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Optical Model Analyses for the Elastic Scattering of ^{8}B, ^{7}Be and ^{6}Li with ^{12}C

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Abstract

Fission, break-up and direct reactions of stable, halo or weakly bound nuclei have intensively been investigated in recent years. The elastic scattering angular distributions of ^{8}B , ^{7}Be and ^{6}Li on a ^{12}C target have been analyzed within the framework of the optical model by using the phenomenological and microscopic potentials. The effect of clustering in explaining the nuclear deformation for the fission and break-up cases is very important and total reaction cross sections have been calculated from the elastic scattering analysis for the systems. The results are in very good agreement with the experimental data and the break-up effects have an important effect in explaining $^{8}\mathrm{B}+^{12}\mathrm{C}$ system within the cluster model.

1 Introduction

Structure and dynamics of the halo nuclei have generated much interest and a great number of papers have been published over the last decade [1, 2]. One neutron halo in ^{11}Be and two neutron halo in ^{11}Li are well established by experiments but the existence of a proton halo in ^{8}B is still a controversial question. It is argued that electric quadrupole moment, much larger than the shell model would predict, is a strong evidence for the existence of a proton halo in ^{8}B [3, 4].

Fission, fusion, break-up and direct reactions of halo or weakly bound nuclei have intensively been investigated in recent years [5, 6]. Due to the low binding energy, the weakly bound system produces large break-up or transfer cross-sections even at relatively low incident energies. In this respect, several experiments have been performed especially with neutron-rich nuclei such as ^{6}He [7, 8, 9, 10, 11] and theoretical models have also been suggested to understand the reaction observables with weakly bound nuclei [5]. Nuclear reactions induced by ^{8}B projectile have been one of the most studied reactions, because ^{8}B is a proton-halo nucleus with low break-up threshold. However, its half-time is relatively short so experimental data for the proton-halo ^{8}B nucleus are very rare. There now exists a large number of data on the elastic scattering of ^{8}B projectile over the ^{58}Ni target at around the barrier energy [12, 13, 14, 15]. For instance, measurements for elastic scattering of ^{8}B and its core nucleus ^{7}Be on a ^{58}Ni target [15] and fusion cross sections have been measured for the exotic proton-halo nucleus ^{8}B incident on a ^{58}Ni target at several energies near the Coulomb barrier which is the first experiment to report on the fusion of a proton-halo nucleus [16]. Analysis of total reaction cross-sections show that neutron and proton-halo nuclei have larger cross-section than those of normal weakly bound nuclei. The enhancement originates from the break-up of the proton-halo nuclei. In Ref. [17], measurements and analysis of the elastic scattering angular distributions of ^{8}B, ^{7}Be, and ^{6}Li on a ^{12}C target have been presented systematically for the elastic scattering of weakly bound light nuclei. In their paper, the effect of breakup in the elastic scattering of ^{8}B+^{12}C is investigated by performing CDCC calculations. Very recently, fusion radial potential barrier for the ^{8}B +^{58} Ni system is determined from a simultaneous optical model analysis of elastic scattering angular distributions and fusion data [18]. All of the studies mentioned above have shown an important evidence of the proton halo for ^{8}B.

Therefore, in this paper, we aim to investigate the effects of break-up on ^{8}B + ^{12}C elastic scattering by using the cluster model. The elastic scattering and break-up cross sections have been studied theoretically for ^{8}B, ^{7}Be and ^{6}Li + ^{12}C systems at E_{lab} = 25.8, 18.8 and 12.3 MeV, respectively to investigate the behavior of the optical potential and the effect of break-up coupling to the ^{8}B + ^{12}C reaction.

In the next section, we discuss the optical model and double folding model used to describe the elastic scattering data and present cluster model calculations. The energy dependence of the reaction cross sections are investigated in Section III and we conclude in Section IV.

2 Theoretical Analysis Of The Elastic Scattering

2.1 Optical model analysis

The elastic angular distributions of ^{8}B, ^{7}Be and ^{6}Li nuclei on ^{12}C target have been analyzed with the optical model by using phenomenological Wood-Saxon Saxon and microscopic double-folding type potentials. In our phenomenological optical model analysis, as a first step, we have used the following phenomenological complex potentials

$$V_{nuclear}(r) = \frac{-V}{1+e^{\frac{r-R_{\mathrm{V}}}{a_{\mathrm{V}}}}} + i\frac{-W}{1+e^{\frac{r-R_{\mathrm{W}}}{a_{\mathrm{w}}}}}, \tag{1}$$

Here, $R_i = r_i(A_p^{1/3} + A_t^{1/3})$ (i = V or W) where $A_p^{1/3}$ and $A_t^{1/3}$ are the masses of projectile and target nuclei and r_{V} and r_{W} are the radius parameters of the real and imaginary parts of the nuclear potential, respectively [19]. The WS potential parameters are listed in Table 1 and the parameters are taken from Refs. [20, 21, 22].

In the second step, we have used microscopic double-folding (DF) model to determine the real part of the complex nuclear potential ($V_{nuclear}(r)$). The realistic DF potential can be evaluated by using the nuclear matter distributions for projectile and target nuclei with an effective nucleon-nucleon interaction potential (ν_{nn}) [19]

$$V_{\mathrm{DF}}(r) = \int\int \rho_{\mathrm{P}}(r_1)\rho_{\mathrm{T}}(r_2)\nu_{nn}(|\vec{r} + \vec{r_2} - \vec{r_1}|)d^3r_1d^3r_2, \tag{2}$$

where ρ_{P} and ρ_{T} denote the nuclear matter density of projectile and target nucleus, respectively. For the nuclear matter density, we use the two-parameter Fermi (FM) form for all the projectile and target densities defined as

$$\rho(r) = \rho_0[1 + exp(\frac{r-c}{a})]^{-1}, \tag{3}$$

Table 2 shows the parameters ρ_0 , c, a and corresponding $\langle\rho^2\rangle^{1/2}$ values for ^{12}C , ^{8}B , ^{7}Be and ^{6}Li nuclei. The effective nucleon-nucleon interaction potential (ν_{nn}) have chosen the most common use, which is the M3Y nucleon-nucleon (Michigan 3 Yukawa) realistic interaction, given by

$$\nu_{nn}(r) = 7999\frac{exp(-4r)}{4r} - 2134\frac{exp(-2.5r)}{2.5r} + J_{00}(E)\delta(r)MeV \tag{4}$$

where J_{00} (E) represents the exchange term, since nucleon exchange is possible between the projectile and the target. J_{00} (E) is varying with the energy as

$$J_{00}(E) = 276[1 - 0.005E/A_p]MeVfm^3 \tag{5}$$

The results of phenomenological and microscopic double folding calculations are shown in Figures 1, 3 and 5 in comparison with the experimental data for ^{8}B , ^{7}Be and ^{6}Li + ^{12}C systems at $E_{lab} =$ 25.8, 18.8 and 12.3 MeV. Both phenomenological and microscopic double folding calculations provide a very good agreement with the experimental data for these systems at different energies.

2.2 Cluster calculations

In this section, we carry out a theoretical study of the breakup effect on the elastic angular distributions for the ^{8}B + ^{12}C system, using the cluster model.

As we show in Figure 2, the proton halo ^{8}B nucleus is considered as an inert ^{7}Be core plus one proton valance (^{7}Be + p) in our cluster calculations. The core-target (^{7}Be + ^{12}C) and valance-target (p + ^{12}C) potentials are taken into account separately. The WS-3 parameters are given in Table 1 have been used for the core-target potential and the valance-target potential parameters have been taken from Ref. [23]. The results of our cluster calculations are shown in Figure 4 in comparison with the experimental data.

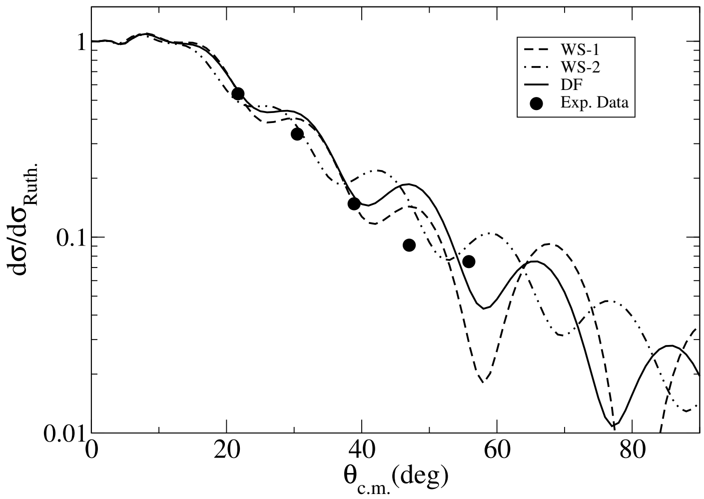

Figure 1: The differential cross section for the elastic scattering ^{12}C(^{8}B,^{8} B)^{12}C at 25.8 MeV incident laboratory energy. The curves are OM calculations with the parameters listed in Table I and II.

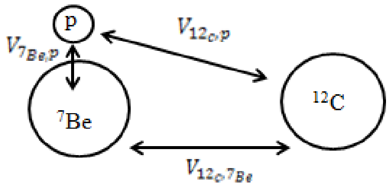

Figure 2: The differential cross section for the elastic scattering ^{12}C(^{8}B,^{8} B)^{12}C at 25.8 MeV incident laboratory energy. The curve is the result of the cluster model calculations. Figure 2 shows a schematic design of the cluster model for the ^{8}B + ^{12}C system.

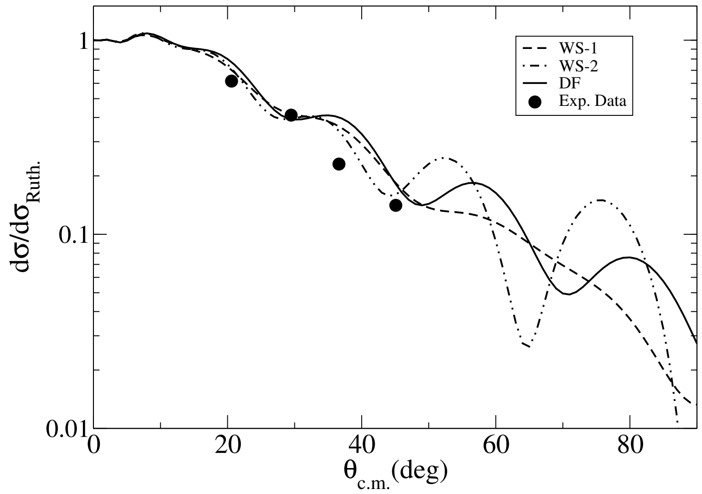

Figure 3: The differential cross section for the elastic scattering ^{12}C(^{7}Be,^{7} Be)^{12}C at 18.8 MeV incident laboratory energy. The curves are OM calculations with the parameters listed in Table I and II.

3 Total reaction cross section

The total reaction cross section is useful to investigate the role of breakup for weakly-bound nuclei. We use different projectiles with different geometrical effects (size, mass, charge *etc.*) on the same ^{12}C target to calculate the total cross section. In order to eliminate these trivial geometrical effects, we use a reduction procedure proposed by Gomes *et al.* [24]. The reduced cross sections and energies are given by

$$\sigma_{red} \rightarrow \frac{\sigma_R}{(A_p^{1/3}+A_t^{1/3})^2} \quad \text{and} \quad E_{red} \rightarrow E_{cm}\frac{(A_p^{1/3}+A_t^{1/3})}{Z_pZ_t} \tag{6}$$

with $Z_P(Z_T)$ and $A_P(A_T)$ are charge and mass of the projectile (target), respectively. This reduced energy and cross section have been composed with Wong formula [25] based on reduced quantities. Wong [25] has derived the following analytic expression for the total cross section

$$\sigma_R^W = R_B^2\frac{\hbar\omega_0}{2E}In[1+exp(\frac{2\pi(E-V_B)}{\hbar\omega_0})], \tag{7}$$

could also be reduced to

$$\sigma_{red}^W = \frac{\epsilon_0 r_0^2}{2E_{red}}In[1+exp(\frac{2\pi(E_{red}-V_{red})}{\epsilon_0})], \tag{8}$$

where the cross sections are in fm^2 and $R_B = r_0(A_p^{1/3}+A_t^{1/3})$, $\epsilon_0 = \hbar\omega_0\frac{(A_p^{1/3}+A_t^{1/3})}{Z_pZ_t}$ and $V_{red} = V_0\frac{(A_p^{1/3}+A_t^{1/3})}{Z_pZ_t}$ are denoted as the Wong-model parameters. When we use this reduction procedure and Wong formula for the ^{8}B, ^{7}Be and ^{6}Li data, we find the fit shown in Figure 6 .

Table 1: Optical-model potential parameters used in the calculations. Radii are given by $R_i = r_i(A_p^{1/3}+A_t^{1/3})$. The depths are in MeV and the radius and diffuseness are in fm.

Potential	V	r_v	a_v	W_v	W_s	r_w	a_w	r_c	Reference
WS-1	245.70	0.75	0.70	11.40	-	1.17	0.49	1.24	[20]
WS-2	60.00	1.18	0.60	32.60	-	1.18	0.60	0.63	[22]
WS-3	152.00	0.65	0.77	8.55	-	1.22	0.89	0.59	[21]

Table 2: Parameters of the 2-parameter Fermi distribution.

Nucleus	^{12}C	^{8}B	^{7}Be	^{6}Li
$\rho_0(fm^{-3})$	0.1527	0.1506	0.1529	0.1520
c (fm)	2.518	2.000	1.874	1.635
a (fm)	0.334	0.486	0.483	0.556
$\langle\rho^2\rangle^{1/2}(fm)$	2.314	2.380	2.310	2.314

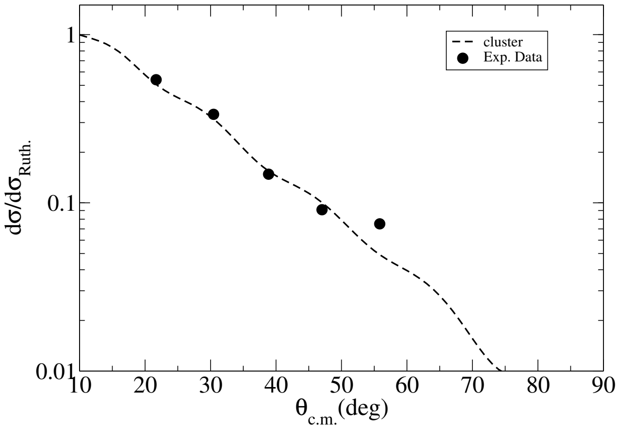

Figure 4: The differential cross section for the elastic scattering $^{12}C(^{8}B,^{8}B)^{12}C$ at 25.8 MeV incident laboratory energy. The curve is the result of the cluster model calculations. Figure 2 shows a schematic design of the cluster model for the ^{8}B + ^{12}C system.

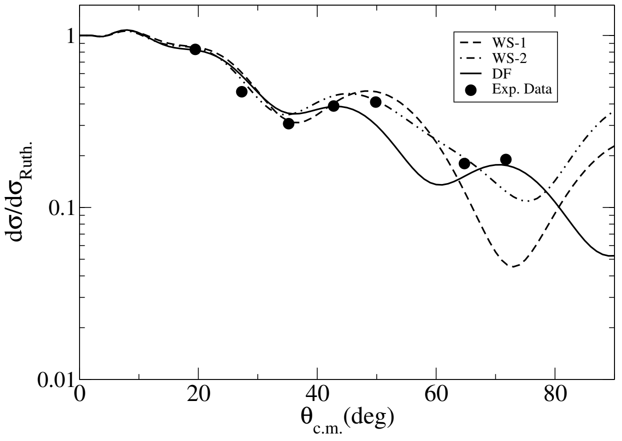

Figure 5: The differential cross section for the elastic scattering $^{12}C(^{6}Li,^{6}Li)^{12}C$ at 12.3 MeV incident laboratory energy. The curves are OM calculations with the parameters listed in Table I and II.

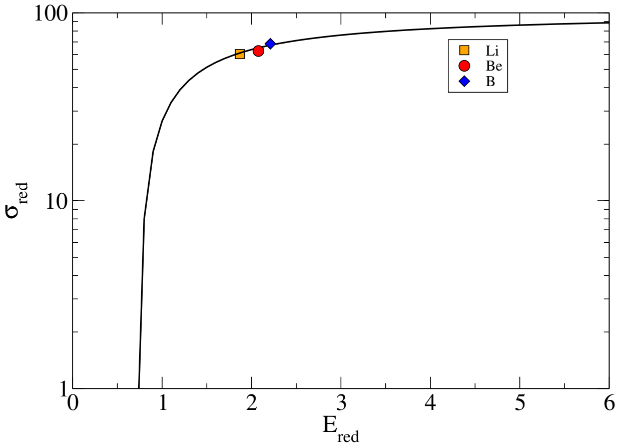

Figure 6: The reduced reaction cross sections for the ^{8}B , ^{7}Be and ^{6}Li + ^{12}C systems.

4 Summary and Conclusion

We have performed a systematic study of the total reaction cross sections for the weakly bound light nuclei. The elastic scattering of the light nuclei ^{8}B , ^{7}Be and ^{6}Li on ^{12}C target has been analyzed at $E_{lab} =$ 25.8, 18.8 and 12.3 MeV, respectively [17]. The elastic scattering angular distributions were firstly analyzed within the framework of optical model by using both phenomenological Woods-Saxon (WS) and microscopic double-folding nuclear potentials. The calculations with all of these potentials provide a good description of the elastic scattering data as well as the total cross sections. Our findings are inline with the caculations performed in the literature by using Optical, Coupled-Channels and CDCC calculations [26, 27, 28]

Fission or the projectile break-up is an important reaction channel in the scattering of weakly bound nuclei. At this point, the effect of the break-up on the elastic scattering has been investigated for the weakly bound ^{8}B nucleus by performing a cluster model calculation. In the cluster model, the proton halo ^{8}B nucleus is represented by ^{7}Be + p. The core-target (^{7}Be + ^{12}C) and valance-target (p + ^{12}C) potentials are taken into account by the cluster model calculations. The results are in very good agreement with the experimental data. Therefore, it is possible to claim that cluster calculations are very important to describe the scattering observables for weakly bound nuclei and it should be taken into account in the description of the elastic scattering data for such systems.

As a continuation of this work, in the following studies, it is aimed to include the inelastic channels in the Coupled-Channels calculations to observe the effect of clustering in explaining the fission products of the heavy nuclei such as $^{236}U^{*}$ and $^{240}Pu^{*}$ compound nuclei formed in $^{232}Th(\alpha, f)$, $^{236}U(\alpha, f)$.

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