

DOUBLE FOLDING CLUSTER POTENTIAL FOR $^{12}\text{C}+^{12}\text{C}$ ELASTIC SCATTERING

M.A. Hassanain¹ and Awad A. Ibraheem²

¹ *Sciences and mathematics Department, Assuit University, El-Kharga,
New-Valley, Egypt.*

² *Physics Department, faculty of Science, Al-Azhar University, (Assuit-
Egypt)P.O 71524*

Abstract

Using the total contribution for microscopic α - α interaction, α - N interaction and N - N interaction double folding cluster potential, the differential cross-section for the elastic scattering of $^{12}\text{C} + ^{12}\text{C}$ have been well described without renormalization at different sets of the incident energies. These potentials are generated by using the density distribution of α -like cluster and uncluster nucleon for the projectile and the target in the usual double folding procedure. Also, the double folding cluster potentials were calculated based upon the density distribution $m\alpha$ -cluster inside projectile and target with the α - α effective interaction. The energy-dependence with total reaction cross-section and the volume integral real and imaginary part were investigated.

1 INTRODUCTION

In the hindermost years, there are many attempts have been made to develop a folding formulations of the optical model potential for the analyses of the elastic and inelastic heavy ions (HI) scattering [1-6]. The original version of the folding model [7] was given a good description in most of cases where the HI interaction is dominated by the strong absorption, which makes the HI elastic scattering data are sensitive only to the surface part of the nucleus-nucleus potential. However, the situation is different if a refractive or rainbow scattering is observed, where the data are sensitive to the HI optical potential over a wider radial domain, the simple double folding model [7] failed to give a good description to the data. Refractive scattering contribution in HI systems, such as $^{12}\text{C}+^{12}\text{C}$, $^{12}\text{C}+^{16}\text{O}$, $^{16}\text{O}+^{16}\text{O}$, have been found in several experiments [8].

One of these attempts is to impose on the M3Y effective nucleon-nucleon (NN) interaction [9] an explicit density dependence to account effectively for the in-medium effects which are more substantial at internuclear distances, the so-called DDM3Y interaction [1]. Dao T. Khoa, et al.[2], they were using the new density dependent versions on the M3Y effective interaction for analyses the elastic scattering of $^{12}\text{C}+^{12}\text{C}$, $^{16}\text{O}+^{16}\text{O}$ data, the so-called BDM3Y.

Another attempt, Farid, et al. [4,5] and M. Karakoc et. al. [6], they extended the α -cluster folding formalism, to generate light HI double folding cluster (DFC) potentials using the α -cluster structures of both projectile and target nuclei. Most of these attempts failed to obtain a good description to the HI elastic scattering data without renormalization ($N_R=1.0$).

Recently, Abdullah et al. [3,10,11] proposed a single-folding model (SFM), in which the nucleons in the target nucleus are considered primarily in α -like clusters and the rest of time in an unclustered nucleonic configuration. This leads to the folding potential as a sum of two potentials, one convoluted over the α -density distribution and another over the nucleonic-density distribution. The new idea of the model is that the resulting potential does not need any renormalization and describes the differential cross-section data of α - ^{16}O , α - $^{40,44,48}\text{Ca}$ and ^{16}O - ^{12}C elastic scattering cross-section successfully.

Based of the successfully results in the recent papers [3,10,11], we suggested the using this proposed model in our work to generate two different types of the double folding cluster (DFC) potential for analyses the elastic scattering for the $^{12}\text{C} + ^{12}\text{C}$ data at different sets of incident energies.

In the following section we present a theoretical formwork for the proposed for two models, based on a composite distribution of the $m\alpha$ -cluster inside the projectile and target nuclei [4,5,6], and the other one α -like cluster and unclustered nucleon in the projectile and target nuclei [3,10,11]. The analysis is given in section 3 section 4 deals with the discussion and conclusions.

2 THEORETICAL FORMALISM

Our aim is described the $^{12}\text{C} + ^{12}\text{C}$ elastic scattng from 70.8 to 360 MeV by two different microscopic potentials for the real double folding potentials, the one double folding cluster model potential (DFC1), which can generate α - α interaction potential between the α - cluster inside projectile and target [4,5,6]. The other one (DFC2) can generate the general potential (the sum of α - α , α -nucleon and nucleon-nucleon effective interaction) between α -like cluster and unclustered nucleons in the projectile and target.

For the first microscopic potential, if one denotes the density distributions of the α -cluster inside the projectile and the target by ρ_{CP} and ρ_{CT} , respectively, the DFC1 potential can be written as

$$U_{DFC1}(R) = \int \int \rho_{CP}(r_1) \rho_{CT}(r_2) V_{\alpha-\alpha}(R - r_1 + r_2) d^3 r_1 d^3 r_2 \quad (1)$$

where $V_{\alpha-\alpha}$ the effective α - α interaction.

And, for the second microscopic potential, if one denotes the density distributions of the α -like cluster and uncluster nucleon in the projectile and target by $\rho_{\alpha P}$, ρ_{NP} , $\rho_{\alpha T}$ and ρ_{NT} respectively, the DFC2 potential can be written as

$$U_{DFC2}(R) = \int \int \rho_{\alpha P}(r_{\alpha P}) \rho_{\alpha T}(r_{\alpha T}) V_{\alpha-\alpha}(R - r_{\alpha P} + r_{\alpha T}) d^3 r_{\alpha P} d^3 r_{\alpha T} \\ + \int \int \rho_{\alpha P}(r_{\alpha P}) \rho_{NT}(r_{NT}) V_{\alpha-N}(|R - r_{\alpha P} + r_{NT}|) d^3 r_{\alpha P} d^3 r_{NT}$$

$$\begin{aligned}
& + \int \int \rho_{\alpha T}(r_{\alpha T}) \rho_{NP}(r_{NP}) V_{\alpha-N}(|R - r_{\alpha T} + r_{NP}|) d^3 r_{\alpha T} d^3 r_{NP} \\
& + \int \int \rho_{NT}(r_{NT}) \rho_{NP}(r_{NP}) V_{N-N}(|R - r_{NT} + r_{NP}|) d^3 r_{NT} d^3 r_{NP}
\end{aligned} \quad (2)$$

where $V_{\alpha-\alpha}$, $V_{\alpha-N}$ and V_{N-N} are the effective α - α effective, α - N effective and N - N effective interaction, respectively.

2-1 Alpha-cluster Density Inside Projectile and Target Nuclei

The $m\alpha$ -cluster distribution for ^{12}C can be obtain from three sets, the first set, the matter of a nucleus is known as

$$\rho_M(r) = \rho_{0M} (1 + \omega r^2) \exp(-\beta r^2) \quad (3)$$

Where $\rho_M(r)$ is the modified form of the Gaussian shape for ^{12}C density. The matter density of an α nucleus can also be obtained from

$$\rho_\alpha(r) = \rho_{0\alpha} \exp(-\lambda r^2) \quad (4)$$

The parameters for $\rho_{0\alpha}$, ρ_{0M} , ω , β and λ used in Eqs. (3) and (4) are given in Table 1.

The second set, If $\rho_C(r')$ is the α -cluster distributions function inside the nucleus, then we can relate the nuclear matter density distribution functions of the nucleus, $\rho_M(r)$, to that of the α -particle nucleus, $\rho_\alpha(r)$, as

$$\rho_M(r) = \int \rho_C(r') \rho_\alpha(|\vec{r} - \vec{r}'|) d^3 r' \quad (5)$$

The final set, from the densities of the nucleus and the $m\alpha$ -particle can be calculated from Eqs. (3) and (4), by using Fourier transform techniques [7] for expression (5), we can obtain the $m\alpha$ -cluster distribution function $\rho_C(r')$ for ^{12}C as

$$\rho_C(r') = \rho_{0C} (1 + \gamma r'^2) \exp(-\xi r'^2) \quad (6)$$

where

$$\xi = \frac{\beta\lambda}{\eta} \quad \eta = \lambda - \beta \quad \gamma = \frac{2\omega\lambda^2}{[\eta(2\eta - 3\omega)]}$$

Inserting this α -cluster distribution together with the effective α - α interaction potential of [12], we can obtain the DFC1 from Eq. (1).

Table 1. The parameters of nuclear matte densities of ^{12}C and ^4He [4,5,6].

Nuclei	$\rho_{0\alpha}(\rho_{0m})$ (fm-3)	ω (fm-2)	$\beta(\lambda)$ (fm-2)	$\langle r^2 \rangle^{1/2}$ (fm)
^{12}C	0.1644	0.4988	0.3741	2.407
^4He	0.4229	0	0.7024	1.460

2-2 Alpha-like Cluster and Uncluster Nucleon Density in the Projectile and Target

The density distribution of the α -like cluster and uncluster nucleon in the projectile and target are take to be of the modified Gaussain form [12-14] given by

$$\rho_{ij}(r) = \rho_{0ij} (1 + w_j r^2) \exp(-\beta_{ij} r^2) \quad \text{where } i = \alpha, N \text{ and } j = P, T \quad (7)$$

If the projectile and target nucleus with its mass number A_j is composed of $4A_{\alpha j}$ nucleons making $A_{\alpha j}$ α -like clusters and A_{Nj} unclustered nucleons, then one can write the normalization integral as

$$\int \rho_{\alpha j}(r_{\alpha j}) d^3 r_{\alpha j} + \int \rho_{Nj}(r_{Nj}) d^3 r_{Nj} = 4 A_{\alpha j} + A_{Nj} = A_j \quad (8)$$

Inserting the α -like cluster and uncluster density distribution together with the effective α - α interaction, α - N interaction and N - N interaction potential, [12-16], we can obtain the DFC2 from Eq. (2).

2-3 The Nucleus-Nucleus Effective Interaction

Following the basic premise of [12], the α - α potential has been parameterized as

$$V_{\alpha-\alpha}(r) = V_R \exp(-\mu_R^2 r^2) - V_A \exp(-\mu_A^2 r^2) \quad (9)$$

Where, V_A and V_R are the attractive and ℓ -independent repulsive parts of the potential with range parameters μ_A and μ_R , respectively.

For the α - N potential, the following form [13] is used

$$V_{\alpha-N}(r) = -V_{0\alpha N} \exp(-K^2 r^2) \quad (10)$$

Where, K is range parameter.

For the N - N potential is take to be of the Gaussain form one term [15,16], as

$$V_{N-N}(r) = V_0 \exp\left[\frac{-r}{a}\right]^2 \quad (11)$$

Where, the $V_0 = -20.97$ MeV and $a = 1.47$ fm parameters are taken from Ref. [15,16].

3 ANALYSIS

The real two types microscopic potential, DFC1 and DFC2 generated from Eq.(1) and Eq. (2) were evaluated by the using of the Fourier-transform technique [7]. The imaginary part, as in most of the optical potential, is taken as phenomenological Wood-Saxon shape (WS). Then the obtained potentials were fed into the computer code HI-OPTIM-94 [17] to calculate the elastic scattering differential cross sections. Only, two parameters were adjusted in order to obtain the best fits to the observed elastic scattering angular distributions, V_R and W_0 .

In the first type DFC1, we obtained the parameters of the $m\alpha$ -cluster distribution function $\rho_C(r')$ for ^{12}C Eq.(3) and (4) by using Fourier techniques while, the parameters α -like clusters $A_{\alpha j}$ and the unclustered nucleons A_{Nj} in the ^{12}C are obtained, following the folding procedure of

SFM [3]. The initial parameters of the densities distributions for ^{12}C are taken from [3]. The best fit values for the energy-independent parameters are $\rho_{cj} = 0.0336 \text{ fm}^{-3}$, $\rho_{Nj} = 0.2186 \text{ fm}^{-3}$, $\beta_{cj} = 0.381 \text{ fm}^{-1}$, $\beta_{Nj} = 0.9 \text{ fm}^{-1}$, and $w_j = 0.96$. These yield $A_{cj} = 2.35$, $A_{Nj} = 2.6$, $4A_{cj} + A_{Nj} = 12.0$ and the root-mean-square (RMS) radius $\langle r_j^2 \rangle^{1/2} = 2.22 \text{ fm}$.

For analysis of the $^{12}\text{C}+^{12}\text{C}$ data, the parameter values $V_A = 122.62 \text{ MeV}$ and $\mu_A = 0.469 \text{ fm}^{-1}$ are taken from Buck et al., [13], $V_{0\alpha N} = 47.3 \text{ MeV}$ and $K = 0.435 \text{ fm}^{-1}$ from Sack et al. [14] are fixed for all the incident energies. The range parameter for the repulsive part in (10), $\mu_R = 0.54 \text{ fm}^{-1}$, is constant at all energies.

In the current work, we use different routine searches than [3], but we based on [4,5], where the searches were carried out considering an average value 10% for all experimental errors of the considered data to minimize the χ^2 value, which is defined as:

$$\chi^2 = 1/N \sum_i \left[\frac{\sigma(\theta_i)^{cal} - \sigma(\theta_i)^{exp}}{\Delta\sigma(\theta_i)} \right]^2 \quad (12)$$

where N is the number of differential cross-section data points and $\sigma(\theta_i)^{cal}$ is the i th calculated cross section. $\sigma(\theta_i)^{exp}$ and $\Delta\sigma(\theta_i)$ are the corresponding experimental cross section and its relative uncertainty, respectively.

Table 2. The depth parameters V_R and W_0 are in MeV , for DFC1 and DFC2 optical potentials and J_R, J_I in $MeVfm^3$ σ_R and χ^2 at different incident energies. $r_w = 1.23 \text{ fm}$. and $a_w = 0.505 \text{ fm}$. are constant at all incident energies for the WS potential.

<i>Microscopic potential</i>	E (MeV)	V_R (MeV)	W_0 (MeV)	J_R $MeVfm^3$	$\langle r_R^2 \rangle^{1/2}$ (fm)	J_I $MeVfm^3$	σ_R (mb)	χ^2
DFC1	70.7	33.0	11.0	340.7	3.81	61.6	1259	36.6
DFC2		166.0	11.2	286.8	4.01	62.7	1280	35.8
DFC1	78.8	28.0	12.3	351.7	3.8	68.5	1285	28.3
DFC2		156.0	12.4	300.4	4.01	69.7	1308	30.0
DFC1	89.7	28.0	22.7	353.9	3.8	115.8	1373	53.2
DFC2		152.0	21.5	305.0	4.02	120.6	1402	54.3
DFC1	106.9	28.0	13.8	349.5	3.8	85.9	1334	10.9
DFC2		167.0	13.5	285.5	4.01	75.9	1321	10.3
DFC1	112.0	30.0	14.4	247.3	3.8	91.0	1344	17.5
DFC2		168.0	14.2	284.1	4.01	79.4	1328	11.0
DFC1	117.1	30.0	14.1	347.3	3.8	88.0	1339	13.4
DFC2		188.0	13.8	267.8	4.01	77.2	1316	12.3
DFC1	122.0	31.0	15.3	345.1	3.8	95.7	1353	15.2
DFC2		172.0	15.3	278.7	4.01	85.5	1338	17.8
DFC1	126.7	35.0	15.0	336.2	3.81	98.0	1356	17.8
DFC2		182.0	14.7	265.0	4.01	82.7	1326	12.4
DFC1	158.0	37.0	17.8	331.8	3.81	113.8	1380	47.7
DFC2		164.0	18.6	289.5	4.01	104.2	1371	25.9
DFC1	300.0	76.0	18.1	245.6	3.9	107.7	1321	22.8
DFC2		198.0	19.4	243.4	4.0	108.8	1325	23.9

DFC1	344.0	76.0	13.6	245.6	3.91	76.6	1225	9.6
DFC2		198.0	11.8	243.4	4.0	66.0	1185	8.1
DFC1	360.0	90.0	14.9	219.1	3.95	90.0	1257	24.2
DFC2		232.0	15.3	197.4	3.99	85.6	1240	13.2

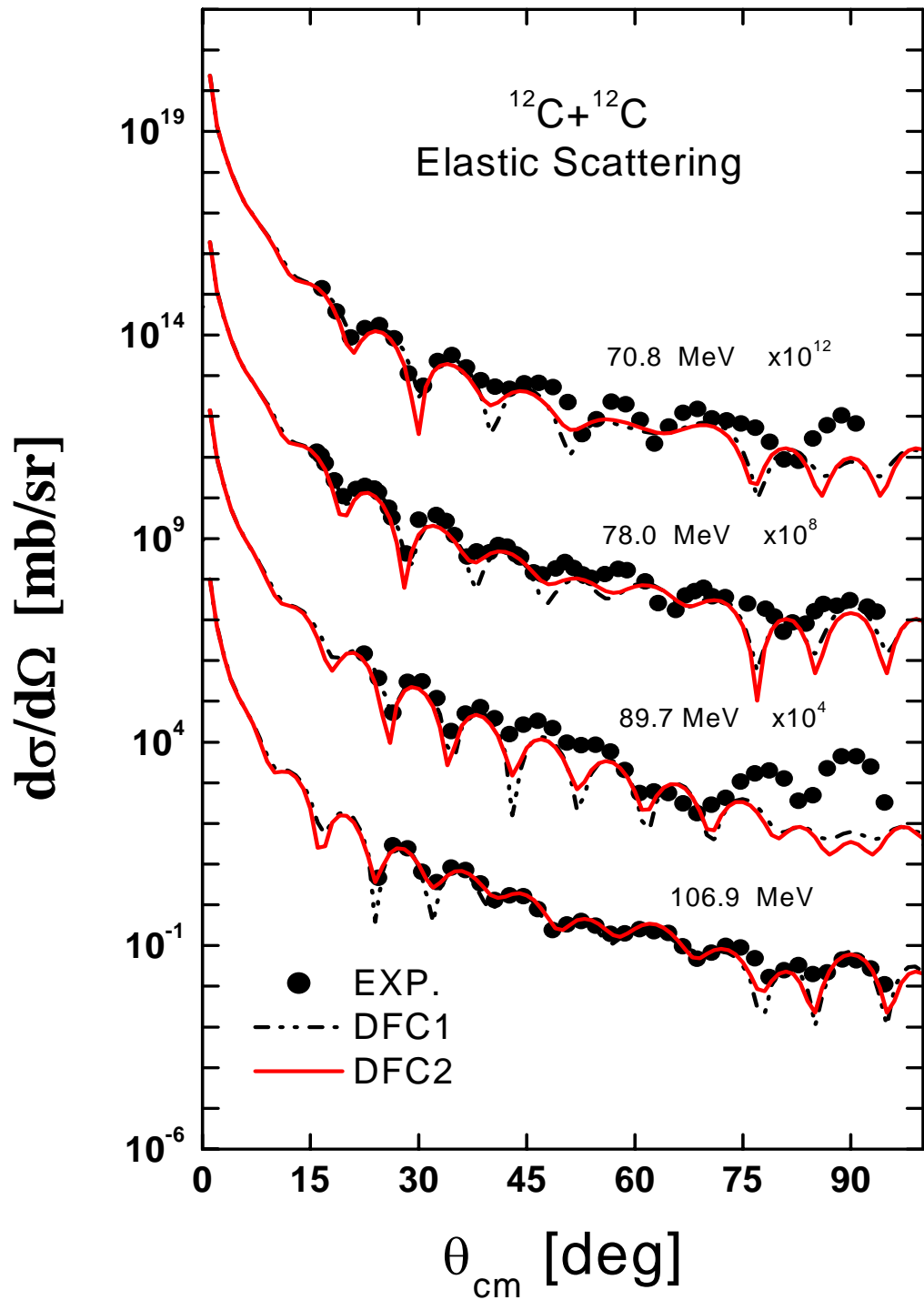


Fig. 1. Experimental differential cross-sections (solid dots) are compared with the predicted cross-section (dash-dot-dot line and solid line) for elastic scattering of $^{12}\text{C}+^{12}\text{C}$,

at $E_{Lab} = 70.8, 78.0, 89.8$ and 106 MeV, reproduced by DFC1 and DFC2 double folding cluster potential.

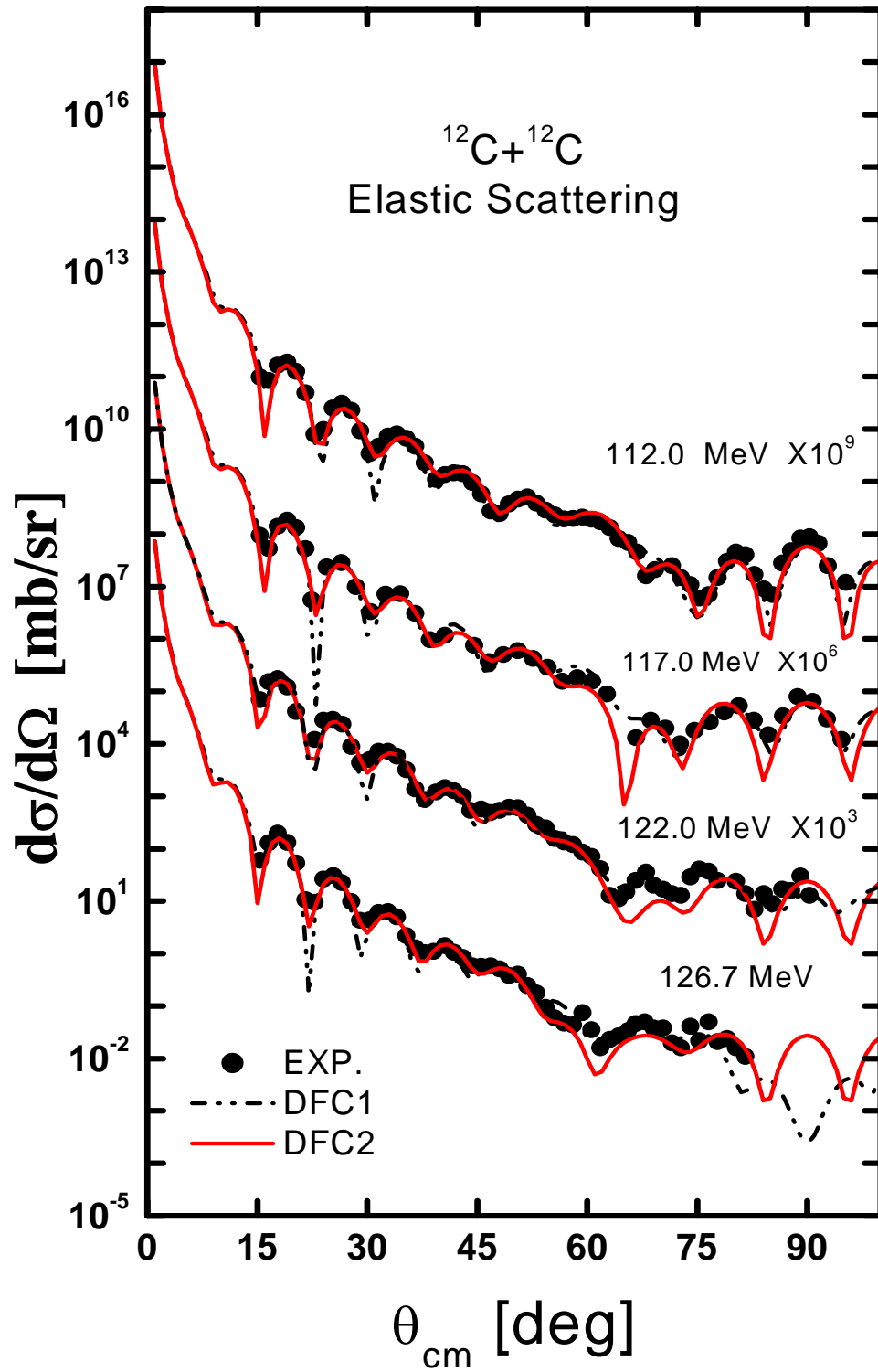


Fig.2. The same as Fig. 1. but at 112, 117, 122, and 126.7 MeV.

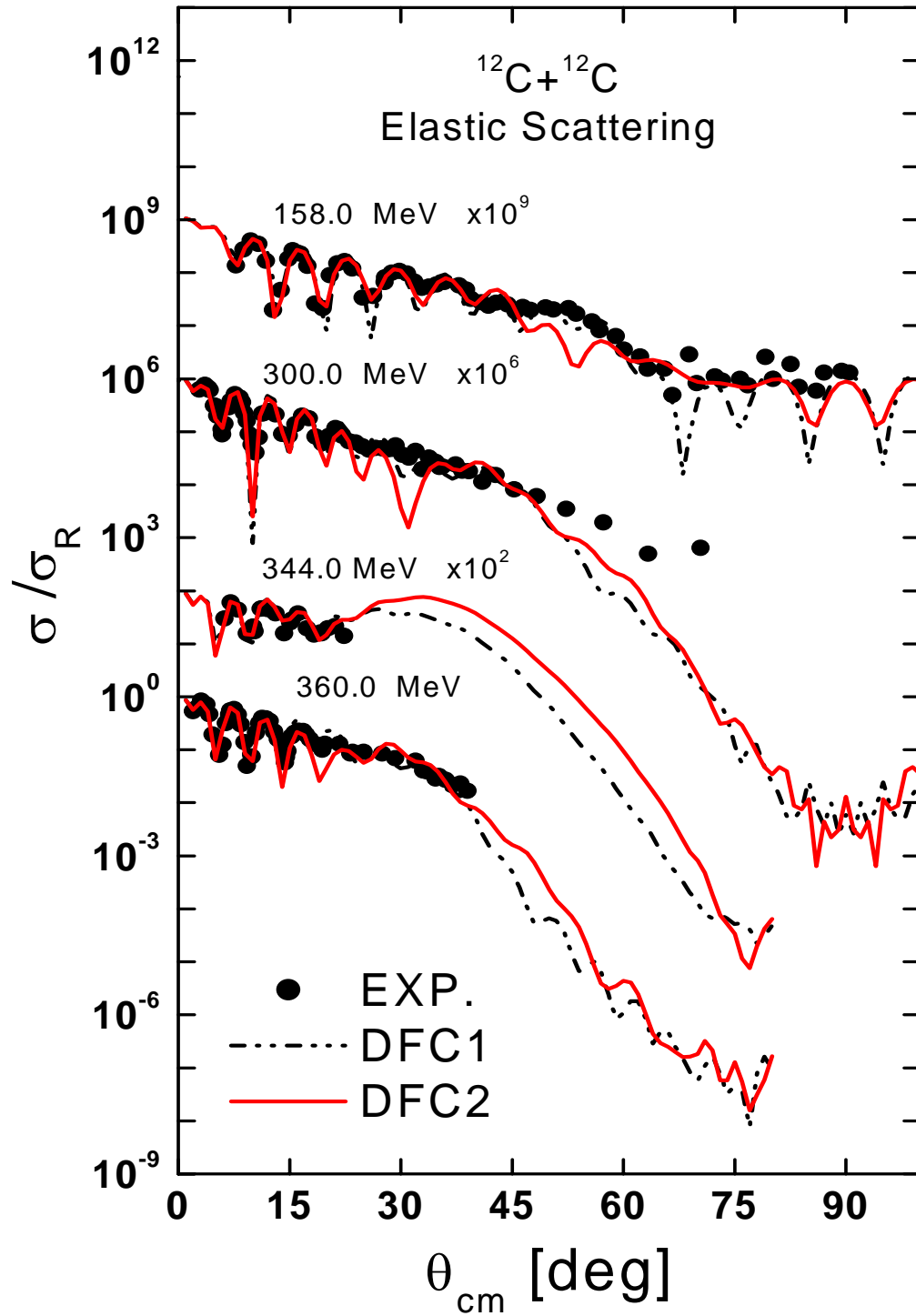


Fig.3. The same Fig.1, but the differential cross-section as ratio to Rutherford, for the elastic scattering of the $^{12}\text{C} + ^{12}\text{C}$ reaction at $E_{Lab} = 158, 300, 344,$ and 360 MeV.

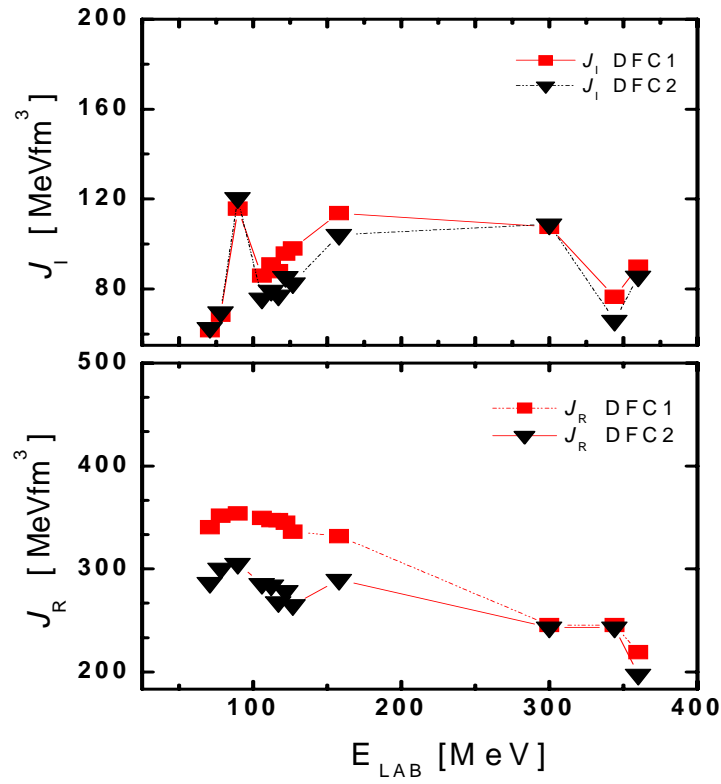


Fig.4. The energy-dependence of the real volume integral, J_R (lower part), and imaginary volume integral, J_I (upper part), of the DFC1, DFC2 and imaginary WS shape potentials deduced from the folding cluster analyses of the elastic scattering $^{12}\text{C}+^{12}\text{C}$ data at all energies sets.

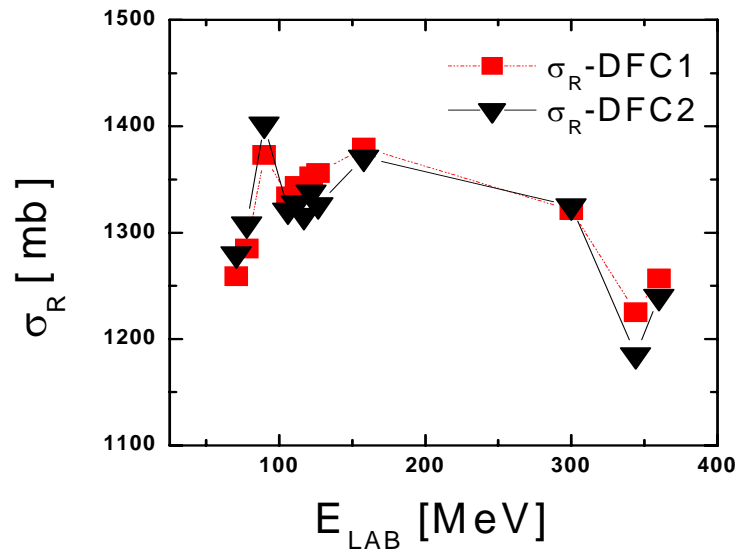


Fig.5. The energy-dependence of the total reaction cross-sections, deduced from the cluster DFC1 and DFC2 folding analyses of elastic scattering $^{12}\text{C}+^{12}\text{C}$ data at different sets of energies.

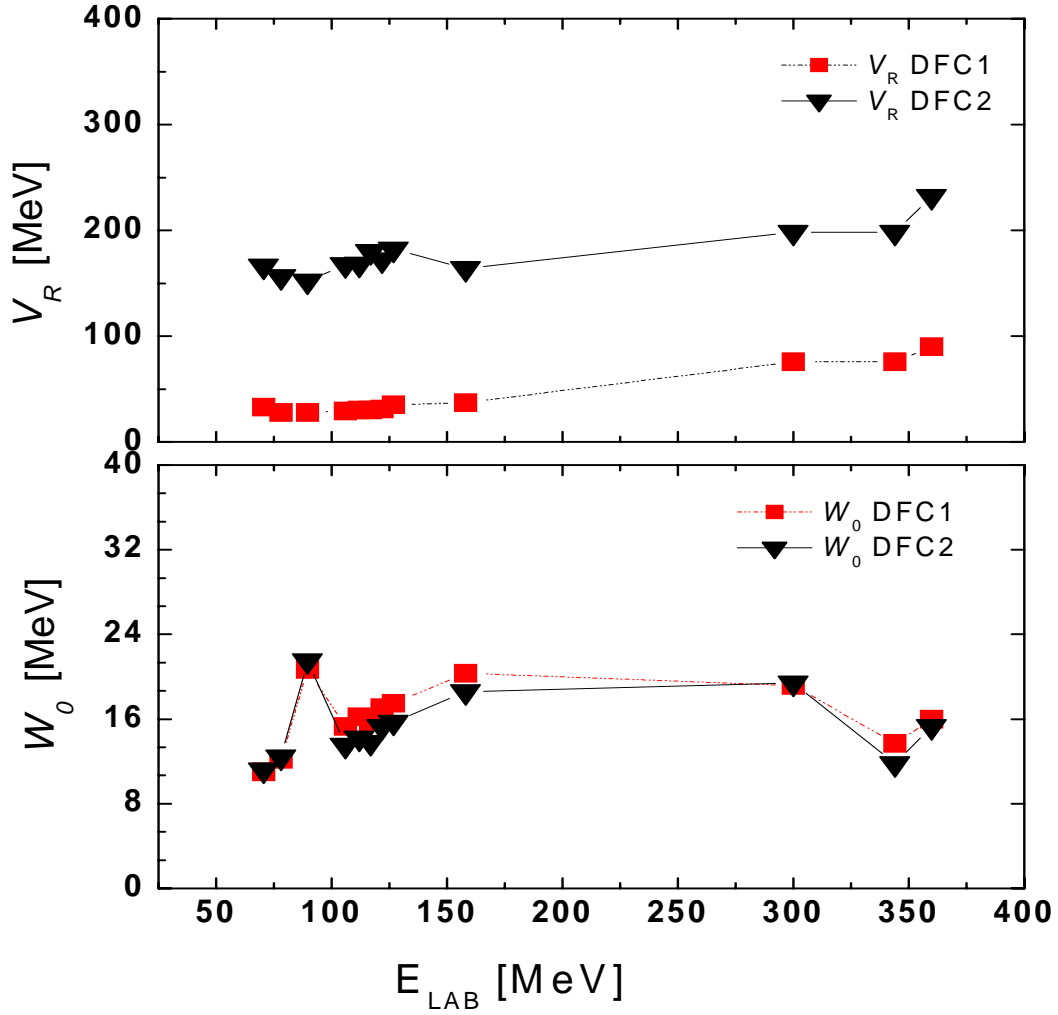


Fig.6. The energy-dependence of the real repulsive part for α - α interaction in DFC1 and DFC2 potentials (upper part), and the depth of W imaginary potential (lower part), which best fit the measured angular distribution of each energies.

4 RESULTS AND DISCUSSION

In the present paper, differential cross-section for $^{12}\text{C} + ^{12}\text{C}$ elastic scattering at energies from $E_{Lab}=70.7$ to 360 MeV are fitted using the above procedure, following the previous optical model analyses [2, 18, 19], we have assumed the WS shape the imaginary potential. The fits are shown in Figs. 1-3 and the associated parameters at various energies for DFC1 and DFC2 potentials are given in Table 2. Good fits are obtained using the DFC2 potential at all energies. The only reasonable fit is found at $E_{Lab}=89.7$ MeV, Fig. 1. The DFC1 gives good fitting to data at low energies, $E_{Lab}=70.7$, 78.8, and 89.7 MeV than those obtained by DFC2, see Fig. 1. As shown in Fig.1, 2, 3 the calculated elastic scattering cross-section have reasonable good fits to experimental data without renormalization coefficient. As shown in Table 2. and from all the results that are

obtained, we notice that the DFC1 and DFC2 potential have the same behavior, excepted the value of V_R that obtained by DFC2 it is greater than those obtained by using DFC1. Comparing our results with those obtained by previous studies we found that the present fits data are better than those obtained using the phenomenological potentials [20-23] and using the microscopic using the DFC and DFCM [4]. On the other side, we found that our results using DFC1 and DFC2 have an equivalent success to that obtained by other phenomenological potentials analyses [7,19] and using the microscopic using DDM3Y and BDM3Y [2,7, 19]. This is indication the constructed model in our work is successful to describe the $^{12}\text{C}+^{12}\text{C}$ system in this energy range. From Table 2, we notice the real volume integrals J_R is seemed slightly decreases as the energy increases. While the imaginary volume integrals J_I did not show a clear behavior with energy. The corresponding variation of the values J_R and J_I are shone in lower part and upper part, respectively, in Fig.4. It can seen from Table 2. in the present work, the obtained J_R values are lower than the corresponding values obtained by the DDM3Y and BDM3Y, interaction potentials [2] at $E_{Lab} = 112, 126.7, 300$ MeV and it nearly equivalent to those found by phenomenological [19, 23, 24] and the microscopic DDM3Y [25] optical potentials. Farid *et al.* [4] obtained the same results for the imaginary volume integral with most of the energy sets. These results agree quit well with a realistic energy dependence of J_R values deduced from the earlier optical model analyses of the elastic ^{12}C [19] and ^{16}O [20] scattering. And From this discussion we can conclude, the same results [2], that the energy dependence of the real HI optical potential is predicted quit well by our model. The obtained χ^2 values for the fits to the data were listed in the Table 2, we notice also, the χ^2 values in our studies are less than those obtained by Farid et al [4] at all energies, while it is nearly equal with that obtained by Dao T. Khoa, [2], on the other side, they [2,4] obtained their results with renormalization ($N_R \cong 1.$) by using many parameters to obtained good fit. Anther quantity, that are listed in Table 2, the obtained values of σ_R , we found it decreases when energy increases. The corresponding variation of the values σ_R are shone in Fig.5. Comparing our values for σ_R with those obtained by previous studies we found that the present is smaller than those obtained by using the DDM3Y, BDM3Y microscopic potentials [2,26]. As shown in Table 2, the obtained values of V_R , real repulsive part of α - α effective interaction and, W , the depth of the imaginary part potential we notice the V_R values are increases with energy increases while W values did not show a clear behavior with the energy, see Fig. 6.

5. CONCLUSIONS

In the present study we generated two types of the real double folding optical potentials for the $^{12}\text{C}+^{12}\text{C}$ system, DFC1 and DFC2. The first type DFC1 potential is calculated with the contribution from the α - α attractive, α - α repulsive effective interaction potential, folded with the α -cluster density distribution inside projectile and target. While the second type DFC2 is calculated with the total contribution from the α - α attractive effective, α - α repulsive effective, α - N effective and N - N effective interaction, folded with α -like cluster and unclustered nucleon density distribution in the projectile and target. A phenomenological WS shape was considered for the imaginary part, following the previous optical model analyses. Twelve sets of elastic scattering angular distribution for $^{12}\text{C}+^{12}\text{C}$ data in the energy range $E_{LAB} = 70.8$ -360 MeV were analyzed using the DFC1 and DFC2 potentials. The results showed that our method is successful to

described the $^{12}\text{C}+^{12}\text{C}$ system in this energy range. On the other hand, when we compared the preset results with the previous analyses, we found that the DFC1, DFC2 potentials predictions small χ^2 values and better fit than those produced by phenomenological potential. At all energies the DFC1 and DFC2 potentials in our work predictions small χ^2 values and better fit than those results obtained by the microscopic DF or DFC potentials. The success of the DFC1 and DFC2 potentials in our work to describe $^{12}\text{C}+^{12}\text{C}$ elastic scattering data is equivalent to that gained using the DDM3Y and BDM3Y potentials.

Most of the volume integral and total reaction cross-section results are small or equal with those reported by the phenomenological or microscopic potentials.

In general, one may conclude that the our constructed model is valid to produce successful prediction to describe $^{12}\text{C}+^{12}\text{C}$ elastic scattering data at this energy range without any need for renormalization. Thus a usable form of α - α interaction add to α -nucleon and nucleon –nucleon effective interaction potential, valid for all kinds of HI nuclei.

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