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Optical Model Analysis of the $^{16}O+^{16}O$ Nuclear Scattering Reaction around E_{LAB}=5MeV/Nucleon[1]

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ABSTRACT
In this study, the experimental data on elastic scattering of $^{16}O+^{16}O$ reaction at the incident energies E_{LAB}=75.0, 80.6 and 87.2MeV have been analyzed theoretically within the framework of the Optical model formalism by using the Fresco code. Our cross-section calculations have revealed a good agreement with the experimental data as much as the previous theoretical works. It is suggested that, more suitable fits with the experimental data may be obtained in coupled-channels formalism by considering the absorption due to the 3^- and 2^+ channels.

Key Words: Optical Model, $^{16}O+^{16}O$ Elastic Scattering, Cross-section.

1. INTRODUCTION

In a scattering experiment of a light heavy-ion reaction, important information can be obtained about the properties of the process and the nuclear structure such as the size of the nucleus and the characteristics of the nuclear forces [1, 2]. Although scientists have been investigating the elastic and inelastic interactions of light heavy ions for more than 40 years, the subject has not been fully explained yet.

The $^{16}O+^{16}O$ scattering, as a light heavy-ion reaction, has been studied intensively both experimentally [1, 3-6] and theoretically [1, 3, 6-9] in nuclear physics. The main problem of investigating the light-heavy ion reactions by using nuclear reaction models is to determine the most suitable potential form to explain the experimental data. Optical model, one of the models that developed to explain nuclear reactions, investigates the elastic scattering in a general way by considering absorption effects. Recently many precise elastic differential cross-sections measurements have been performed for various incident energies, and significant progress has been reported about understanding the form of the optical potential between two light heavy-ions ([1] and references therein).

The interaction between the heavy ions is governed by strong absorption which leads to compound nucleus formation, but for certain light heavy–ions, including the $^{16}O+^{16}O$ system, the number of open reaction channels is small [10] and absorption is weaker. Due to this weaker absorption, refractive effects and nuclear glories occur. By observing those effects, nucleus-

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nucleus potential is developed at smaller interaction radii. Those effects have been studied extensively for the $^{16}O+^{16}O$ system. In the literature it is reported that two regimes are observed [6] according to the elastic scattering excitation functions of the $^{16}O+^{16}O$ reaction at $\theta_{CM}=90^o$; resonance regime [11] at low energies (E≤5MeV/nucleon) and refractive regime [12] at following higher energies. The differential cross-sections measurements [4-6] of the $^{16}O+^{16}O$ elastic scattering have provided a better understanding of the inner part of the interaction potential.

In this paper, the Optical model and the properties of the optical potential are introduced in the following section. In the third section, the elastic scattering differential cross-section analyses of $^{16}O+^{16}O$ reaction at the laboratory energies around 5MeV per nucleon are studied theoretically by using various potentials. Then the fits obtained from the calculations are compared to the experimental data. In the last section, our approach is discussed and suggestions are made for further related analyses.

2. OPTICAL MODEL (OM) AND OPTICAL POTENTIAL

The interactions between two nuclei can not be fulfilled exactly for the nuclear reactions since it requires to work out the many-body problem which unfortunately has lots of complex mathematical difficulties [2]. Therefore for a many-body system, it is logical to work on simplified models instead of taking into account individual forces between particles and particles, and particles and particle groups. These simplified models, such as Optical model [2, 13-15], Distorted-wave Born approximation [2, 15] and Folding model [15], must physically have the same important properties of the particles that establish the particle systems.

The Optical model (OM) probes the elastic scattering in a general way by only considering the behavior of the incoming particle and by allowing for the absorption effects. In this model, the projectile deals with a potential well which is analogous to that used in the shell model, but it also includes an imaginary component. In Optical model calculations, which are particularly very successful to explain the nuclear scattering reactions, it is assumed that the absorbed particles vanish in the elastic channels. Since the Optical model is only practical to discuss the common behavior of the scattering reactions, it can indirectly explain the microscopic properties of nuclei [2, 14].

In a nuclear reaction, the form of a potential, which represents the two-body interaction between the projectile and the target nucleus, must be appropriate to the elastic scattering and the reactions take place between the projectile and the target. Generally, the real part of the interaction potential represents the elastic scattering and the imaginary part corresponds to the absorption (inelastic scattering and the reactions). This complex potential is called optical potential (or Optic model potential). First optical potential in the literature which is suitable with this description was suggested by Feshbach et al. [16]. This potential has a square-well shape as

$$V(r)=\begin{cases}-(V_0+iW) & r\le r_0A^{1/3}\\ 0 & r\ge r_0A^{1/3}\end{cases} \quad (1)$$

where V_0 and W represent the real and the imaginary parts of this optical potential respectively.

Two approaches are used to describe an optical potential. In the first one, starting from the fundamental nuclear structure theory, the interactions of the nucleons are considered. In the second one, the potential form has been determined which fits the experimental data best. A satisfying optical potential can be obtained by composing those two approaches and by using the fundamental theories for the potential [13].

When applying the Optical model to a reaction, one needs to start with establishing an appropriate potential shape. Since the nucleon-nucleon interaction between the projectile and the target decreases exponentially at large distances, the optical potential should exhibit the same behavior [14]. In 1954, the Woods-Saxon (WS) form was announced to be the most appropriate shape for the optical potential [17], because it exponentially decreases with increasing radius and it is good enough to satisfy the saturation features of the nuclear forces. The general profile of the Woods-Saxon form factor used in the optical potential formalism can be written as

$$f(r,r_i,a_i)=\frac{1}{1+\exp\left[\dfrac{r-r_iA^{1/3}}{a_i}\right]} \quad (2)$$

where r is the distance between the centers of the projectile and the target, r_i is the radius where the nucleus potential dropped to the half of the central value and a is known as the diffuseness parameter. Moreover, f falls from 0.9 to 0.1 over a distance $4.4a$ centered on $r=R$ (see Figure 1). Here $R=r_iA^{1/3}$ and $A^{1/3}=A_p^{1/3}+A_t^{1/3}$ where A_p and $A_t^{1/3}$ are the mass numbers of the projectile and target respectively. The behavior of the Woods-Saxon form factor $f(r,r_i,a_i)$ function and its derivative $g(r,r_i,a_i)$ according to the distance r are shown in Figure 1.

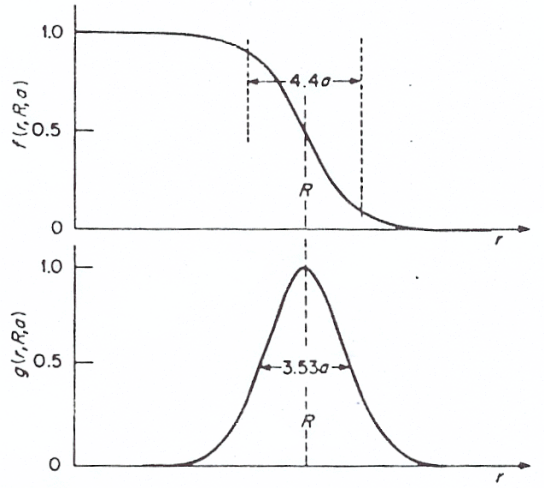

Figure 1: WS form factor and its derivative (adapted from [2]).

In a scattering problem, according to the OM, the form of the interaction (or effective) potential is usually given by

$$V(r)=V_{COUL}(r)+V_{CR}(r)+iW_{CI}(r)+\hbar^2\{V_{SR}(r)+iW_{SI}(r)\}\left(\vec{S}\cdot\vec{L}\right)+V_l(r) \tag{3}$$

The terms in Equation (3) are the Coulomb potential, the real and the imaginary parts of nuclear (or central) potential, the real and the imaginary parts of the spin-orbit potential and the centrifugal potential respectively [13]. All these potentials depend on the distance, r, between the center of masses of the projectile and the target. $\vec{S}$ and $\vec{L}$ are the spin and orbital angular momentum operators of the projectile.

Coulomb potential V_{COUL}, which is treated as the potential of a uniformly charged sphere with a radius, $R_C=r_CA^{1/3}$, that must be considered in the interaction of charged particles. Coulomb potential [1] can be written as

$$V_{COUL}(r)=\begin{cases}\dfrac{Z_pZ_te^2}{2R_C}\left(3-\dfrac{r^2}{{R_C}^2}\right) & r<r_CA^{1/3}\\ \dfrac{Z_pZ_te^2}{r} & r\geq r_CA^{1/3}\end{cases}, \tag{4}$$

where Z_pe and Z_te represent the charge of the projectile and the charge of the target. From the experimental analyses r_C was found to be *1.4 fm* for the $^{16}O+^{16}O$ system, but through the quantum mechanical corrections it has been understood that $r_C=1.2$ *fm* [1].

In general, the real part of the central potential, V_{CR}, has the Woods-Saxon (WS) or Woods-Saxon square (WS2) shape which can be represented as

$$V_{CR}(r)=\frac{-V_0}{\left[1+\exp\left(\dfrac{r-r_0A^{1/3}}{a_0}\right)\right]^n} \tag{5}$$

here $n=1$ for WS form and $n=2$ for WS2 form. Since the imaginary part of the central potential is related to the inelastic scattering process, W_{CI} is more responsive to the details of the interaction than the real potential V_{CR}. Besides the real part, a central potential has to have that imaginary part even for the elastic scattering case. This imaginary part is composed of two components: one is related to the absorption in the nucleus volume and the other component is associated with the absorption in the nucleus surface ($W_{CI}=V_{CI}+V'_{CI}$). The volume component of the imaginary part could have WS form ($n=1$) or WS2 form ($n=2$)

$$V_{CI}(r)=\frac{-W_V}{\left[1+\exp\left(\dfrac{r-r_VA^{1/3}}{a_V}\right)\right]^n}. \tag{6}$$

The absorption in the nucleus surface for the imaginary part can be represented by a Gaussian type surface potential

$$V'_{CI}(r)=-W_S\exp\left\{-\left[\frac{\left(r-r_SA^{1/3}\right)}{b}\right]^2\right\} \tag{7}$$

or a Woods-Saxon differential type surface potential

$$V'_{CI}(r)=-4a_SW_S\left\{-\frac{d}{dr}\left[\frac{1}{1+\exp\left(\dfrac{r-r_SA^{1/3}}{a_S}\right)}\right]\right\}. \tag{8}$$

The polarizations due to the scattering reaction can be added to the optical potential equation by a spin-orbit potential term, and this term must be in complex form as well [13]. The suggested form for this potential is

given as Thomas shape [2]. Thus the real and imaginary parts of the spin-orbit potential term can be written as

$$V_{SR}(r)=\frac{2}{\hbar^2 r}V_{SO}\left\{-\frac{d}{dr}\left[\frac{1}{1+\exp\left(\frac{r-r_{SO}A^{1/3}}{a_{SO}}\right)}\right]\right\} \quad (9)$$

and

$$V_{SI}(r)=\frac{2}{\hbar^2 r}W_{SO}\left\{-\frac{d}{dr}\left[\frac{1}{1+\exp\left(\frac{r-r_{SO}A^{1/3}}{a_{SO}}\right)}\right]\right\} \quad (10)$$

respectively. Finally the centrifugal potential, due to the relative angular momenta of the target and projectile, depends on the angular momentum quantum number, l and can be given as

$$V_l(r)=l(l+1)\hbar^2/2\mu r^2 . \quad (11)$$

Therefore, the optical potential equation (Equation (3)) can be rearrenged as

$$\begin{aligned}V(r)=&V_{COUL}(r)-V_0 f^n(r,r_0,a_0)-iW_V f^n(r,r_V,a_V)-iW_S 4a_S\frac{d}{dr}f(r,r_S,a_S)\\&+(V_{SO}+iW_{SO})\frac{2}{r}\frac{d}{dr}f(r,r_{SO},a_{SO})(\vec{L}\cdot\vec{S})+V_l(r)\end{aligned} \quad (12)$$

where $n=1$ for WS form and $n=2$ for WS2 form. Equation (12), which gives the general form of the optical potential, has fourteen adjustable parameters. Eight of them are the geometry parameters (r_0 , a_0 , r_V , a_V , r_S , a_S ,r_{SO} and a_{SO}) and the rest are the dynamical parameters (V_0 , W_V , W_S , V_{SO} , W_{SO} and V_l). Usually same values are used for the surface and the volume geometry parameters of the imaginary part of the central potential (r_V = r_S and a_V = a_S) [13]. Since $\vec{L}\cdot\vec{S}=0$ for the ^{16}O+^{16}O reaction, the spin-orbit potential terms in Equation (12) are omitted. Thus the number of the geometry parameters reduces to four. Although the properties of the Coulomb potential and the centrifugal potential are well known, the structure of the central potential in Equation (12) is unclear. In fact, the main problem for investigating the heavy light-ion reactions is to determine the formation of this potential.

3. RESULTS AND DISCUSSION

In order to explain the experimental scattering and the reaction cross-sections, the necessary potentials are obtained by using a computer code. The programs Fresco [18], Ptolemy [19] and ECIS [20] are the most common reaction analyzing codes written for this purpose. In the analyses where the phenomenological potentials are used, the real and the imaginary parts can have the form of WS, WS2, WS derivative type or the combinations of these forms.

To examine the ^{16}O+^{16}O nuclear scattering reaction within the framework of the Optical model by using the Fresco code, one needs to start with deciding the structure of the central potential that is to be used in the computer program. It is reported by the previous works [1, 3, 6, 9] that, the optical potential for the ^{16}O+^{16}O reaction is generally constructed by a central potential which is a combination of a weak, WS2 volume type imaginary potential part and a deep, attractive, WS2 volume type real potential part [21]. From this point of view, the most suitable central potential form has been searched for the cases;

i-) $V_{CENTRAL}=V_{CR}(WS2\,volume)+iW_{CI}(WS2\,volume)$,
ii-) $V_{CENTRAL}=V_{CR}(WS2\,volume)+iW_{CI}(WS\,volume)$ and
iii-) $V_{CENTRAL}=V_{CR}(WS2\,volume)+i\left[W_{CI}(WS\,volume)+W_{CI}(WS2\,surface)\right]$.

In the Fresco code, we used those central potential forms with the parameter sets of the previous work [6] to perform the cross-section analysis. The comparisons of the calculated results with the experimental data have shown that, the most suitable central potential form obtained in the first case where the imaginary potential part has the WS2 volume form (see Figure 2). Thus, the interaction potential (Equation (12)), that is required to use in our OM calculations, becomes

$$V(r)=V_{COUL}(r)-V_0 f^2(r,r_0,a_0)-iW_V f^2(r,r_V,a_V)+V_l(r) . \quad (13)$$

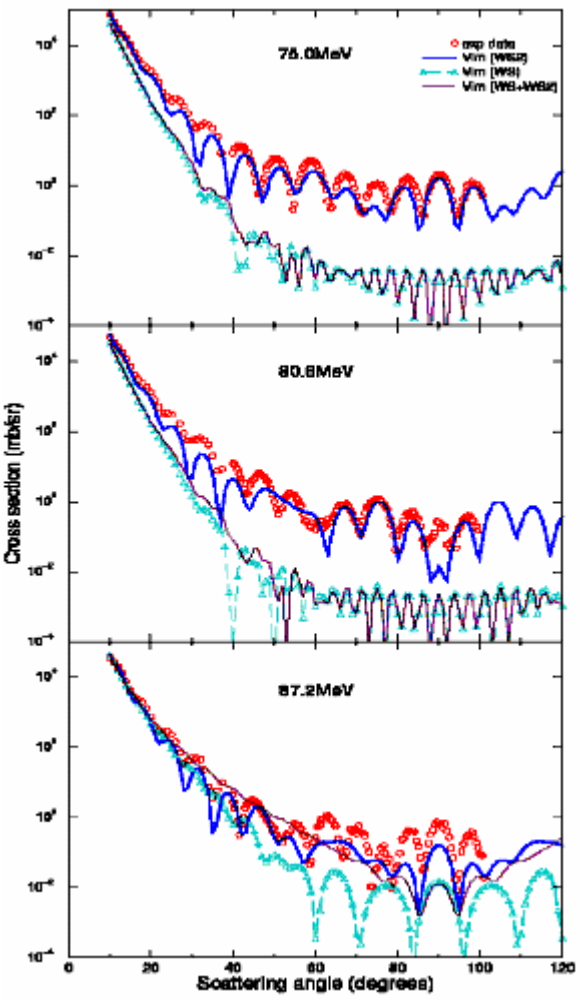

Figure 2: Examination of the central potential structure that is to be used in the code Fresco (The solid blue lines represent the fits obtained from the case i, the dashed light blue lines with triangles represent the fits obtained from the case ii and the solid violet lines represent the fits obtained from the case iii, while the circles symbolize the experimental data).

In this study, the experimental elastic scattering angular distribution data, obtained from the angular distribution measurements [6] of the $^{16}O+^{16}O$ reaction at the bombarding energies E_{LAB}=75.0, 80.6 and 87.2MeV, have been compared to the fits obtained from the Fresco code that performs calculations according to the OM (Figure 3a). In the calculations, WS2 volume form has been used for the imaginary part of the central potential and the real part of this potential has been chosen in WS2 form, which has the same behavior as the folded potential [1, 3, 6]. The new parameters of the phenomenological optical potentials, used in the code Fresco, are given in Table 1 (the parameters used for the real part (V_0 , r_0 , a_0) and for the imaginary part (W_V , r_V , a_V)).

The agreement between the theoretical and the experimental data has been determined by the χ^2 error calculation given below

$$\chi^2 = \frac{1}{N_\sigma}\sum_{i=1}^{N_\sigma}\frac{(\sigma_{th}-\sigma_{ex})^2}{(\Delta\sigma_{ex})^2} \qquad (14)$$

where σ_{th} , σ_{ex} and $\Delta\sigma_{ex}$ are the theoretical cross-section, the experimental cross-section and the error variation of the experimental cross-section respectively. N_σ represents the total number of the angles measured. The χ^2 values have been calculated by running a Fortran program (see Table 1). The χ^2 values obtained from the Fresco code outputs are found to be in agreement with the previous theoretical work [6].

In this study, we have performed an analysis that tends to keep the real part of the central potential constant as much as possible for all the energies. The depth of the potential has values between 417 and 419MeV. r_0 is fixed at 0.775fm and a_0 varies very little (see Table 1). Unfortunately this could not be achieved for the imaginary part of the central potential.

It is also possible to calculate the real central potential with a microscopic analysis via the folding model [2, 15]. The variations of the real potential values according to the radius are directly put in to the calculations with the aid of this model [22], and the imaginary parts are defined by a phenomenological way. To be able to fit the calculations with the experimental data, the normalization factor and the imaginary potential parameters must be adjusted. A double-folding analysis (see Figure 3b) has been performed using a Fortran program which was developed by the Nuclear Physics Group at Erciyes University. This program works in a similar way with the folding model. The normalization factor was set to 1 for the double-folding analysis of the $^{16}O+^{16}O$ reaction whereas the same imaginary potential parameters with the phenomenological analysis case were used. Double-folding analyses have showed an agreement with those performed using phenomenological potentials, but could not explain the experimental data better.

Last examination on the $^{16}O+^{16}O$ system has been done by α–cluster analysis [23] which uses double-folding cluster potentials (V_{cdf}). This analysis based on the assumption that ^{16}O nucleus can be represented as if it consists of 4 α-particles. To achieve this analysis, another Fortran program was used where the real potential was directly put in to the calculations as being in the folding model. The imaginary part was defined phenomenologically by the parameters used before. The cross-section analyses, which use the double-folding cluster potential, are shown in Figure 3c. The fits obtained from the cluster model analysis correspond to the least agreement with the experimental data. This agreement might be improved by adjusting the normalization factor and imaginary potential parameters better.

Table 1: Parameter values of the optical potential obtained by the code Fresco from an analysis of the $^{16}O+^{16}O$ reaction at the energies E_{LAB}=75.0, 80.6 and 87.2MeV.

E_{LAB} (MeV)	V_0 (MeV)	r_0 (fm)	a_0 (fm)	W_V (MeV)	r_v (fm)	a_v (fm)	χ^2
75.0	419.28	0.775	1.52	68.01	0.439	2.34	26.83
80.6	417.10	0.775	1.57	28.18	0.860	2.17	20.21
87.2	417.10	0.775	1.57	31.85	0.890	2.37	44.24

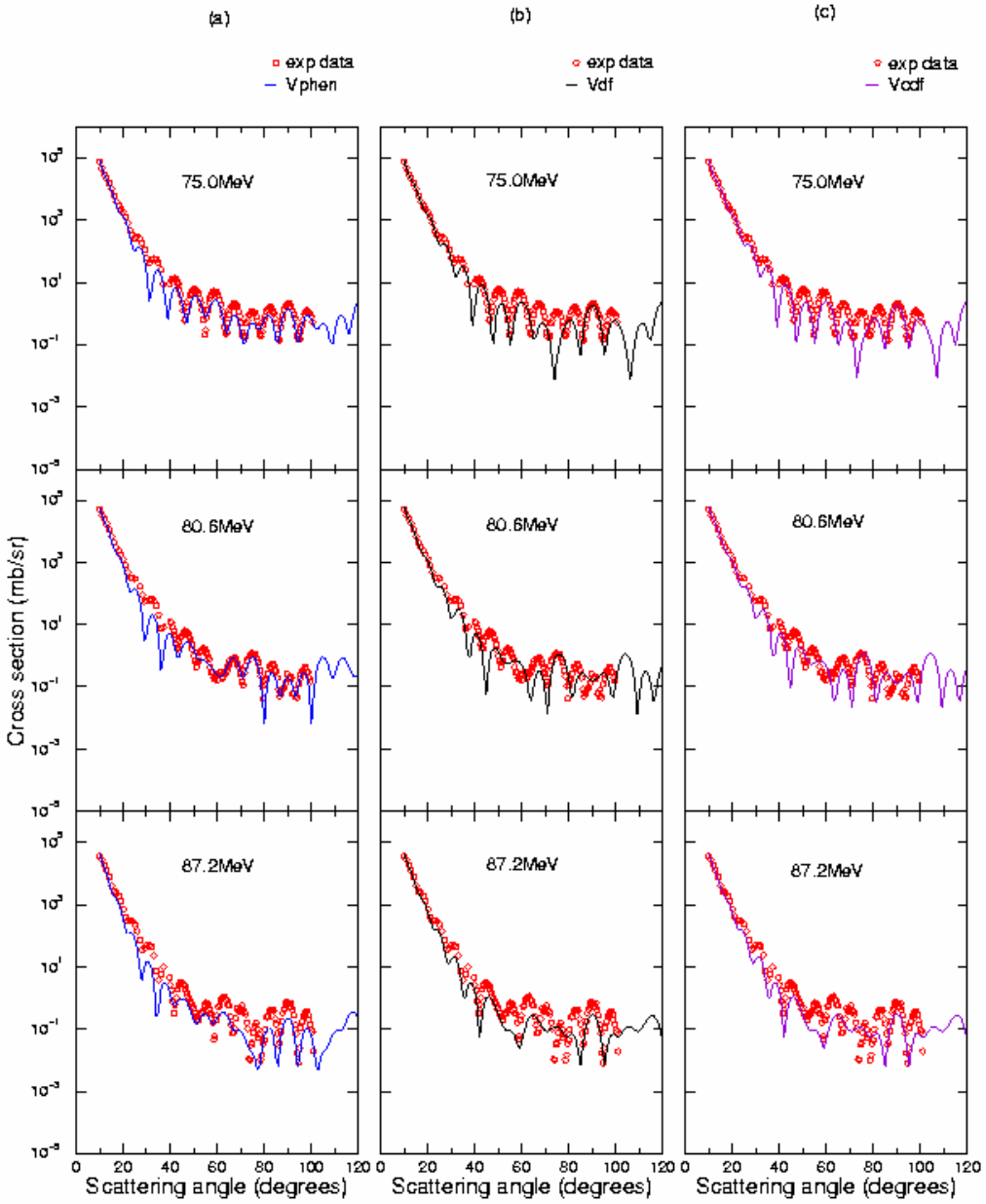

Figure 3: Elastic angular distributions of the $^{16}O+^{16}O$ reaction and fits for the energies E_{LAB}=75.0, 80.6 and 87.2MeV (X-axes represent the scattering angles in the CM frame and Y-axes represent the Rutherford differential cross sections in logarithmic scale). a-) Experimental data (circles) versus the fits (lines) obtained from phenomenological potentials by the code Fresco. b-) Experimental data (circles) versus the fits (lines) obtained from double-folding potentials. c-) Experimental data (circles) versus the fits (lines) obtained from cluster double-folding potentials

4. CONCLUSION

Some main models exist to investigate the nuclear reactions, however there is no single model developed yet to explain the entire experimental results of a specific reaction [24]. The Optical model, its formalism is expansively given in the text, is particularly successful to explain the elastic scattering of a light heavy-ion reaction.

In this study, the angular distributions of the $^{16}O+^{16}O$ elastic scattering at the bombarding energies E_{LAB}=75.0, 80.6 and 87.2MeV, have been analyzed theoretically. The form of the optical potential has been determined by using the elastic differential cross-section measurements. It is found that, at the incidence energies around 5MeV per nucleon the most suitable potential form with the experimental data for the $^{16}O+^{16}O$ system has been reached when the form of the central potential constructed by a weak, WS2 type imaginary part plus a deep, attractive, WS2 type real part. The analyses using the phenomenological, double-folding and cluster double-folding potentials have been compared to the experimental data. The Optical model calculations from the code Fresco have given the most suitable fits among these analyses and our χ^2 values very much agree with the previous theoretical work. The double-folding and cluster double-folding analyses displayed closer results to each other, but they have given poorer fits with the experimental data. This may occur due to keeping the normalization factor constant and the potential parameters same for all analyses.

Agreement with the experimental data can be improved further by taking into account the absorption due to the $1^{\pi}=3^{-}$ and 2^{+} channels [25] in coupled-channels formalism and by using the new coupling potential form developed by Boztosun and Rae [26].

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