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Detailed Phenomenological Study of ^{14}N Elastically Scattered on ^{12}C in a wide Energy Range

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Abstract**—**An experiment was performed with a 24.5 MeV ^{14}N beam on a ^{12}C target in the cyclotron DC-60 located in Astana, Kazakhstan, to study the elastic scattering of ^{14}N on ^{12}C; the scattering was also analyzed at different energies for tracking the phenomenon of remarkable structure at large angles. Its aims were to extend the measurements to very large angles, and attempt to uniquely identify the elastic scattering potential. Good agreement between the theoretical and experimental data has been obtained with suitable optical potential parameters. Optical model calculations with l -dependent imaginary potentials were also applied to the data and relatively good agreement was found.

Keywords**—**Optical Potential Codes, Elastic Scattering, SPIVAL Code.

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I. INTRODUCTION

IN the last few years angular distributions of heavy-ion elastic scattering have been studied extensively. Theoretical analyses have been more or less successful. Especially, angular distributions with pronounced structure at large angles provide some difficulties. Complex potentials of Woods-Saxon type with or without a hard core were used to fit such distributions [1], although the physical meaning of optical potentials for heavy ions is somewhat doubtful. On the other hand, the mechanism of elastic transfer is used to explain oscillations at large angles [2, 3].

Recently, many experiments of elastic and inelastic scatterings and transfer reaction using heavy ions have been attempted, and several methods have been applied successfully to the analysis of the results. The success of analysis has contributed much to the study of the nuclear reaction mechanism and the nuclear structure. Detailed knowledge of the elastic scattering is necessary to elucidate the reaction mechanism of heavy ions as well as to obtain the parameters to be used in the analysis of the transfer reactions.

II. EXPERIMENTAL PROCEDURE

This paper contains the experimental measurements of ^{14}N+ ^{12}C angular distribution performed at the cyclotron DC-60 in Astana, Kazakhstan. The extracted beam of ^{14}N was accelerated up to 1.75 MeV/nucleon and then directed to carbon self-supporting target of thickness 20 µg/cm^2. The beam current was nearly equal to 18 nA during the experiment, the angular distribution was measured in a wide range of angles 20-120^o 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. The spectrum files show two peaks, one is corresponding to ^{14}N and the second for ^{12}C using the program MAESTRO.

III. OPTICAL MODEL ANALYSIS

In a scattering experiment of a light heavy-ion reaction, important information can be obtained about the properties of the process and the nuclear structure such as the size of the nucleus and the characteristics of the nuclear forces [4, 5]. Although scientists have been investigating the elastic and inelastic interactions of light heavy ions for more than 40 years, the subject has not been fully explained yet.

The ^{14}N+^{12}C scattering, as a light heavy-ion reaction, has been studied intensively both experimentally and theoretically in nuclear physics. The main problem of investigating the light-heavy ion reactions by using nuclear reaction models is to determine the most suitable potential form to explain the experimental data. Optical model, one of the models that developed to explain nuclear reactions, investigates the elastic scattering in a general way by considering absorption effects.

The interactions between two nuclei cannot be fulfilled exactly for the nuclear reactions since it requires to work out the many-body problem which unfortunately has lots of complex mathematical difficulties [5]. Therefore for a many-body system, it is logical to work on simplified models instead of taking into account individual forces between particles and particles, and particles and particle groups. These simplified models, such as Optical model [5, 6-8], Distorted-wave Born approximation [5, 8] and Folding model [8], must physically have the same important properties of the particles that establish the particle systems.

The Optical model (OM) probes the elastic scattering in a general way by only considering the behavior of the incoming particle and by allowing for the absorption effects. In this model, the projectile deals with a potential well which is

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analogous to that used in the shell model, but it also includes an imaginary component. In Optical model calculations, which are particularly very successful to explain the nuclear scattering reactions, it is assumed that the absorbed particles vanish in the elastic channels. Since the Optical model is only practical to discuss the common behavior of the scattering reactions, it can indirectly explain the microscopic properties of nuclei [5, 7].

The nucleus-nucleus interaction potential is a key ingredient in the analysis of nuclear reactions. By using the potential between nuclei we can evaluate the cross sections of different nuclear reactions. The interaction potential between nuclei consists of nuclear, Coulomb and centrifugal parts. The Coulomb and centrifugal interactions of two nuclei are well-known. In contrast to this the nuclear part of nucleus-nucleus interaction is known worse.

$$U(R) \approx V_C(R) - V\left[1 + \exp\left(\frac{R - R_V}{a_V}\right)\right]^{-1} - iW\left[1 + \exp\left(\frac{R - R_W}{a_W}\right)\right]^{-1} \quad (1)$$

Where,

$$\begin{aligned} V_C(R) &= \frac{Z_1 Z_2 e^2}{R}, \qquad R \geq R_C \\ V_C(R) &= \frac{Z_1 Z_2 e^2}{R}\left[\frac{3}{2} - \frac{R^2}{2R_C^2}\right], \qquad R < R_C \end{aligned} \quad (2)$$

In addition to the experimental data obtained from the cyclotron DC-60 at energy 1.75 MeV/nucleon (E_{lab}=24.5 MeV), we also analyzed this reaction at different energies (21.34, 22.5, 27.3, 78, 88, and 280) MeV from literature survey [9, 10, 11, 12, 13], in order to make analysis for this reaction in a wide range of energies. Good agreement between the experimental and theoretical calculations has been obtained with optimal optical potential parameters able to fit the data. The optical model code SPIVAL [14] was used successfully for all energies mentioned above, while better results could be obtained by using SPIVAL with *l*-dependent imaginary potential for energies (21.34, 22.5, and 27.3) MeV. The most interesting feature for that reaction is shown at energies (21.34, 22.5, and 27.3), the angular distribution of ^{14}N on ^{12}C at these energies exhibit remarkable structure at large angles. Where, these pronounce structure at large angles was shown to be result partially from surface reactions rather than the elastic transfer.

Barker and Gobbi et al., [3] have calculated angular distributions of ^{12}C on ^{13}C and ^{14}N on ^{12}C, respectively, by adding coherently a contribution of the elastic transfer reactions ^{13}C(^{12}C,^{13}C)^{12}C and ^{12}C(^{14}N,^{12}C)^{14}N, respectively, to the elastic potential scattering. This method suggests that oscillations at large angles are created only by the elastic transfer reaction.

IV. RESULTS AND DISCUSSION

The optimal optical potential parameters obtained using SPIVAL code for the elastic scattering of ^{14}N on ^{12}C at energies (21.34, 22.5, 27.3, 78, 88, and 280) MeV are shown in table 1. A comparison between the experimental data and the theoretical predictions for the angular distribution is shown in figures 1and 2. The optical model code SPIVAL was used for fitting the experimental data; coulomb radius was fixed at 0.95 fm during search. While, better fitting could be obtained at energies (21.34, 22.5, and 27.3) MeV using SPIVAL code with *l*-dependent imaginary potential with *L* and Δ*L* values listed in table 2, and the comparison between the experimental data and the theoretical predictions for the angular distribution at these energies are shown in figure 3. Figure 4 shows the relationship between the real and imaginary potential depth with energy, V_0 decrease steadily with increasing energy, and for W_0 increase with energy and then becomes nearly constant.

TABLE I
THE OPTIMAL OPTICAL POTENTIAL PARAMETERS OBTAINED USING THE SPIVAL CODE FOR ^{14}N ELASTICALLY SCATTERED ON ^{12}C AT DIFFERENT ENERGIES, $R=r_0\,(A_P^{1/3}+A_T^{1/3})$

E (MeV)	V_0 (MeV)	r_r (fm)	a_r (fm)	W_0 (MeV)	r_i (fm)	a_i (fm)	J_v (MeV/F^3)	J_w (MeV/F^3)	r_c (fm)
21.34	375.24	0.703	0.661	6.11	0.74	0.222	470.8	6.67	0.95
22.5	354.66	0.603	0.498	9.77	1.02	0.969	262.7	37.76	0.95
24.5	350.03	0.649	0.690	10.22	1.12	0.888	373.06	115.18	0.95
27.3	324.06	0.803	0.688	11.77	1.22	0.559	505.3	60.65	0.95
78.0	82.21	0.809	0.817	12.8	1.34	0.708	230.1	164.4	0.95
88.0	68.0	0.423	1.1	12.8	0.699	1.01	274.8	21.85	0.95
280	61.12	0.915	0.733	13.3	1.205	0.945	157.17	78.71	0.95

TABLE II
THE OPTICAL POTENTIAL PARAMETER OBTAINED FROM THE SPIVAL CODE WITH L-DEPENDENT IMAGINARY POTENTIAL FOR ^{14}N ELASTICALLY SCATTERING ON ^{12}C AT DIFFERENT ENERGIES

E (MeV)	V_0 (MeV)	r_r (fm)	a_r (fm)	W_0 (MeV)	r_i (fm)	a_i (fm)	J_v (MeV/F^3)	J_w (MeV/F^3)	r_c (fm)	L	Δ*L*
21.34	439.43	0.653	0.687	6.22	1.12	1.136	473.3	33.1	1.25	6.3	1
22.5	462.88	0.653	0.632	6.26	1.12	0.569	473.41	25.48	1.25	5.8	1
27.3	124.36	0.910	0.660	67.8	1.175	0.275	300.12	29.23	1.25	6.3	1

V. SUMMARY

In this work, the elastic scattering of ^{14}N on ^{12}C at different energies was studied within the framework of an optical code SPIVAL. The agreement between the experimental data and the theoretical predictions is fairly good in the whole range, better fitting could be obtained using SPIVAL code with *l*-dependent imaginary potential with specified values of *L* and Δ*L* as listed in table 2. The J_V and J_W values obtained with the WS1 also agree closely with the global systematic found for light HI elastic scattering. The angular distributions of ^{14}N on ^{12}C at energies (21.34, 22.5, 27.3) MeV exhibit remarkable structure at large angles. Where, these pronounce structure at large angles was shown to be result partially from surface reactions rather than the elastic transfer.

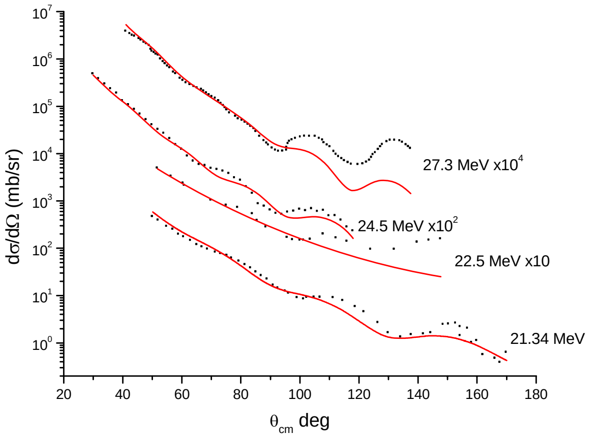

Fig .1 shows the angular distribution for ^{14}N elastically scattering on ^{12}C at different energies (21.34, 22.5, 24.5, and 27.3 MeV). The solid black squares represent the experimental data; red curves represent the calculations using SPIVAL code

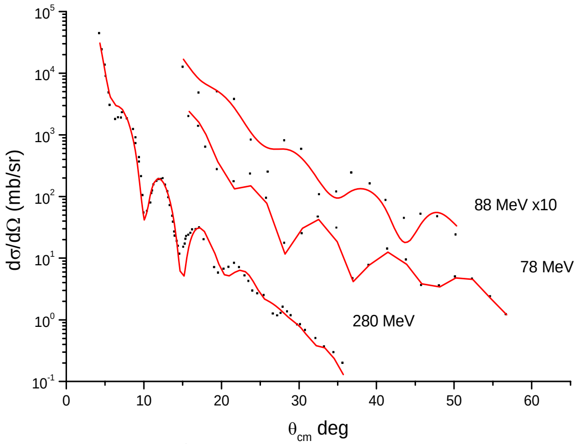

Fig .2 the same as figure 1 but at energies (78, 88, and 280 MeV)

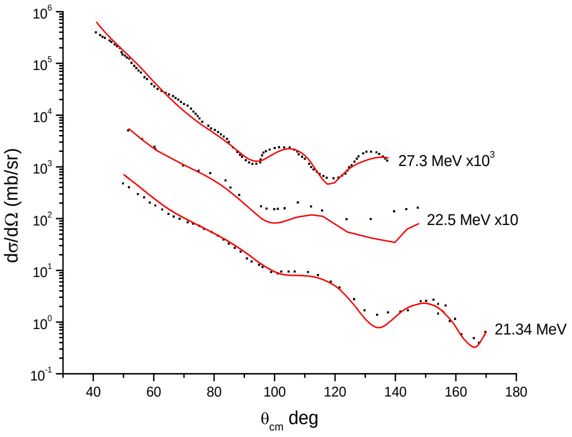

Fig .3 shows the angular distribution for ^{14}N elastically scattering on ^{12}C at different energies (21.34, 22.5, and 27.3 MeV). The solid black squares represent the experimental data; red curves represent the calculations using the optical potential code SPIVAL with *l*-dependent imaginary potential.

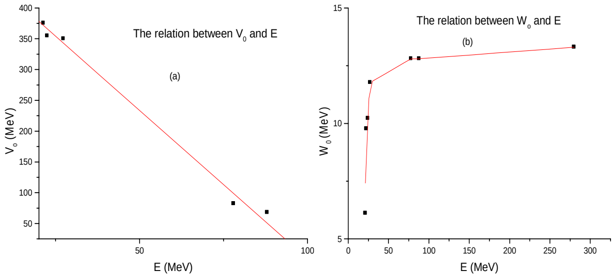

Fig.4 represents a)- the relation between the real potential depth V_o and E, b)- the relation between the imaginary potential depth W_o and E

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