The Effect of Breakup on Angular Distribution of Scattering Cross Sections in $^6$He+$^{197}$Au, $^6$He+$^{209}$Bi, and $^8$He+$^{208}$Pb Systems at Energies Close to Coulomb Potential Barrier

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Abstract. Effects of breakup channel on elastic and inelastic scattering have been studied using the nuclear potential Woods-Saxon (WS) for $^6$He+$^{197}$Au, $^6$He+$^{209}$Bi, and $^8$He+$^{208}$Pb systems, which contain weakly bound nuclei (halo nuclei) as projectiles. The Continuum-discretized coupled-channels (CDCC) method have been used to employed single channel (SC) and coupled channels (CC) calculations. Cross-sections of elastic and inelastic scattering were extracted from the optical potential fits, to achieve the optimum comparability between the theoretical calculations of $d\sigma_{tot}/d\sigma_R$ and experimental data for the systems reviewed. The breakup process at near Coulomb barrier energies play essential role in the results of cross section as a function of angle in angular distribution.

1 Introduction

One of the primary region of study in low-energy nuclear physics has been the reaction mechanisms involved in colliding both stable and unstable nuclei of near-barrier energy. Extensive experimental data and theoretical calculations were made to understand the multiple mechanisms of the collision, including the main interconnections. A number of detailed review studies on this topic have been published [1]. The nucleus-nucleus interaction is crucial for understanding nucleus activities [2], and it has been utilized to characterize nucleus-nucleus collisions [3]. The nucleus-nucleus potential determines the interaction energy of colliding nuclei [4]. It has been. Long-range repulsive coulomb potential exists between protons in nuclei, while nuclear potential occurs between protons and neutrons [5]. The Woods-Saxon (WS) equation from [6], is frequently used to explain the nuclear interaction, which is defined by the depth $V_0$, radius $r_0$, and propagation $a_0$ variables [7]. The concept of nuclear potential surface property has been investigated using the WS shape of a simple exponential [8]. The WS potential is vital in nuclear physics because it is viewed as a realistic potential [9]. For elastic scattering values, which are largely reactive to the surface propagation coefficient, the conventional value of roughly 0.63 fm has been used defines halo nuclei as weakly bound exotic nuclei that exhibit unique states in which protons and neutrons extend beyond the nuclear drip line [10]. There has
been a lot of interest in investigating halo/weakly bound nucleus collisions in the last decade. Furthermore, the coupling of the disintegration channels had a significant effect on elastic distribution and fusion [11]. Nuclear reactions have included loosely bound nuclei, and direct reactions have higher energy in general.

The term "direct reaction" refers to a wide variety of nuclear processes. The most fundamental direct reaction is elastic scattering, which keeps the target nucleus in its ground state. When a projectile collides with a target nucleus and transfers some of its energy to it, it causes

In this research, the elastic and inelastic scattering cross sections of $^6\text{He}^+\text{Au}$, $^6\text{He}^+\text{Bi}$, and $^8\text{He}^+\text{Pb}$ systems in cases of single and coupled channels are calculated. The theoretical calculations are compared with the practical values available as functions of the scattering angle in the center of mass coordinates.

### 2 Theoretical Background

The optical potential is composed of two components: the nuclear portion $V_N$, which is well and appropriately characterized by the Woods Saxon form, which has real and imaginary portions, and the Woods Saxon form, which is described by [12].

$$V_N(r) = \frac{-V_0}{1 + e^{(r-R_0)/a_0}}$$

where $V_0$ is the potential depth, $a$ is the surface diffuseness parameter, where $r$ is the center of mass distance between the target nucleus and the projectile nucleus and $R_0$ is described by [13].

$$R_0 = r_0\left(\frac{3}{\sqrt{A_P}} + \frac{3}{\sqrt{A_T}}\right)$$

which is the system's radius, $A_T$ the mass number of target nucleus and $A_P$ the mass number of projectile nucleus.

Between the projectile and the target, there is an effective potential that separates them by the relative distance $r$ as a function of the center of mass. It is divided into two parts, each of which is described below by [14].

$$V_{\text{eff}}(r) = V_N(r) + V_C(r)$$

For the complete wave function, the Schrödinger equation would be [15].

$$\left(-\frac{\hbar^2}{2\mu} \nabla^2 + V_{\text{eff}}(r) + H_0(\xi) + V_{\text{coup}}(\xi)\right)\psi(\vec{r}, \xi) = E\psi(\vec{r}, \xi)$$

where $r$ denotes the center of mass distance between accidental contact nuclei, and $V(r)$ denotes the naked potential in the absence of coupling, where $V_{\text{eff}}(r) = V_N(r) + V_C(r)$. $H_0(\xi)$ denotes the Hamiltonian for intrinsic motion, $V_{\text{coup}}(\xi)$ denotes the noted coupling, and $\psi(\vec{r}, \xi)$ denotes the complete wave equation would be chosen to give by $\vec{r}$ and $\xi$, where $\xi$ is internal degree of freedom. We can write the rate of elastic differential cross section by using equation [16]:

$$\frac{d\sigma_{\text{el}}}{d\sigma_R}(E, \theta) = \sum_{j\ell l} k_{nl} \left| \frac{f_{j\ell l}(E, \theta)}{f_C(E, \theta)} \right|^2$$

where $f_C(E, \theta)$ is the Coulomb scattering amplitude and $f_{j\ell l}(E, \theta)$ elastic scattering amplitude.
3 Results and Discussion

Figure 1 shows the total cross section of scattering to the cross section of Rutherford $\sigma/\sigma_{Rh}$ was determined with angle center of mass $\theta_{cm}$ for the $^{6}\text{He}+^{197}\text{Au}$ system at energy centre of mass 26.2 MeV, where the projectile $^{6}\text{He}$ is two neutron halo nucleus and the target $^{197}\text{Au}$ is heavy ion, using CDCC method and CC code for all orders coupling channels with Akyüz-Winther potential parameters $V_0 = 80.0$ MeV, $a_0 = 0.53$ fm, and $r_0 = 1.2$ fm, and breakup channel with imaginary part potential parameters $W_0 = 46.7$ MeV, $a_i = 0.38$ fm, and $r_i = 1.35$ fm, which are listed in Table 1. The best fitting between theoretical predictions and the measured data was in case of coupled channels for all calculation of this system.

Table 1. Akyüz-Winther potential parameters for $^{6}\text{He}+^{197}\text{Au}$, $^{6}\text{He}+^{209}\text{Bi}$ and $^{8}\text{He}+^{208}\text{Pb}$ nuclear reactions.

<table>
<thead>
<tr>
<th>System</th>
<th>$V_0$ (MeV)</th>
<th>$r_0$ (fm)</th>
<th>$a_0$ (fm)</th>
<th>$W_0$ (MeV)</th>
<th>$r_i$ (fm)</th>
<th>$a_i$ (fm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{6}\text{He}+^{197}\text{Au}$</td>
<td>80.00</td>
<td>1.2</td>
<td>0.53</td>
<td>46.70</td>
<td>1.35</td>
<td>0.38</td>
</tr>
<tr>
<td>$^{6}\text{He}+^{209}\text{Bi}$</td>
<td>81.50</td>
<td>1.2</td>
<td>0.73</td>
<td>51.20</td>
<td>1.25</td>
<td>0.8</td>
</tr>
<tr>
<td>$^{8}\text{He}+^{208}\text{Pb}$</td>
<td>83.75</td>
<td>1.2</td>
<td>0.63</td>
<td>53.77</td>
<td>1.30</td>
<td>0.77</td>
</tr>
</tbody>
</table>

Figure 2 shows the total cross section of scattering to the cross section of Rutherford $\sigma/\sigma_{Rh}$ was determined with angle center of mass $\theta_{cm}$ for the $^{6}\text{He}+^{209}\text{Bi}$ system at energy centre of mass 18.47 MeV in panel (A), and 21.87 MeV in panel (B), where the projectile $^{6}\text{He}$ is two neutron halo nucleus and the target $^{209}\text{Bi}$ is heavy ion, using CDCC method and CC code for all orders coupling channels with Akyüz-Winther potential parameters $V_0 = 81.50$ MeV, $a_0 = 0.73$ fm, and $r_0 = 1.2$ fm, and breakup channel with imaginary part potential parameters $W_0 = 51.20$ MeV, $a_i = 0.8$ fm, and $r_i = 1.25$ fm, which are listed in
Table 1. The best fitting between theoretical predictions and the measured data was in case of coupled channels for all calculation of this system.

Fig. 2. Uncoupled channel and coupled channels calculations for $^6\text{He}^+^{209}\text{Bi}$ system by dashed and solid red curves respectively: Panel (A) total scattering cross section ratio at 18.47 energy mass center, panel (B) total scattering cross section ratio at 21.87 energy mass center, and the purple circles are experimental data from Ref. [18].

Figure 3 shows the total cross section of scattering to the cross section of Rutherford $\sigma/\sigma_{Rh}$ was determined with angle center of mass $\theta_{cm}$ for the $^8\text{He}^+^{208}\text{Pb}$ system at energy centre of mass 21.19 MeV, where the projectile $^8\text{He}$ is two neutron halo nucleus and the target $^{208}\text{Pb}$ is heavy ion, using CDCC method and CC code for all order coupling channels with Akyüz-Winther potential parameters $V_0 = 83.75\text{ MeV}$, $a_0 = 0.63\text{ fm}$, and $r_0 = 1.2\text{ fm}$, and breakup channel with imaginary part potential parameters $W_0 = 53.77\text{ MeV}$, $a_i = 0.77\text{ fm}$, and $r_i = 1.30\text{ fm}$, which are listed in Table 1. The best fitting between theoretical predictions and the measured data was in case of coupled channels for all calculation of this system [20].

Fig. 3. Uncoupled channel and coupled channels calculations for $^8\text{He}^+^{208}\text{Pb}$ system by dashed and solid curves respectively, purple circles act experimental data from Ref. [19].
4 Conclusions

The coupling of any the selected systems improved the calculations for total scattering. We conclude that the breakup effect is very important for weakly bound projectiles, suppressed on heavy target nuclei, and, oppositely, is enhanced for some weakly bound projectiles at energies around the Coulomb barrier. In $^8\text{He} + ^{208}\text{Pb}$, we conclude measured values at incident energies that are identical with no-coupled and coupled calculations.

References