Analysis of Continuum Spectra for the ^{58}Ni(p,d)^{57}Ni Reaction with Direct Reaction Model

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Abstract

Double differential cross sections (DDXs) for one nucleon transfer of ^{58}NI(p,d)^{57}Ni reaction at 42 MeV have been studied within the framework of the distorted wave born approximation (DWBA) analyses. The scattering laboratory angles are 30^o, 35^o, 45^o and 60^o. An asymmetric Lorentzian form response function having energy dependent spreading width is adopted in the DWBA analyses, which gives good prediction for the DDXs in the direct reaction region.

***Keywords*:** double differential cross section, (p,d) nuclear reactions, direct reaction model, DWBA analysis

1. Introduction

Nuclear data are needed for different types of uses or applications such as, transmutation of nuclear waste, energy production, space development, cancer therapy, accelerator driven system etc. For these applications, nuclear data for various nuclei in the energy region from several tens of MeV to a few GeV are required. So the precise simulation of nuclear reactions is required for the engineering design work. However, experimental data for differential cross section are very discrepant and even exist, these need evaluation.

Theoretical model becomes a useful tool for evaluating the cross section and evaluation is a continuous process. So the demand for the calculation based on theoretical models always exists. From this point of view, it is indispensable to develop a theoretical model which can reproduce well the continuum spectra in the direct reaction regions. However, the models available to study the continuum spectra for one nucleon transfer reaction cannot reproduce well the experimental data [1, 2].

For the theoretical investigation of double differential cross section, an approach proposed by Lewis [3] is adopted, in parallel with the prediction models described by Crawley [4] and Gales et al. [5]. In agreement with Lewis [3]. Matoba et al. [6, 7] reached eventually to a decision to solve this critical problem.

This model previously successfully measured the double differential cross sections for the (p,d) reactions on ^{27}Al, ^{48}Ca and ^{58,60,62,64}Ni, ^{96,100}Mo, ^{197}Au, ^{209}Bi over the incident energy range 48-68 MeV [8-14]. The present work is concerned with the (p,d) reaction on ^{58}Ni using proton beam at 42 MeV for the laboratory angles 30^o, 35^o, 45^o and 60^o. Then the experimental DDXs are compared with the calculated DDXs. The experiment was performed at the TIARA facility of JAERI. Details of the experimental procedure and the results have been reported in ref. [15].

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2. Materials and Methods

In the present method, the theoretical calculations of the double differential cross-sections have been done by considering a direct reaction model as an incoherent sum of the direct reaction components, which are based on the DWBA predictions and expressed as below:

$$\frac{d^2\sigma}{d\Omega dE} = 2.30\sum_{l,j}\left[\frac{C^2 s_{l,j}(E)}{2j+1}\times\left(\frac{d\sigma}{d\Omega}\Big|_{l,j}^{DW}(E)\right)\right] \qquad (1)$$

where $d\sigma/d\Omega\big|_{l,j}^{DW}(E)$ is the cross-section calculated by a DWBA code, DWUCK-4 [16] and $C^2S_{l,j}(E)$, the spectroscopic factor expressed as

$$C^2S_{l,j}(E) = \left(\sum C^2S_{l,j}\right)\times f_{l,j}(E). \qquad (2)$$

where $\sum C^2S_{l,j}$ is the sum of the spectroscopic factors of all the predicted states and the distribution of strength function over the spectra is obtained by using an asymmetric Lorentzian function [6, 7, 17]

$$f_{l,j}(E) = \frac{n_0}{2\pi}\frac{\Gamma(E)}{\left(|E-E_F|-E_{l,j}\right)^2+\Gamma^2(E)/4} \qquad (3)$$

and

$$\int_0^{\alpha} f_{l,j}(E)dE = 1 \qquad (4)$$

where n_0 is the renormalization constant and E_F is the Fermi energy. The Fermi energy can be calculated by using an empirical formula given in [18]. The sums of spectroscopic factors and the centroid energies ($E_{l,j}$) for J = $l\pm{}^1/_2$ shell orbits have been estimated by using BCS calculations. In these calculations, single particle energies required to calculate the centroid energy are calculated by the prescription of Bohr and Mottelson [19]. Spreading width (Γ) is expressed by a function proposed by Brown and

Rho [20] and by Mahaux and Sartor [17], as,

$$\Gamma(E)=\frac{\varepsilon_0(E-E_F)^2}{(E-E_F)^2+E_0^2}+\frac{\varepsilon_1(E-E_F)^2}{(E-E_F)^2+E_1^2} \qquad (5)$$

where ε_0, ε_1, E_0 and E_1 are constants which express the effects of nuclear damping in the nucleus [6]. The estimated parameters [6] are

$$\varepsilon_0 = 19.4 \text{ MeV}, \quad E_0 = 18.4 \text{ MeV}$$
$$\varepsilon_1 = 1.40 \text{ MeV}, \quad E_1 = 1.60 \text{ MeV}. \qquad (6)$$

The sum rule of the spectroscopic factors of nucleon orbits for $T \pm \frac{1}{2}$ isospin states are estimated with a simple shell model prescription [21]

$$\sum C^2 S_{l,j} = \begin{cases} n_n(l,j) - \dfrac{n_p(l,j)}{2T+1} & for \quad T_< = T - \dfrac{1}{2} \\ \dfrac{n_p(l,j)}{2T+1} & for \quad T_> = T + \dfrac{1}{2} \end{cases} \qquad (7)$$

Here $n_n(l,j)$ and $n_p(l,j)$ are the numbers of neutrons and protons respectively for each l, j orbit and T is the isospin of the target nucleus.

3. Results and Discussion

DDXs were obtained for the ^{58}Ni(p,d)^{57}Ni reaction at 42 MeV for the four laboratory angles of 30°, 35°, 45° and 60° as shown in Figs. 1- 4. Experimental and theoretical results are given by the circles and lines respectively. Three global potentials were used here for protons, while for deuteron an adiabatic potential [22-24] based on the proton and neutron potentials were constructed for the DWUCK4 calculations as shown in Table 1. The solid, dotted and short-long-dashed lines represent the DDX for Beccheti and Greenlees [22], Koning and Delaroche [23] and Menet et al. [24] potentials respectively.

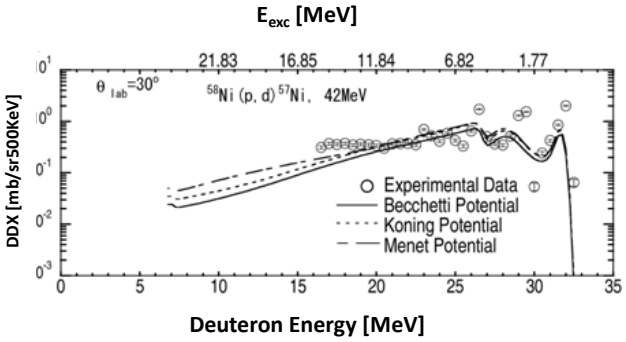

Fig. 1: Double differential cross sections for ^{58}Ni(p,d)^{57}Ni reaction at 30° laboratory angle for 42 MeV incident energy

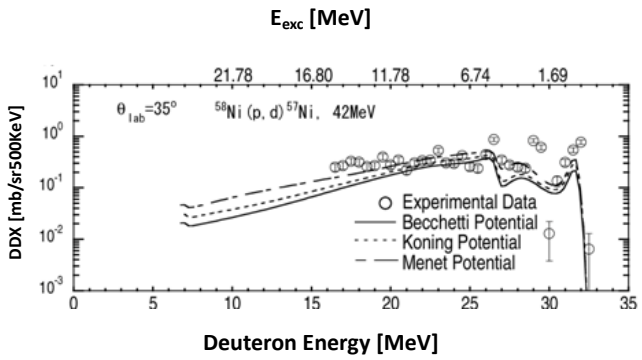

Fig. 2: Double differential cross sections for ^{58}Ni(p,d)^{57}Ni reaction at 35° laboratory angle for 42.0 MeV incident energy

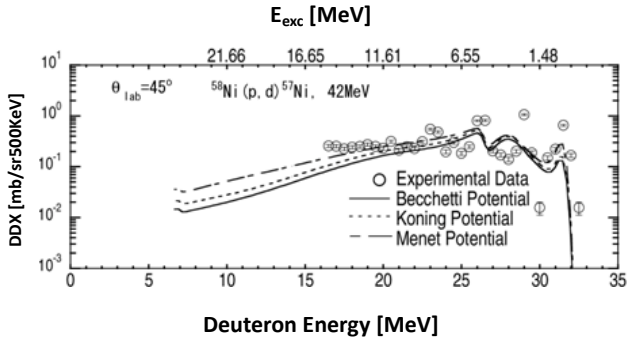

Fig. 3: Double differential cross sections for ^{58}Ni(p,d)^{57}Pb reaction at 45° laboratory angle for 42.0 MeV incident energy

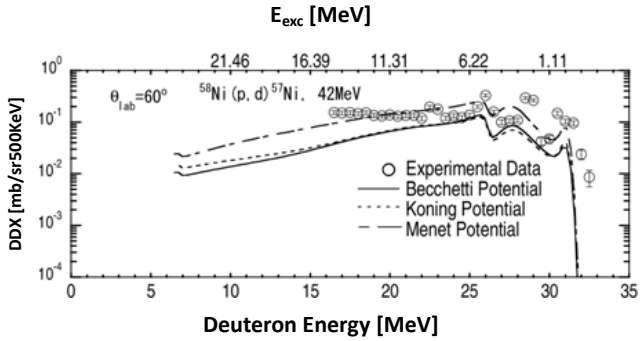

Fig. 4: Double differential cross sections for ^{58}Ni(p,d)^{57}Ni reaction at 60° laboratory angle for 42.0 MeV incident energy

Figs. 1- 4 show that the spectra have no distinct structures and are continuous. The calculated data generally agree with the experimental data only above tens of MeV energy region because our calculated energy spectrum regions are treated in direct reaction scheme. These Figs. Also show that the calculated DDXs [22-24] are in good agreement for all potentials with the experimental data at the laboratory angles of 30° and 45° but for the laboratory angles of 35° and 60°, the DDXs for Menet et al. [24] potentials are in better agreement with the experimental data compared to other potentials.

Thus from the above discussion, we can see that the calculated model reproduce well the experimental DDXs for Menet potentials [24] at all laboratory angles [30^0, 35^0, 45^0 and 60^0] but for Koning and Delaroche [23], and Beccheti and Greenlees [22] potentials, it has discrepancies. In order to understand the observed discrepancies, further analyses with the use of different potential are needed for calculation of the DDXs.

The results of DDXs generally agree with the experimental data but have a little disagreement.

Table 1: Optical model parameters used in the DWBA calculations for the ^{58}Ni(p,d)^{57}Ni reactions

Becchetti and Greenlees potential [22]

Particle	V (MeV)	r (fm)	a (fm)	r_c (fm)	W_v (MeV)	W_s (MeV)	r′ (fm)	a′ (fm)	V_{so} (MeV)	r_{so} (fm)	a_{so} (fm)
Proton	44.28	1.17	0.75	1.25	6.54	1.71	1.32	0.53	6.20	1.01	0.75
Deuteron	a	1.17	0.78	1.25	b	b	1.29	0.58	6.20	1.06	0.75
Neutron	c	1.25	0.65								

[a]$V = [110.3 – 0.64(E_d/2) + 0.4Z/A^{1/3}]$ MeV

[b]$W_v = [0.44(E_d/2) – 4.26]$ MeV, $Ws = [24.8 – 0.50(E_d/2)]$ MeV, E_d is the deteron kinetic energy

[c]Well depth adjusted to fit the separation energy

Koning and Delaroche potential [23]

Particle	V (MeV)	r (fm)	a (fm)	r_c (fm)	W_v (MeV)	W_s (MeV)	r′ (fm)	a′ (fm)	V_{so} (MeV)	r_{so} (fm)	a_{so} (fm)
Proton	39.97	1.20	0.67	1.26	4.37	5.33	1.28	0.54	5.00	1.02	0.59
Deuteron	A	1.20	0.67	1.26	A	a	1.28	0.54	a	1.02	0.59
Neutron	B	1.25	0.65								

[a]Adiabatic potentials [23]

[b] Well depth adjusted to fit the separation energy

Menet potential [24]

Particle	V (MeV)	r (fm)	a (fm)	r_c (fm)	W_v (MeV)	W_s (MeV)	r′ (fm)	a′ (fm)	V_{so} (MeV)	r_{so} (fm)	a_{so} (fm)
Proton	44.46	1.16	0.75	1.25	4.98	2.64	1.37	0.44	6.04	1.06	0.75
Deuteron	a	1.16	0.75	1.25	b	b	1.37	c	6.04	1.06	0.75
Neutron	d	1.25	0.65								

[a]$V = [99.8 – 0.44(E_d/2) + 0.4Z/A^{1/3}]$ MeV

[b]$W_v = [2.4 + 0.18(E_d/2)]$ MeV, $Ws = [8.40 – 0.10(E_d/2)]$ MeV, E_d is the deteron kinetic energy

[c]$a' = 0.74 – 0.008(E_d/2) + 1.0(N\text{-}Z)/2A$, [d]Well depth adjusted to fit the separation energy

For all potentials nonlocality parameters and finite-range parameters are shown below:

	Nonlocality parameters	Finite-range parameter	λ= 25
proton	0.85fm	0.621	
neutron	0.85fm	0.621	
deuteron	0.54fm		

4. Conclusion

The double-differential cross sections of the ^{58}Ni(p,d)^{57}Ni reaction at 42 MeV incident energy have been measured at four different angles of 30^o, 35^o, 45^o and 60^o. DWBA has been used here for the predictions of the theoretical double-differential cross section in the direct reaction region. Three global potentials are used for proton and deuteron in this theoretical model. Quite satisfactory results to the DDX have been obtained by our method of calculation in the direct reaction region for this reaction. The precise simulation of nuclear potential may improve the theoretical results to fit with the experimental ones.

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