Material Science Research India Vol. **7**(1), 145-151 (2010)

The behavior of reaction cross-section at low and intermediate energies by considering in-medium effects in σ_{NN} for light and heavy target nuclei

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(Received: May 04, 2010; Accepted: June 26, 2010)

ABSTRACT

The in-medium effects in nucleon-nucleon cross-section were treated using different approaches. We study the variation of σ_R with different values of rms. Also we study the variation of σ_R with different values of incident energy per projectile nucleon for light interacting pair ^{12}C-^{12}C and heavy target nucleus pair ^{12}C-^{208}Pb. The coulombs repulsion was taken into consideration by assuming a simple model. We found that the in-medium effects on σ_R are small when the target nucleus becomes heavy.

Key words: Nucleon-nucleon cross-section, light & heavy target nuclei.

INTRODUCTION

In recent years the total reaction cross-section of heavy ions has become the focus of extensive theoretical[1-4] and experimental[5] attention. The reaction cross-section also finds applications in diverse research areas such as radiobiology and space science[6,7]. Moreover the total reaction cross-section, $\sigma_{R,}$ is one of the most important physical quantities describing the properties of nuclear reaction. The reaction cross-section is used to calculate the nuclear root mean square radius (rms) which is necessary to understand the nucleus-nucleus reactions and scattering mechanisms[1]. In Ref. [6], the effective rms radii of nucleon distribution of B, Be and He isotopes had been deduced by comparing the experimental data for the reaction cross-section by theoretical calculations based on Glauber theory. The optical limit to Glauber theory is usually used with appreciable success to describe the reaction cross section between complex nuclei[2,3,8]. The inputs to these calculations are the nucleon- nucleon (NN) reaction cross-section, σ_{NN}, and the density distribution of the interacting nuclei. Recently, this method has been used to determine the rms radii of the interacting nuclei and to study halo nuclei[3,6,8,9]. The value of σ_R for a pair of interacting nuclei calculated in the frame work of the optical limit of Glauber theory is affected by different factors. One of these factors is the method of treating in-medium effects. Also, it is sensitive to the range of the NN force and the values of rms radii of the nuclei considered. σ_R is usually calculated by assuming the zero-rang force [3] of the interacting nucleons and the NN reaction cross-section is considered through different approaches [1,5,9]. First, σ_{NN} is taken directly as free NN cross-section, σ^f_{NN} [8], without density dependence or evaluated at constant density usually assumed to be equal to saturation nuclear matter density (ρ=0.17 fm^{-3})[1,9].This approach in treating in-medium effects permits extracting σ_{NN} out of integrations since, in this case, it has constant value. Moreover for constant value of σ_{NN} and assuming Gaussian shapes for the density distribution, most of the integrals in calculating σ_R can be performed analytically which means that the evaluation of σ_R is numerically very simple.

The in-medium effects in NN cross section[10-13] at low and ntermediate energies is due to Pauli blocking, which prevents the scattered nucleons to go into occupied states in binary collisions between the projectile and target nucleons.

The accurate treatment of in-medium effects is the geometric approach of Pauli blocking which needs numerical calculations of five fold integral to get σ_{NN}. Due to this complexity, many authors simplified this effect by assuming different approximations[10-13]. Recent expression for σ_{NN} was derived in Ref's [1,9] which takes in-medium effects through density and energy dependence in σ_{NN}. When σ_{NN} (ρ) is determined from local matter density in each volume element of the nuclear overlap region, the value of σ_R is reduced by few percent compared with that obtained using free NN cross section σ^f_{NN} [10,14]. This is because the constant effective global density ρ in σ_{NN} which produces the same value of σ_R as the more complicated correct treatment of density dependence is too small compared to the saturation nuclear matter density ρ = 0.17 fm^{-3} [9]. Since the calculated value of σ_R is affected by several factors like the method of treating in-medium effects, rms radii of nuclei and range of NN force, it is needed to study the variation of σ_R with these factors.

The aim of the present work is to study the variation of the reaction cross-section at low and intermediate energies with different approaches of considering in-medium effects of σ_R .In this study we assume spherical shapes for both target and projectile nuclei and we consider different values of rms radius of the interacting nuclei. We use the recent density and energy dependent σ_{NN} derived in Ref.[9]. In the present study we first take σ_{NN} to be the free NN cross-section then we evaluate it at constant density value ρ =0.175 fm^{-3}. We compare the values of σ_R calculated by these two methods with the results obtained assuming local density variation in each volume element through the integration process.

The next section briefly describes the method of calculating σ_R using the optical limit of Glauber theory. The results and discussion are given in section -3.

Formulation

In the optical limit of Glauber theory, calculations of σ_R need a knowledge of the nuclear transparency T(b). This quantity is the probability that a projectile with impact parameter b will be transmitted through the target. Assuming purely absorptive and zero range approximation of the interacting nucleons, T(b) is given by

$$T(b)=\exp[-\int_{-\infty}^{\infty} dz \int d\vec{r}\ \ \bar{\sigma}_{NN}(\rho, E_{Lab}/A_p)\ \rho_p(r)\ \rho_T(|\vec{R}+\vec{r}|) \quad ...(1)$$

where $\vec{R}$ is the separation vector joining the centers of mass of the interacting nuclei and is the incident energy per projectile nucleon in the laboratory system. is the in-medium nucleon-nucleon cross-section at the given incident energy.

The iso-spin averaged NN cross section is evaluated at density value $\rho=\rho_p(r)+\rho_T(|\vec{R}+\vec{r}|)$ and averaged over the reaction cross sections of neutron-neutron,, proton-proton and neutron-proton , as

$$\bar{\sigma}_{NN}=\frac{N_T N_p \sigma_{nn}+Z_p Z_T \sigma_{pp}+(N_p Z_T+N_T Z_p)\sigma_{np}}{A_p A_T} \quad ...(2)$$

E_{Lab}/A_p $\sigma_{NN}(\rho_p E_L/A_p)$ $\bar{\sigma}_{NN}$ $\langle r^2\rangle^{1/2}$

where $A_{P(T)}$,$Z_{P(T)}$ and $N_{P(T)}$ are the projectile (target) mass, charge, and neutron numbers, respectively.

The reaction cross-section is obtained after integration of the nucleus-nucleus over all impact parameters as,

$$\sigma_R\ \ (E_{Lab}/A_p)=2\pi\int_0^{\infty} b\ \ db\ \ [1-T(b)] \quad ...(3)$$

We assume that the density of the heavy spherical nuclei is given by the Fermi shape

$$\rho(r)=\frac{\rho_0}{1+\exp\left(\frac{r-R}{a}\right)} \quad ...(4)$$

For light nucleus, we take the density parameters from Ref.[15]. The root mean square radius of the nucleus is defined by

$$\langle r^2\rangle=\frac{\int\rho(r)r^2 d\vec{r}}{\int\rho(r)d\vec{r}} \quad ...(5)$$

A correct parameterization of the cross-section between two free nucleons is given by Charagi and Gupta [1]. It depends on the incident nucleon energy in laboratory system as

$$\sigma^f_{nn} = 13.73 - 15.04\beta^{-1} + 8.76\beta^{-2} + 68.67\beta^4$$
$$\sigma^f_{np} = -70.67 - 18.18\beta^{-1} + 25.26\beta^{-2} + 113.85\beta \quad ...(6)$$

where

$$\beta = \sqrt{1.0 - \frac{1.0}{\gamma^2}} \quad , \quad \gamma = \frac{E_{lab}}{931.5} + 1.0$$

In-medium effects modify the free space cross-section in the following way,

$\sigma_{nn}(\rho, \frac{E_L}{A_p}) = \chi_{nn}\sigma^f_{nn}$ for two similar nucleons,

$\sigma_{np}(\rho, \frac{E_L}{A_p}) = \chi_{np}\sigma^f_{np}$ for two different nucleons ...(7)

The multiplicative factors which take medium effects into consideration are given by [9],

$$\chi_{nn} = (1 + 7.772E^{0.06}\rho^{1.48})/(1 + 18.01\rho^{1.46})$$
$$\chi_{np} = (1 + 20.88E^{0.04}\rho^{2.02})/(1 + 35.86\rho^{1.9}) \quad ...(8)$$

In using the last equations, the correct treatment of ρ–dependence is to take the density ρ as the sum of the projectile and target densities in each volume element . This corresponds to the local density at each point along the trajectory. Another approach to consider approximate medium effects is to evaluate at constant global density which is usually equal to the value of saturated nuclear matter density. In case of neglecting in-medium effects in calculating σ_R we use equations (6) for σ_{NN} instead of equations (7,8). In the present work the reaction cross-section is calculated for the light and heavy target pairs ^{12}C-^{12}C and ^{12}C-^{208}Pb at different values of incident energy per projectile nucleon in the range (10-1000 MeV/nucleon).

RESULTS AND DISCUSSIONS

The aim of the present paper is to show the dependence of the reaction cross-section for light and heavy target nuclei on the method of treating in-medium effects in . For this purpose we calculate the reaction cross-section for the two pairs ^{12}C-^{12}C and ^{12}C-^{208}Pb. Fermi shape matter density distribution is assumed for the heavy target nucleus ^{208}Pb. The calculations are done at different values of the incident energy per projectile nucleon, E_{Lab}/A_p, and different values of rms radius of ^{12}C-nucleus had been taken from 2.32 fm [16] to 2.5 fm [5]. In the present work the values of energy considered, start from 10 MeV/ nucleon up to 1000 MeV/ nucleon. In-medium effects are included in $\bar{\sigma}_{NN}$, by considering local-variation of density in each volume element during the integration process, , then $\bar{\sigma}_{NN}$ is calculated at global constant value of density. Also we calculated σ_R variation with energy using which corresponds to density value =0.0 fm^{-3}.

Fig's (1) , (2) and tables (1) , (2) shows how the method used to treat ñ -dependence in affects, we present in tables (1) and (2) the values of for ^{12}C and ^{208}Pb target nuclei calculated by different methods and at different energy values. Each table contains the calculations of for two values of rms radius of ^{12}C-nucleus. For light target nucleus, table (2a) shows that the percentage difference between σ^{exct} and is about 4.49 % and 3.75%, for rms values = 2.32 fm & 2.5 fm respectively at E_{Lab}/A_p =300 MeV/ nucleon. But for the heavy target nucleus the above differences are 1.66% and 1.53% for the same energies as shown in table (2b). In case of coulomb modification, for light target nucleus, table (2c) shows that the percentage difference between σ^{exct} and is about 4.11 % and 3.58%, for rms values = 2.32 fm & 2.5 fm respectively at E_{Lab}/A_p =300 MeV/ nucleon. But for the heavy target nucleus the above differences are 1.67% and 1.55% for the same energies as shown in table (2d).

At high E_{Lab}/A_p =1000 MeV/ nucleon for light and heavy target nucleus no change in the value of σ^{exct} in case of with and without coulomb modifications as shown (last row) in tables (3a,b). Tables(3a,b) represent also no change in the value of σ^{free} , it means that the coulomb repulsion is important at low incident energies without in-medium effect.

Table 1(a): The same as table (1a) but for ^{12}C-^{208}Pb

C-C	E=50		E=300		E=1000	
	m	b	m	b	m	b
ρ free	75.428	-66.57	49.2	-35.07	57.65	-45.2
ρ exact	76.14	-70.5	49.44	-39.04	57.85	-48.39
ρ 0.175	69.28	-59.08	43.8	-28.81	52.81	-39.21

Table 1(b): show the η -dependence in affects σ_R for ^{12}C-^{12}C

C-Pb	E=50		E=300		E=1000	
	m	b	m	b	m	b
ρ free	76.71	199.54	59.59	182.35	65.37	187.56
ρ exact	78.41	192.15	60.91	174.08	66.55	180.69
ρ0.175	73	195.23	55.8	179.17	62.07	184.55

Table 2(a): Shows the values of ^{12}C-^{12}C cross-sections for different values of (σ and rms) without coulomb modification

For C-C ….without c. modification

E_L/A_P	rms	σ^{free}	σ^{exact}	X
50	2.32	108.43	106.18	-2.12
	2.5	122.02	119.9	-1.76
300	2.32	79.07	75.67	-4.5
	2.5	87.93	84.75	-3.75
1000	2.32	88.56	85.85	-3.16
	2.5	98.94	96.28	-2.76

Table 2(b): The same as table (1a) but for ^{12}C-^{208}Pb

For C-Pb ….without c. modification

σ_{NN}

E_L/A_P	rms	σ^{free}	σ^{exact}	X
50	2.32	377.55	374.1	-0.92
	2.5	391.4	388.24	-0.81
300	2.32	320.65	315.41	-1.66
	2.5	331.4	326.4	-1.53
1000	2.32	339.25	335.1	-1.24
	2.5	351.05	347.1	-1.14

Table 2(c): The same as table (2a) but for with coulomb modification

For C-C ….without c. modification

E_L/A_P	rms	σ^{free}	σ^{exact}	X
50	2.32	105.26	103.05	-2.14
	2.5	118.67	116.57	-1.8
300	2.32	82.66	79.39	-4.11
	2.5	92.2	89.01	-3.58
1000	2.32	88.41	85.7	-3.16
	2.5	98.79	96.13	-2.76

Table 2(d): The same as table (2c) but for ^{12}C-^{208}Pb

For C-Pb ….without c. modification

E_L/A_P	rms	σ^{free}	σ^{exact}	X
50	2.32	334.64	331.4	-0.97
	2.5	347.72	344.74	-0.86
300	2.32	314.06	308.89	-1.67
	2.5	324.71	319.76	-1.55
1000	2.32	337.21	333.07	-1.24
	2.5	348.98	345.04	-1.14

X = [(sexact- sfree)/ sexact] x100

Table 3(a): Comparison between σ^{exact} and σ^{free} at minimum rms and maximum rms with and without coulomb modification for the pair ^{12}C-^{12}C

E_L/A_P	σ^{exact} (rms=2.32)		σ^{free} (rms=2.32)		σ^{exact} (rms=2.5)		σ^{free} (rms=2.5)	
	Without C.mod.	With C.mod.	without C.mod.	with C.mod.	without C.mod.	with C.mod.	without C.mod.	with C.mod.
10	148.32	129.75	149.43	130.79	168.6	148.83	169.6	149.79
50	106.18	103.05	108.43	105.26	119.9	116.57	122.02	118.67
80	93.8	91.96	96.52	94.66	105.6	103.64	108.2	106.23
100	88.37	86.94	91.32	89.87	99.3	97.8	102.15	100.62
150	80.3	79.39	83.59	82.66	89.97	89.01	93.17	92.2
300	75.67	75.23	79.07	78.62	84.58	84.12	87.93	87.46
500	79.06	78.78	82.2	81.92	88.47	88.18	91.56	91.27
800	83.75	83.58	86.6	86.42	93.87	93.69	96.67	96.48
1000	85.85	85.7	88.56	88.41	96.28	96.13	98.94	98.79

Table 3(b): The same as table (3a) but for ^{12}C-^{208}Pb

E_L/A_P	σ^{exact} (rms=2.32)		σ^{free} (rms=2.32)		σ^{exact} (rms=2.5)		σ^{free} (rms=2.5)	
	Without C.mod.	With C.mod.	without C.mod.	with C.mod.	without C.mod.	with C.mod.	without C.mod.	with C.mod.
10	453.47	218.2	455.71	219.86	471	231.51	473	232.89
50	374.1	331.4	377.55	334.64	388.24	344.74	391.4	347.72
80	350.6	324.77	354.7	328.7	363.51	337.21	367.33	340.89
100	340.2	319.85	344.62	324.13	352.55	331.84	356.72	335.87
150	324.56	311.31	329.54	316.18	336.4	322.59	340.8	327.21
300	315.41	308.89	320.65	314.06	326.4	319.76	331.4	324.71
500	321.97	318.02	326.82	322.82	333.3	329.27	337.92	333.86
800	331.07	328.56	335.43	332.9	342.86	340.3	347..02	344.44
1000	335.1	333.07	339.25	337.21	347.1	345.04	351.05	348.98

The coulomb interaction can affect the reaction cross-section especially at small energies. It deflects the projectiles away from the reaction region. It can be taken into consideration by modifying the trajectories using the equation

Table 4: Experimental data for C-C

E_L/A_P	σ_R (fm)^2
8.386	144.52
29.383	131.75
80.611	96.133
197.75	86.553
247.37	87.181
293.25	85.94
850.21	93.721

$$b' = \frac{\eta + \sqrt{\eta^2 + k^2 b^2}}{k}$$

where η is the sommerfield parameter given by $\eta = \frac{Z_P Z_T e^2}{\hbar v}$. Table (4) show the experimental data for ^{12}C-^{12}C. From fig.(3) the value of decrease by increasing E_{Lab}/A_p until reached E_{Lab}/A_p =300 MeV/ nucleon (bottom) then increase gradually by increasing E_{Lab}/A_p . The experimental data gives good agreement with our results at low energy for rms = 2.32 and at high energy with rms =2.5.

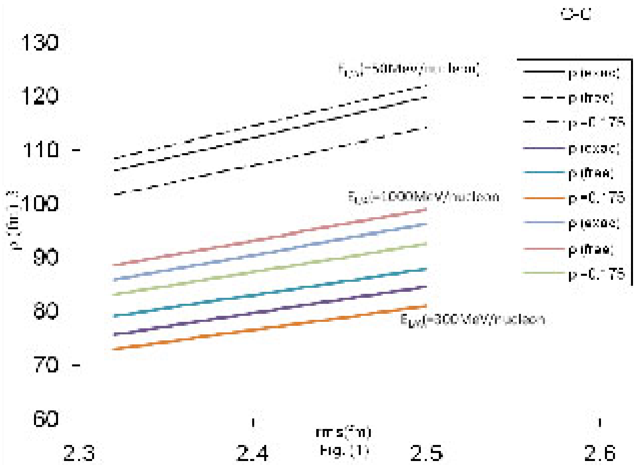

Fig. 1: Show the σ-dependence in affects σ_R for ^{12}C-^{12}C

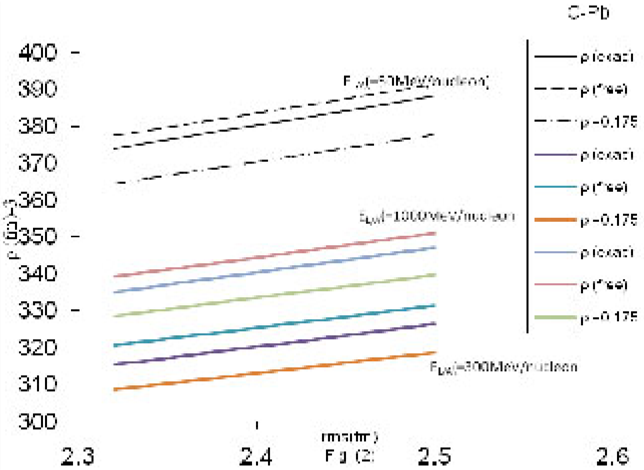

Fig. 2: Show the σ-dependence in affects for ^{12}C-^{12}C

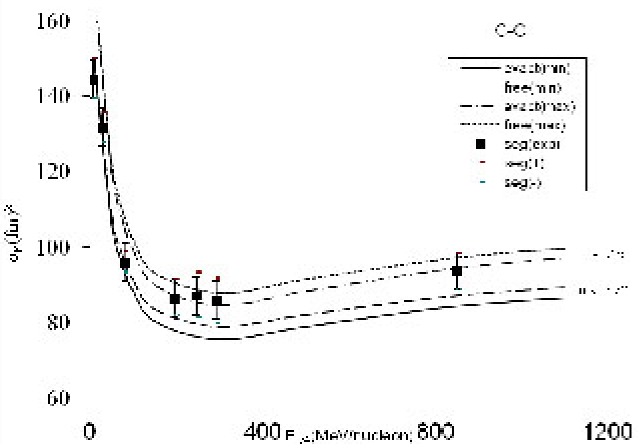

Fig. 3: Shows the variation of reaction cross-section for the pair ^{12}C-^{12}C. with (E_L/A_p) considering two values of rms radius of ^{12}C nucleus (2.32& 2.5 fm)

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