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Interaction of $1p$ nuclei: Case of ^{14}N+^{12}C Elastic Scattering at 21.0 MeV

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Abstract. Optical model analysis has been conducted for the elastic scattering of $1p$-shell nuclei around the Coulomb barrier energies. We have used both microscopic double-folding and phenomenological potentials for the real part of the complex nuclear potential. The imaginary potential has the shape of phenomenological Wood-Saxon volume. The case ^{14}N+^{12}C for $1p$-shell nuclei has been studied in detail and it is noticed that a large normalization of the strength of the double-folding real potential is needed to explain the structure observed in the experimental data. A good agreement between experimental data and theoretical results is obtained for the phenomenological potential case.

1. Introduction

The interaction of $1p$-shell nuclei presents a variety of rich structure from clustering effect to nucleon transfer. The reactions around the Coulomb barrier and over the barrier have different diffraction patters. While around the Coulomb barrier, the experimental data presents a Fresnel type, over the Coulomb barrier it changes to Fraunhofer type diffraction pattern. The potential approach in Optical and Coupled-channels models in order to explain the experimental data have certain difficulties to reproduce the certain aspects of the structure observed. The experimental data have a structured peak at forward angles and an oscillatory behavior at intermediate angles while at large angles, the measured cross-section has a backward rise. Theoretical models attempting to explain the experimental data ranging from cluster exchange to parity dependent potential have difficulties to explain the oscillatory structure and backward rise of the data. These theoretical studies have shown that the real part of the complex optical potential should be deep while the imaginary part should be weak, that is a surface transparent potential approach. The backward rise of the experimental data has also related to the α-particle exchange between projectile and target nuclei [1, 2, 3, 4, 5, 6, **?**, **?**, 9, 10, 11, 12].

The experimental measurements for ^{14}N+^{12}C nuclear system as an example of $1p$-shell nuclei were performed in the cyclotron DC-60 located in Institute of Nuclear Physics, Almaty-

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Kazakhstan [13]. The ^{14}N ion beam has been accelerated up to energies 1.25, 1.5, and 1.75 MeV/A and then directed to ^{12}C target nuclei of thickness 31.9 $\mu g/cm^2$. The beam current was nearly equal to 20 nA during the experiment, the angular distribution was measured in a wide range of angles $\approx$ 20-130° in center of mass system. Energy spectra of scattered particles were recorded with a semiconductor silicon surface barrier detector ORTEC company sensitive layer with a thickness of 100 microns. The energy resolution of the registration system was 250-300 keV, which is mainly determined by the energy spread of the primary beam. Only one detector was used in our measurements which detect both ^{14}N fragment and ^{12}C residual peaks. Spectrum analysis has been performed using program MAESTRO [14]. The details of experimental measurements can be found in Ref. [15]. As it can be seen from the experimental data, it does not present an oscillatory structure and a fall off at the intermediate angles. A backward rise is not also observed as opposed to similar systems.

Therefore, in order to understand the underlying reaction mechanism, we have conducted a theoretical study of ^{14}N+^{12}C reaction at E_{Lab}=21.0 MeV. We have used both optical and coupled channels analysis to explain the elastic scattering data.

In the next section, we introduce our Optical model and potential parameters to explain the observed experimental data. Then, we show the results of optical and coupled-channels model analyzes in section 3. Our conclusion is given in Section 4.

2. The Model

In the present calculations, we have used both a phenomenological deep and double-folding real potentials with a volume type imaginary potential [16, 22]. Our total real potential for these cases consists of the nuclear potential, $V_{Nuclear}$, and the Coulomb and centrifugal potentials, V_{Coul}, V_{Cent} respectively

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

The phenomenological nuclear potential is assumed to have the square of a Woods-Saxon shape:

$$V_{Nuclear}(r) = \frac{-V_0}{(1 + exp(r - R)/a)^2} \tag{2}$$

where V_0=275.0 MeV and R=$r_0({A_a}^{1/3}+{A_A}^{1/3})$ with r_0=0.780 fm and a=1.4 fm.

The Coulomb potential [16] due to a charge $Z_a e$ interacting with a charge $Z_A e$, distributed uniformly over a sphere of radius R_c, is also added.

$$V_{Coulomb}(r) = \frac{1}{4\pi\epsilon_\circ}\frac{Z_a Z_A e^2}{r}, \qquad r \geq R_c \tag{3}$$

$$= \frac{1}{4\pi\epsilon_\circ}\frac{Z_a Z_A e^2}{2R_c}(3 - \frac{r^2}{R_c^2}), \qquad r < R_c \tag{4}$$

where R_c=5.64 fm is the Coulomb radius, and Z_a and Z_A denote the charges of the projectile a and the target nuclei A respectively.

Microscopic nuclear potential we have also used to analyze the experimental data for ^{14}N+^{12}C system is based on the double-dolding model [17]. Double folding potential is calculated by using the nuclear matter distributions of both projectile and target nuclei together with an effective nucleon-nucleon interaction potential (ν_{NN}) are used. Thus, the double folding potential is

$$V_{\rm DF}(\mathbf{r}) = \int d\mathbf{r}_1 \int d\mathbf{r}_2 \rho_P(\mathbf{r}_1)\rho_T(\mathbf{r}_2)\nu_{NN}(r_{12}) \tag{5}$$

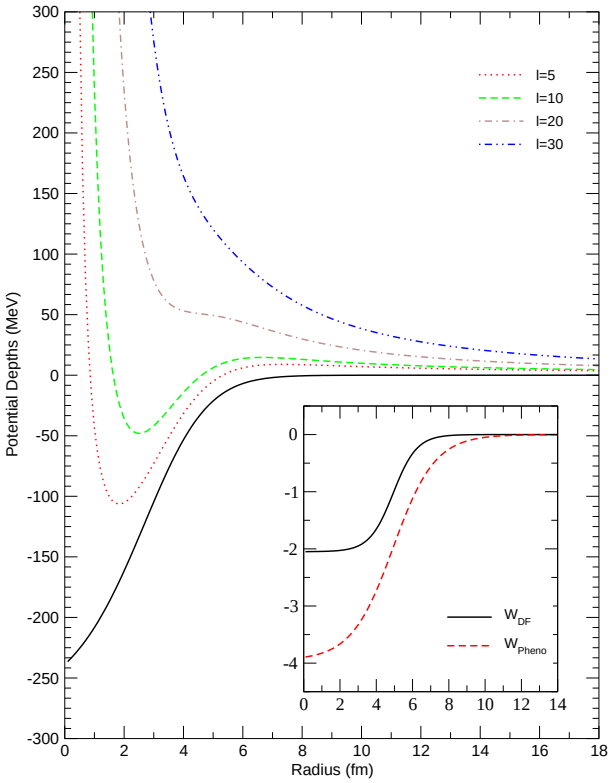


Figure 1. Interaction potential between ^{14}N and ^{12}C for various values of the orbital angular momentum quantum number, l. The parameters are given in the text.

where $\rho_P(\mathbf{r}_1)$ and $\rho_T(\mathbf{r}_2)$ are the nuclear matter density of projectile and target nuclei, respectively. Gaussian density distributions (GD) have been used for both nuclei [18, 19, 20] defined as:

$$\rho(r) = \rho_0 \exp\,(-\beta r^2) \tag{6}$$

where β is adjusted to reproduce the experimental value for the rms radius of the ^{14}N=2.58 fm and ^{12}C=2.472 fm [21]. ρ_0 values can be obtained from the normalization condition

$$\int \rho(r) r^2 dr = \frac{A}{4\pi} \tag{7}$$

where A is the mass number.

The effective nucleon-nucleon interaction, ν_{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 based on the so-called M3Y-Paris interaction [17]. In the present work, we use the former form with the relevant exchange correction term due to the Pauli principle, given by

$$\nu_{NN}(r) = 7999\,\frac{\exp(-4r)}{4r} - 2134\,\frac{\exp(-2.5r)}{2.5r} + J_{00}(E)\delta(r)\ \text{MeV}, \tag{8}$$

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

$$J_{00}(E) = \ 276\ [1 - 0.005\ E_{\rm Lab}/A_p]\ \text{MeV fm}^3 \tag{9}$$

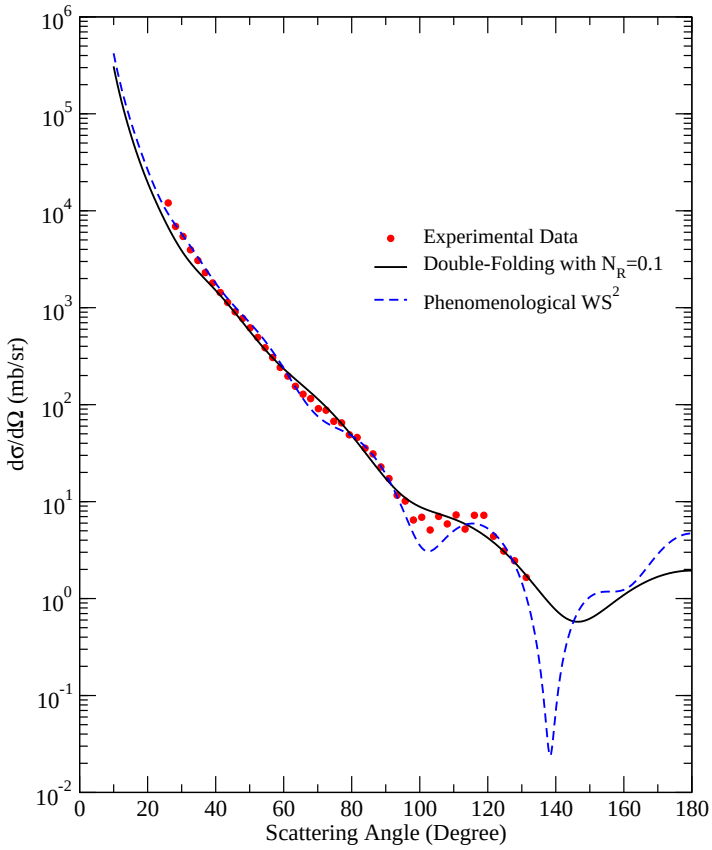


Figure 2. The results of Double-folding and phenomenological Woods-Saxon-squared potentials in comparison with the experimental data at 21.0 MeV.

The sum of the nuclear, Coulomb and the centrifugal potentials for both microscopic double-folding and phenomenological Wood-Saxon squared potentials is shown in figure 1 for various values of the orbital angular momentum. The sum of these potential create a pocket in the total effective potential. This pocket is very important for the interference of the barrier and internal waves, which creates the oscillatory structure observed in the cross-section [16].

The imaginary part of the potential [22] was taken as Woods-Saxon volume shaped

$$W(r) = -\frac{W_V}{(1 + exp((r - R)/a))} \tag{10}$$

with W_V=3.95 MeV, r_V=1.050, a_V=1.151 fm. The imaginary potential for the double-folding potential has the same shape but we had to change the parameters in order to obtain a better agreement. Thus, the parameters of the imaginary potential for the double folding calculations are W_V=2.05 MeV, r_V=1.050, a_V=0.651 fm.

The shape of the imaginary potentials for the double-folding and phenomenological potential calculations is shown in the inset of Fig. 1 for E_{Lab}=21.0 MeV.

3. The Results

The results obtained by using the microscopic double-folding and phenomenological nuclear potentials with the above-described models are shown in Fig. 2 in comparison with the experimental data. As it can be seen from this figure that double folding potential requires a large

normalization in order to obtain a reasonable result. Without this normalization, $N_R = 0.1$, we could not get an agreement with the experimental data. The results of double-folding potential calculations are structureless and does not fit the experimental data well at forward angles. The phenomenological Woods-Saxon typed potential has provided a better agreement with the experimental data in comparison with double-folding calculation as seen in the same figure with dashed line. The maximum and minimum observed in the experimental data are in phase with the theoretical results.

4. Summary

In this paper, we have conducted an optical model analysis for the elastic scattering of ^{14}N+^{12}C system around the Coulomb barrier energies. We have used both microscopic double-folding and phenomenological potentials for the real part of the complex nuclear potential. It is shown that a large normalization of the microscopic double-folding potential is needed to explain the measured data. The coupling effect may play an important role for a strongly deformed nucleus as ^{12}C in the coupled-channels calculations. The role of neutron transfer should also be studied in order to clarify the discrepancies observed in the double-folding potential case. Further investigations are being carried out for this and similar systems. For the phenomenological potential case, a good agreement between experimental data and theoretical result is obtained by using a deep real potential.

Acknowledgments

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