0(r) = \rho(0) u_{SF}(r) \quad (19)$$

and

$$\rho_2(r) = -\rho(0) \beta_2 c \frac{d}{dr} u_{SF}(r) \quad (20)$$

where the compact form of the Symmetrized-Fermi function is:

$$u_{SF}(r) = \frac{\sinh(c/a)}{\cosh(c/a) + \cosh(c/a)} \quad (21)$$

With respect to the zeroth order partial wave thickness function $t_{00}(s)$, the integration over z can be carried out analytically using Lukyanov expression [29] *i.e.*

$$t_{00}(s) = 2a\rho(0) u_{SF}(s) P(s) \quad (22)$$

where the nuclear matter:

$$\rho(0) = \frac{3A_T}{4\pi c^3} \left[1 + \left(\frac{\pi a}{c} \right)^2 \right]^{-1}, \quad (23)$$

$$P(s) = \frac{1}{\sqrt{1-x}} \ln \frac{1 + \sqrt{1-x}}{1 - \sqrt{1-x}} \quad (24)$$

and

$$\bar{x} = \frac{2}{\kappa} \frac{\cosh(s/a)}{\cosh(c/a) + \cosh(s/a)} \left\{ 1 + \frac{\kappa - 1}{\cosh(s/a)} \right\} \quad (25)$$

where the parameter κ is defined as:

$$\kappa = e^\delta, \quad \delta = 1.10315 + 0.34597(c/a) - 0.00446(c/a)^2 \quad (26)$$

As a result, the imaginary part of the eikonal phase shift function is:

$$\chi(b, \Omega_p) = \chi_{00}(b) + \chi_{20}(b) \left[\frac{\sqrt{5}}{2} (3\mu^2 - 1) \right] + \chi_{22}(b) \left[\sqrt{\frac{15}{2}} (1 - \mu^2) \cos \phi_p \right] \quad (27)$$

where $\chi_{00}(b)$, $\chi_{20}(b)$ and $\chi_{22}(b)$ are the partial wave eikonal phase shift functions and they can be defined as:

$$\chi_{ij}(s) = \bar{\sigma}_{NN} \int_{-\infty}^{\infty} t_{ij}(b) F(s, b) s ds \quad (28)$$

The above equations for the partial wave eikonal phase shifts take into consideration the finite range of the interaction in $F(s, b)$ function. If we have applied the zero range approximation, for simplicity, then the partial wave eikonal phase shifts are:

$$\chi_{ij}(b) = \bar{\sigma}_{NN} t_{ij}(b) \quad (29)$$

where the partial wave optical thickness functions $t_{00}(s)$, $t_{20}(s)$ and $t_{22}(s)$ have been defined previously in eq.(19). The difference in this case is that the integration is executed in b instead of s plane.

Our aim now is to carry out the integration over the angles of the symmetry axis $\Omega_p = (\theta_p, \phi_p)$. Firstly, let's represent the eikonal phase shift as:

$$\chi(b) = \chi_{00}(b) - A(b, \mu) - B(b, \mu) \cos(2\phi_p) \quad (30)$$

where

$$A(b, \mu) = -\frac{\sqrt{5}}{2} \chi_{20}(b) (3\mu^2 - 1) \quad (31)$$

and

$$B(b, \mu) = -\sqrt{\frac{15}{2}} \chi_{22}(b) (1 - \mu^2) \quad (32)$$

As a result, the reaction cross section takes the form:

$$\sigma_R = 2\pi \int_0^{\infty} b db \left\{ 1 - e^{-\chi(b)} \gamma(b) \right\} \quad (33)$$

where

$$\gamma(b) = \frac{1}{4\pi} \int_{-1}^1 \int_0^{2\pi} \exp[A(b, \mu) + B(b, \mu) \cos(2\phi_p)] d\phi_p d\mu \quad (34)$$

Applying the series expansion to the exponential function and the Binomial theorem, then we get:

$$\gamma(b) = \frac{1}{4\pi} \sum_{Q=0}^{\infty} \frac{1}{Q!} \sum_{q=0}^Q \binom{Q}{q} \int A(b, \mu)^{Q-q} B(b, \mu)^q d\mu \int_0^{2\pi} [\cos(2\phi_p)]^q d\phi_p \quad (35)$$

The integral vanishes unless $\frac{1}{2}q$ is an integer. Therefore, it's convenient to write $q = 2p$, where p is a non-negative integer. Carrying out the elementary integration on ϕ_p and substituting with eq. 's (32,33) [36] we get:

$$\gamma(b) = \frac{1}{2} \sum_{Q=0}^{\infty} \frac{1}{Q!} \left\{ -\frac{\sqrt{5}}{2} \chi_{20}(b) \right\} \sum_{p=0}^{Q} \binom{Q}{2p} \int_{-1}^1 (3\mu^2 - 1)^{Q-2p} (1 - \mu^2)^{2p} d\mu \left\{ \frac{\sqrt{6} \chi_{22}(b)}{\chi_{20}(b)} \right\}^{2p} \frac{1}{4^p} \binom{q}{2p} \quad (36)$$

Then, the final form:

$$\gamma(b) = \sum_{Q=0}^{\infty} W(Q, \chi_{20}, \chi_{22}), \quad (37-a)$$

$$W(Q, \chi_{20}, \chi_{22}) = \left\{ -\frac{\sqrt{5}}{2} \chi_{20} \right\} \sum_{p=0}^{Q} \left\{ \frac{\sqrt{2} \chi_{22}}{\chi_{20}} \right\} \omega(Q, p), \quad (37-b)$$

$$\omega(Q, p) = \frac{1}{Q!} \left(\frac{3}{4} \right)^p \binom{Q}{2p} \binom{2p}{p} G(Q - 2p, 2p) \quad (37-c)$$

and

$$G(Q - 2p, 2p) = 2^{Q-2p} \sum_{m=0}^{\infty} \left(-\frac{3}{2} \right)^m \binom{Q-2p}{m} \frac{(2m+4p)!}{(2m+4p+1)!} \quad (37-d)$$

We limit ourselves to those terms that satisfy $Q \leq 5$:

$$\gamma(b) = 1 + \frac{2}{5}(x^2 + y^2) + \frac{8}{105}(-3x^2y + y^3) + \frac{2}{35}(x^2 + y^2)^2 + \frac{16}{1155}(x^2 + y^2)(-3x^2y + y^3) \quad (38)$$

where:

$$x = -\sqrt{\frac{5}{2}} \chi_{22}(b), \quad y = -\frac{\sqrt{5}}{2} \chi_{20}(b) \quad (39)$$

Now, we intend to calculate the reaction cross section in modified Glauber model I. To do this, we should take into account the Coulomb trajectory distortion for the impact parameter in the zeroth order partial wave eikonal phase shift function *i.e.* the straight line trajectory has been deviated under the influence of the Coulomb potential. Thus, the distance of the closest approach due to this effect [15-18,23]:

$$b \rightarrow b' = \left(\eta + \sqrt{\eta^2 + k^2 b^2} \right) / k \quad (40)$$

where k is the wave number and the Sommerfeld parameter is:

$$\eta = \frac{Z_r e^2}{\hbar v} \quad (41)$$

Then, σ_R^C is given by:

$$\sigma_R^C = 2\pi \int_0^{\infty} b db \{1 - e^{-\chi_{00}(b')} \gamma(b)\} \quad (42)$$

In addition to the above respects, we take into consideration the effect of the influence of the nuclear potential on the straight line trajectory according to modified Glauber model II. The distance of the closest approach in this case, b'' , is given by solving the following equation[25]:

$$E - \frac{Z_T e^2}{r} - \frac{\hbar^2 k^2 b^2}{2\mu r^2} - \text{Re}V_N(r) = 0 \quad (43)$$

where the real nuclear optical potential is taken to be in Woods-Saxon form. The parameters of the optical potential are taken from [25]. Then:

$$b \rightarrow b'' = b' - \frac{\text{Re}V_N(b')}{V'_{\text{eff}}(b')} \quad (44)$$

Again σ_R^{CN} will be given by:

$$\sigma_R^{\text{CN}} = 2\pi \int_0^{\infty} b db \{1 - e^{-\chi_{00}(b')} \gamma(b)\} \quad (45)$$

3. Results and discussion:

In the framework of the Glauber optical model and its modifications, the reaction cross section of proton-nucleus scattering has been calculated for different target nuclei (^{12}C , ^{20}Ne , ^{40}Ca , ^{54}Fe , ^{208}Pb) at 800 MeV. The calculations have been carried out using Symmetrized-Fermi density distribution function. We are comparing between the effects of spherical and deformed axially symmetric rotating nuclei. The nuclear density function has only a quadrupole deformation effect. Also, we take into account the effects of the finite and zero range interactions. All calculations are executed using Fäldt and Glauber procedure [36] for carrying out the integrations on the orientation angles of the symmetry axis Ω_p . The deformation parameters which have been used are the same as that used for the deformed Woods-Saxon optical potential [37-40]. Due to the deficiency of the experimental values of the reaction cross section for proton-nucleus collisions at intermediate energies, we will compare our results in case of proton - ^{12}C interaction only.

In table (1), we are concerned with presenting the results of the above considerations. The 1st column represents the target nuclei. In each block of the target nuclei, the 1st row in the block represents the results for spherical nuclei (i.e. $\beta_2 = 0$) while the 2nd row in the block represents the results taking into account the effect of deformation, as shown in the 2nd column. In the 3rd column, $\sigma_{R(r_0)}$ is the reaction cross section with the finite range effect. The 4th column is the same as the 3rd column but $\sigma_{R(r_0)}^C$ has been calculated in modified Glauber model I. Also, the 5th is the same as the 3rd column except $\sigma_{R(r_0)}^{\text{CN}}$ has been calculated in modified Glauber model II. The

6th, 7th and 8th columns are the same as the 3rd, 4th and 5th columns respectively except that they have been represented using zero range approximation.

In table (1), for P-¹²C interaction, $\sigma_{R(r_0)}$ (spherical) is the maximum value for the reaction cross section in the standard Glauber model. Calculating $\sigma_{R(r_0)}$ takes into account the finite range effect. The deformation effect decreases this result by 2.75 %.

Table (1): The reaction cross section for P-¹²C, ²⁰Ne, ⁴⁰Ca, ⁵⁴Fe and ²⁰⁸Pb scattering at 800 MeV

Target		$\sigma_{R(r_0)}$	$\sigma_{R(r_0)}^C$	$\sigma_{R(r_0)}^{CN}$	$\sigma_{R(0)}$	$\sigma_{R(0)}^C$	$\sigma_{R(0)}^{CN}$
¹² ₆ C	Spherical	270.6117	269.2405	268.1447	251.8164	250.831	249.6677
	Deformed	263.1772	261.7458	260.5738	235.4743	233.9663	232.5943
²⁰ ₁₀ Ne	Spherical	409.8325	407.0996	406.8332	390.4033	388.2348	387.9574
	Deformed	399.6481	396.7928	396.5078	369.9468	366.9611	366.6364
⁴⁰ ₂₀ Ca	Spherical	647.0348	640.3011	639.1108	621.238	615.2258	613.9783
	Deformed	645.6083	638.8359	637.6342	619.2466	612.4967	611.2213
⁵⁴ ₂₆ Fe	Spherical	784.2671	774.7372	746.572	754.44	745.6398	716.3175
	Deformed	779.6647	769.9635	741.0406	747.1049	737.2569	706.2729
²⁰⁸ ₈₂ Pb	Spherical	1805.384	1771.824	1765.556	1743.397	1699.004	1691.348
	Deformed	1802.364	1768.392	1762.003	1740.126	1694.127	1686.261

But if we take into account the zero range approximation, $\sigma_{R(0)}$ is decreased by the deformation factor $\gamma(b)$ (eq.(37)) by 6.5%. The effect of deformation increases slightly in the framework of modified Glauber models I and II. Moreover, $\sigma_{R(r_0)}^C$ (deformed) is the nearest one to the experimental data $\sigma_R^{\text{exp}} = 262 \pm 13$. In case of P-²⁰Ne interaction, it is the same as P-¹²C interaction *i.e.* $\sigma_{R(r_0)}$ (spherical) is the maximum value. The deformation factor $\gamma(b)$ alters by 2.5% and this percentage increases in case of zero range approximation to 5.24%. These percentages increase slightly in modified Glauber models I and II.

In the 3rd block, the results of P-⁴⁰Ca reaction cross section have been introduced. The deformation factor $\gamma(b)$ has a negligible effect either in case of zero or finite ranges in the standard Glauber model and its modifications. On the other side, the effect of inserting the finite range in calculations nearly equates either in case of inserting the deformation effect or not. This refers that ⁴⁰Ca has a spherical shape and it is non-deformed. For P-⁵⁴Fe and P-²⁰⁸Pb in the 4th and 5th blocks, $\sigma_{R(r_0)}$ (spherical) gives the max result for each interaction. The effect of deformation ranges from 0.6% to 1.4% for P-⁵⁴Fe and ranges from 0.167% to 0.3% for P-²⁰⁸Pb interaction. As a

result to these slight effects, in each block, the finite range force gives the same effect in case of spherical and deformed considerations in the standard Glauber model and its modifications.

Generally, as an overall view on the results in table (1), the Coulomb distortion effect increases due to increasing the mass number. The percentage of this effect ranges from 0.5% to 2%. Another treatment for the effect of the finite range force: It ranges from 7.4% to 3.56% for the case of spherical effect consideration in the standard Glauber model. Within the same framework, taking into account the deformation effect, the finite range effect vary from 11.76% to 3.58%. In modified Glauber models I and II slight increments may be added to the above percentages.

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