Annals of Nuclear Energy 51 (2013) 1–4

Contents lists available at SciVerse ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

A theoretical study on $^{120}Sn(^{6}He, ^{6}He)^{120}Sn$ elastic scattering

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ARTICLE INFO

Article history:
Received 25 April 2012
Received in revised form 24 August 2012
Accepted 4 September 2012
Available online 2 October 2012

Keywords:
Optical model
Exotic nuclei interactions
Microscopic approaches
Double folding model
Elastic scattering

ABSTRACT

In this study, we analyze $^{120}Sn(^{6}He,^{6}He)^{120}Sn$ elastic scattering with both the phenomenological (WS) and microscopic double folding (DF) potentials. In the phenomenological calculations we use the optical model (OM) parameters acquired from literature. DF potentials have been obtained for no-core shell model (NCSM) density distribution (DD) of ^{6}He nucleus. The phenomenological results is compared with DF model results as well as the experimental data. These comparison provides information about the similarities and differences of the models used in calculations.

1. Introduction

Unstable nuclei have become one of very interesting subjects of nuclear physics and nuclear astrophysics both experimentally and theoretically since the discovery of their unusual structure (Al-Khalili and Tostevin, 1996a; Baur et al., 2001; Johnson and Riisager, 1998; Orr, 1997; Riisager, 1994; Tanihata, 1996; Thompson and Suzuki, 2001; Zhukov et al., 1993). In order to obtain sufficient 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, a lot of studies have performed both experimentally and theoretically over recent years. The ^{6}He nucleus is the most studied and best-known of halo-type nuclei. 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 (Al-Khalili et al., 1996b; Boztosun et al., 2008; Brodeur et al., 2012; Chatterjee et al., 2008; de Diego et al., 2010; Mohr et al., 2010; Rodríguez-Gallardo et al., 2008; Smith et al., 1991; Wolski et al., 1999). 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.

In previous years, the interactions with the stable nuclei such as ^{40}Ar (El-Azab Farid and Satchler, 1985), $^{16,18}O$ (Sinha et al., 2001), ^{32}S (Tripathi et al., 2001) of ^{120}Sn as target nucleus have extensively been examined by using different methods at various energies. However, recently, the elastic scattering angular distributions of ^{6}He on ^{120}Sn at E_{Lab} = 17.40, 18.05, 19.80 and 20.5 MeV energies above the Coulomb barrier by using the RIBRAS (Radioactive Ion Beams in Brasil) facility have been measured. The results have been analyzed with the optical model (OM) and three- and four-body continuum-discretized coupled-channels calculations (de Faria et al., 2010a). Also, the angular and energy distributions of α particles observed in $^{6}He + ^{120}Sn$ reaction have been examined by de Faria et al. (2010b). In the present work, we aim to reanalyze the elastic scattering angular distribution with two different models such as the phenomenological and double folding model (DFM) for the new measured experimental data of $^{6}He + ^{120}Sn$ reaction.

Recently, 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 with experimental data at low energies. Investigation of the effectiveness of this potential for different systems will be important to study elastic scattering of ^{6}He nucleus with the other target nuclei. DFM is another model used extensively to describe nuclear reactions. This model includes both projectile and target nuclei density distributions. Therefore, density distribution used in DF calculations is very important. Especially, this case can be seen in exotic nuclei. With this goal, Aygun et al. (2010) have performed DFM calculations for different targets by using few-body (FB) and gauss shape density (GD) distributions. They have pointed that the density distributions obtained by means of more sensitive calculations of nuclei gives more convenient results for investigated system. Thus, analysis of this system with density distribution acquired by examining microscopically of the features of the light nuclei will be very interesting and important.

In this study, firstly, $^{6}He + ^{120}Sn$ exotic nucleus reaction is investigated with a phenomenological way for the parameters obtained from literature within the framework the OM calculations.

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http://dx.doi.org/10.1016/j.anucene.2012.09.001

Secondly, the reaction is analyzed with DF calculations for no-core shell model (NCSM) (Navrátil et al., 2000, 2005) density distribution of ^{6}He nucleus. Finally, we compare the phenomenological model results with DFM results as well as the experimental data. The similarities and differences of models used in analysis of elastic scattering angular distributions of ^{6}He + ^{120}Sn system are pleasantly visible in this comparison.

2. Theoretical analysis

In this section, we examine the elastic scattering of ^{6}He on ^{120}Sn by using both the phenomenological and DFM within the framework of the OM at $E_{\rm Lab}$ = 17.40, 18.05, 19.80 and 20.50 MeV energies. For the theoretical calculations, the total effective potential in the OM consists of nuclear, Coulomb and centrifugal potentials as

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

where the Coulomb potential (Satchler, 1983) due to a charge $Z_P e$ interacting with a charge $Z_T e$ distributed uniformly over a sphere of radius R_c is

$$V_{Coulomb}(r) = \frac{1}{4\pi\epsilon_\circ}\frac{Z_P Z_T e^2}{r}, \qquad r \geqslant R_c \quad (2)$$

$$= \frac{1}{4\pi\epsilon_\circ}\frac{Z_P Z_T e^2}{2R_c}\left(3 - \frac{r^2}{R_c^2}\right), \qquad r < R_c \quad (3)$$

where R_c is the Coulomb radius, taken as $0.80(A_P^{1/3} + A_T^{1/3})$ fm in the calculations and Z_P and Z_T denote the charges of the projectile P and the target nuclei T, respectively.

The centrifugal potential is

$$V_{Centrifugal}(r) = \frac{\hbar^2\ l\ (l+1)}{2\ \mu\ r^2} \quad (4)$$

where μ is the reduced mass of the colliding pair.

2.1. Phenomenological analysis

For phenomenological analysis, both real and imaginary potential of the nuclear potential have been taken as the Woods–Saxon (WS) type in the following form

$$V_N(r) = -\frac{V_0}{1+\exp\left((r-R_v)/a_v\right)} - i\frac{W_0}{1+\exp\left((r-R_w)/a_w\right)} \quad (5)$$

where $R_i = r_i\left(A_P^{1/3} + A_T^{1/3}\right)$ $(i = V \text{ or } W)$, where 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. The real and imaginary parts of nuclear potential in phenomenological analysis are obtained with the equations suggested by Kucuk et al. (2009). They have proposed two equations which give the depth-variations of the real and imaginary parts. These equations that change according to the charge number, the mass number and the incident energy of the projectile are given as the following forms

$$V_0 = 110.1 + 2.1\frac{Z_T}{A_T^{1/3}} + 0.65E_{\rm Lab} \quad (6)$$

$$W_0 = 6.0 + 0.48\frac{Z_T}{A_T^{1/3}} - 0.15E_{\rm Lab} \quad (7)$$

where $E_{\rm Lab}$ is the energy of the projectile. The optical potential parameters used in calculations are shown in Table 1. The code FRESCO (Thompson, 1988) has been used for the calculations.

Table 1
The OM parameters used in phenomenological model analysis of ^{6}He + ^{120}Sn reaction.

$E_{\rm Lab}$ (MeV)	V (MeV)	r_v (fm)	a_v (fm)	W (MeV)	r_w (fm)	a_w (fm)	σ (mb)
17.40	142.699	0.9	0.7	8.256	1.5	0.7	1308
18.05	143.121	0.9	0.7	8.158	1.5	0.7	1413
19.80	144.259	0.9	0.7	7.896	1.5	0.7	1657
20.50	144.714	0.9	0.7	7.791	1.5	0.7	1742

2.2. Double folding model analysis

The real part of the complex $V_{Nuclear}(r)$ potential is also determined by using the DFM. In order to obtain the potential, the nuclear matter distributions of both projectile and target nuclei together with an effective nucleon–nucleon interaction potential (v_{NN}) are used. Thus, the DF potential is

$$V_{\rm DF}(\mathbf{r}) = \int d\mathbf{r_1}\int d\mathbf{r_2}\rho_P(\mathbf{r_1})\rho_T(\mathbf{r_2})v_{NN}(r_{12}) \quad (8)$$

where $\rho_P(\mathbf{r}_1)$ and $\rho_T(\mathbf{r}_2)$ are the nuclear matter density of projectile and target nuclei, respectively. In order to make a comparative study, we have used NCSM density distribution (DD), different from the FB distribution for ^{6}He previously used in Aygun et al. (2010). NCSM puts all the nucleons of halo nuclei in active role (Stetcu et al., 2005). In our study, NCSM DD has been taken from reference (Navrátil et al., 2005). The point-proton and point-neutron rms radii of ^{6}He are 1.763 fm and 2.361 fm, respectively by using realistic nucleon-nucleon interactions. In our folding potential analysis, the density distribution of the ^{120}Sn has been taken from Reference Input Parameter Library (xxxx).

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, the M3Y nucleon-nucleon (Michigan 3 Yukawa) realistic interaction. The M3Y has two form, one corresponds to M3Y-Reid and another is bases on the so-called M3Y-Paris interaction (Brandan and Satchler, 1997). In the present work, we use the former form with the relevant exchange correction term due to the Pauli principle. M3Y is given by

$$v_{NN}(r) = 7999\frac{\exp(-4r)}{4r} - 2134\frac{\exp(-2.5r)}{2.5r} + J_{00}(E)\delta(r)\ \text{MeV}, \quad (9)$$

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

$$J_{00}(E) = 276\ [1 - 0.005\ E_{\rm Lab}/A_p]\ \text{MeV fm}^3. \quad (10)$$

The parameters used in calculations are shown in Table 2. While imaginary potential parameters is determined, after r_W is fixed at convenient value, W_0 and a_w are varied to optimize the fit to the data. We tried to find global geometry parameters for the imaginary part without success. We have observed that DFM results

Table 2
The OM parameters and σ values for NCSM and FB DD investigated by using DFM for ^{6}He + ^{120}Sn reaction.

Density distribution	$E_{\rm Lab}$ (MeV)	N	W (MeV)	r_w (fm)	a_w (fm)	σ (mb)
NCSM	17.40	1.00	10.80	1.32	0.72	988
	18.05	1.00	10.90	1.32	0.72	1090
	19.80	1.00	11.00	1.32	0.72	1328
	20.50	1.00	12.00	1.32	0.72	1430
FB	19.80	1.00	11.00	1.32	0.72	1464
	20.50	1.00	12.00	1.32	0.72	1561