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Research Article

A theoretical analysis of the ^{6}He + ^{9}Be reaction: phenomenological and double folding model approximations

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Abstract

We investigate the elastic scattering data of the ^{6}He + ^{9}Be reaction by using the phenomenological and double folding model potentials within the framework of the optical model. In the phenomenological calculations, we use the optical model parameters existed in literature to explain ^{6}He + ^{9}Be reaction. The real potentials in double folding calculations are obtained by using two different density distributions of ^{6}He nucleus. For both the phenomenological and double folding model calculations, the imaginary potentials have the shape of the Woods-Saxon volume. We compare the phenomenological model results with the double folding model ones as well as the experimental data. We present that the folding model results are in better agreement with the experimental data than the phenomenological results for the ^{6}He + ^{9}Be reaction.

Keywords: Optical model, exotic nuclei interactions, microscopic approaches, double-folding model, elastic scattering

1. Introduction

Halo nuclei have become one of the main interests of nuclear physics and nuclear astrophysics both experimentally and theoretically since the discovery of their unusual structure (Tanihata et al. 1985a; Tanihata et al. 1985b; Hansen & Jonson 1987; Zhukov et al. 1993; Riisager 1994; Tanihata 1995; Hansen et al. 1995; Tanihata 1996; Al-Khalili & Tostevin 1996a; Orr 1997; Johnson & Riisager 1998; Baur et al. 2001; Thompson & Suzuki 2001). Both experimental and theoretical studies have provided ample information about their weakly-bound nature and the large radial extent in their densities, enabling the understanding of their internal structure and the dynamics of their interactions. Among these halo-type nuclei, the ^{6}He nucleus is the most studied and best-known. This nucleus has attracted enormous interest both theoretically and experimentally due to its Borromean structure and the large probability of break-up near the Coulomb barrier (Smith et al. 1991; Al-Khalili et al. 1996b; Sánchez Benítez et al. 2005). Consequently, a large body of experimental data over a wide energy range has been accumulated for the elastic scattering of ^{6}He nucleus with different target nuclei.

The interest on ^{6}He + ^{9}Be reaction by using ^{9}Be as target nucleus increases with each passing day. Smith et al. (1991) have presented experimental data of ^{6}He + ^{9}Be reaction at E_{lab}=9 MeV and have investigated by using ^{4}He, ^{6}Li and ^{7}Li optical model parameters. They have indicated that ^{6}Li and ^{7}Li parameters are convenient to fit ^{6}He + ^{9}Be elastic scattering data but not ^{4}He parameters. Tao et al. (2002) measured the quasi-elastic scattering of ^{6}He on ^{9}Be target at 25 MeV/nucleon. They have expressed that relatively large r_v and a_v optical parameters are essential to obtain the large cross section at smaller angles. Ye et al. (2005ab) measured differential cross-sections of quasi-elastic scattering, breakup reaction and 1*n* and 2*n* transfer reactions of ^{6}He + ^{9}Be reaction at 25 MeV/nucleon. They analyzed the results in the context of the coupled-channels and the optical model calculations. Majer et al. (2010) have reported data on elastic, quasi-free scattering and two-neutron transfer for ^{6}He + ^{9}Be reaction at E_{lab}=16.8 MeV. In this work the elastic scattering results have been investigated by a CDCC calculation. Pires et al. (2011) have measured new experimental data for ^{6}He + ^{9}Be reaction at E_{lab}=16.2 and 21.3 MeV. They have investigated the effect of the collective couplings to the excited states of the target in terms of coupled-channels calculations. Additionally, they have studied the effect of the projectile breakup on the elastic scattering by means of three and four body continuum-discretized coupled-channels calculations.

In the present paper, we performe the elastic scattering analysis of ^{6}He + ^{9}Be reaction with two different models called the optical and double folding models at E_{lab}=16.2, 16.8 and 21.3 MeV. As discussed above, in previous studies, for the optical model calculations of ^{6}He + ^{9}Be reaction, ^{6}Li and ^{7}Li parameters were used. However, in recent years, Kucuk et al. (2009) have derived a phenomenological optical potential for elastic scattering of ^{6}He on different targets. They have reported that this potential was in very good agreement

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with experimental data at low energies. The double folding model is another model used extensively to describe nuclear reactions. This model includes both projectile and target nuclei density distributions. Therefore, density distribution used in double folding calculations is very important. This can be especially seen in exotic nuclei. With this goal, Aygün et al. (2010) have performed double folding model calculations for different targets by using few-body and gauss shape density distributions. They have pointed that the density distributions obtained by means of more fine calculations of nuclei gives more convenient results for investigated system.

In this study, firstly ^{6}He + ^{9}Be exotic nucleus reaction is investigated with a phenomenological way for the existing parameters in literature within the framework of the optical model calculations. Secondly, the reaction is analyzed with double folding calculations for two different density distributions of ^{6}He nucleus. Finally, we compare the phenemenological model results with double folding model results.

2. Theoretical Analysis

2.1. Optical Model Analysis

In this part, we investigate the elastic scattering of ^{6}He on the target nuclei ^{9}Be by using the phenomenological model. For the theoretical calculations, the total effective potential in the optical model consists of nuclear, Coulomb and centrifugal potentials

$$V_{total}(r) = V_{Nuclear}(r) + V_{Coulomb}(r) + V_{Centrifugal}(r) \quad (1)$$

Both the real and the imaginary potential of the nuclear potential have been taken the Woods-Saxon type as the following form

$$V_N(r) = \frac{V_0}{1+\exp((r-R_v)/a_v)} - i\frac{W_0}{1+\exp((r-R_w)/a_w)} \quad (2)$$

where

$R_i = r_i(A_P^{1/3} + A_T^{1/3}) \ \ (i = V \text{ or } W)$, A_P and A_T 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. In our study we have used the parameters obtained with the equations suggested by Kucuk et al. (2009). For this purpose, Eqs. (3) and (4) derived for the variation of the depth of the real and imaginary parts of the nuclear potential can be given as the following forms

$$V_0 = 110.1 + 2.1\frac{Z_T}{A_T^{1/3}} + 0.65E \quad (3)$$

$$W_0 = 6.0 + 0.48\frac{Z_T}{A_T^{1/3}} - 0.15E \quad (4)$$

where equations depend on the incident energy of the projectile (^{6}He) with the charge number (Z) and the mass number (*A*) of the target. All parameters used in calculations are shown in Table 1. The code FRESCO (Thompson 1988) has been used for the calculations.

Table 1: The optical model parameters used for the phenomenological model.

E_{Lab} MeV	V MeV	r_v fm	a_v fm	W MeV	r_w fm	a_w fm	σ mb
16.2	124.7	0.9	0.7	4.49	1.5	0.7	1505.6
16.8	125.1	0.9	0.7	4.40	1.5	0.7	1502.2
21.3	128.0	0.9	0.7	3.73	1.5	0.7	1433.4

2.2. Double Folding Model Analysis

In this section, the real part of the complex $V_{nuclear}$(r) potential is determined by using the double folding model. In order to obtain the potential, the nuclear matter distributions of both the projectile and target nuclei together with an effective nucleon-nucleon interaction potential (v_{NN}) are used. Thus, the double-folding potential is

$$V_{DF}(r) = \int dr_1 \int dr_2 \rho_P(r_1)\rho_T(r_2)v_{NN}(r_{12}) \quad (5)$$

where $\rho_P(r_1)$ and $\rho_T(r_2)$ are the nuclear matter density of the projectile and target nuclei, respectively. In order to make a comparative study, we have used two different matter density distributions for the ^{6}He ground state. The first density has been obtained by few-body model calculations taken from Ref. (Al-Khalili & Tostevin 1996a). For the second density in calculations of the double-folding potential we have also used the Gaussian distribution described as (Aygun et al. 2010).

$$\rho(r) = \rho_0 \exp(-\beta r^2) \quad (6)$$

The density distribution of ^{9}Be target nucleus has been taken as in Ref. (Hnizdo et al. 1981)

$$\rho(r) = (A + BC^2r^2)\exp(-C^2r^2) + (D + EF^2r^2)\exp(-F^2r^2) \quad (7)$$

where *A*=0.0651, *B*=0.0398, *C*=0.5580, *D*=0.0544, *E*=0.0332 and *F*=0.4878. This density distribution of the target nucleus gives a root-mean-square (rms) radius of 2.73 fm. The effective nucleon-nucleon interaction, (v_{NN}), is integrated over both density distributions. Several nucleon-nucleon interaction expressions can be used for the folding model potentials. We have chosen the most common one, which is the M3Y nucleon-nucleon (Michigan 3 Yukawa) realistic interaction, given by

$$v_{NN}(r) = 7999\frac{\exp(-4r)}{4r} - 2134\frac{\exp(-2.5r)}{2.5r} + J_{00}(E)\delta(r)\ MeV \quad (8)$$

where $J_{00}(E)$ represents the exchange term, since nucleon exchange is possible between the projectile and the target. $J_{00}(E)$ has a linear energy-dependence and can be expressed as

$$J_{00}(E) = 276\ [1 - 0.005\ E/A_p]\ MeV\ fm^3 \quad (9)$$

3. Results and Discussion

We have presented an extended theoretical analysis for the ^{6}He + ^{9}Be reaction at the energies of 16.2, 16.8 and 21.3 MeV. The optical potential parameters used in the phenomenological model, the double folding model and the cross sections are shown in Table 1 and 2.

Table 2. The optical model parameters and σ values obtained for the density distributions investigated by using the double folding model.

System	E_{Lab}	N	W	r_w	a_w	σ
^{6}He+^{9}Be	*MeV*	-	*MeV*	*fm*	*fm*	*mb*
FB	16.2	0.85	9.30	1.26	0.47	1294.9
	16.8	0.84	11.00	1.26	0.47	1292.8
	21.3	0.85	11.20	1.26	0.47	1272.4
GD	16.2	1.05	10.60	1.26	0.47	1371.1
	16.8	0.82	10.90	1.26	0.47	1284.1
	21.3	0.80	11.00	1.26	0.47	1250.9

In Figure 1, we have shown the results obtained by using the parameters of Ref. (Kucuk et al. 2009). It has been seen that the theoretical results are not in good agreement with the experimental data. Thus, these results should be improved with another theoretical approach.

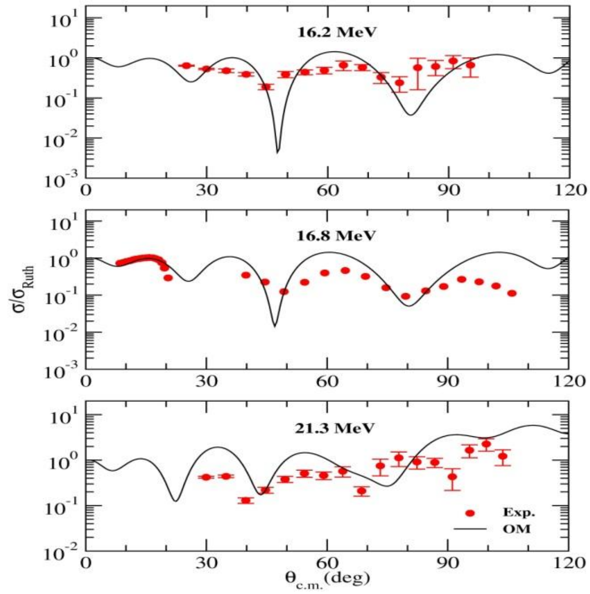

Figure 1. The comparison of the optical model calculations with the experimental data of ^{6}He + ^{9}Be reaction at E_{Lab} = 16.2, 16.8 and 21.3 MeV. The experimental data have been taken from (Pires et al. 2011).

For this purpose, we have also investigated this reaction by means of the double folding model. We have used two different density distributions so that we are able to obtain a real folding potential. The results are displayed in Figure 2. It can be said that all density distribution results generally provide good results in defining the experimental data. For these systems, we have observed the sensitivity to the normalization constant.

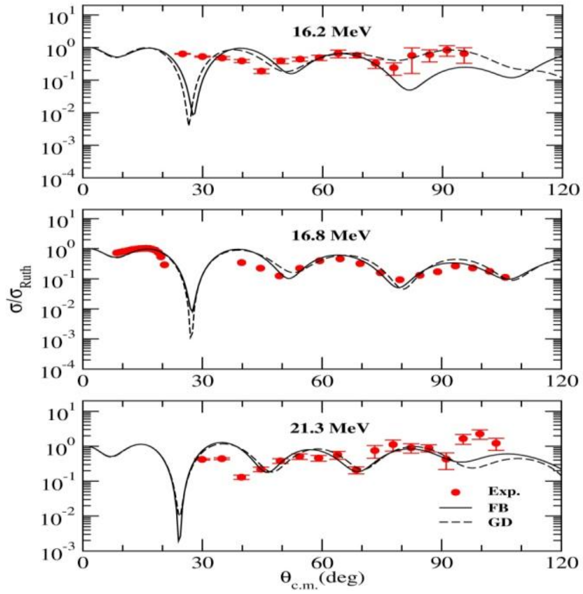

Figure 2. The elastic scattering angular distributions for FB and GD density distributions of ^{6}He + ^{9}Be reaction at E_{Lab} = 16.2, 16.8 and 21.3 MeV in comparison with the experimental data. The experimental data have been taken from (Pires et al. 2011).

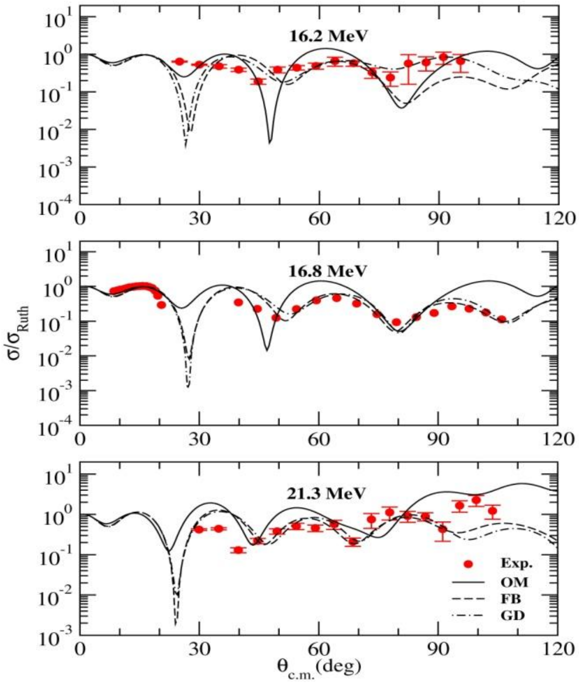

Figure 3. The comparison of the optical model calculations with the double folding model results of ^{6}He + ^{9}Be reaction at E_{Lab} = 16.2, 16.8 and 21.3 MeV.

In Figure 3, we have compared these results with the phenomenological model results as well as the experimental data. In general, these predict the maximum and minimum of the experimental data correctly at forward angles. We should point out that the double folding model results are in better agreement with the experimental data composed to the phenomenological model results.

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