(p,d) Reaction on ^{90}Zr at 68 MeV

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Abstract

The double differential cross sections for the $(p,\vec{d})$ reactions on ^{90}Zr have been measured here at a bombarding energy of 68 MeV and laboratory scattering angles of 25°, 30°, 35° and 45°. Spectrum regions are treated here with an analysis using the direct reaction model, i.e., several tens of MeV energy regions. The analysis is based on the DWBA method and an asymmetric Lorentzian form strength function having an energy dependent-spreading width. The results of the comparisons between the experimental and calculated spectra are described here.

***Keywords*:** Double differential cross section, (p,d), Nuclear reactions, Direct reaction model, DWBA analysis

1. Introduction

The need for wide-ranging of accurate nuclear data still exists for application in many fields of science and technology. A measured, evaluated, and validated set of nuclear data is the basis of all these applications of science and technology. At present, the main fields of application of nuclear data are nuclear reactors, medical science, space science, etc., belonging to different fields of science and technology. However, the success of these applications depends internally much on the use of accurate/reliable nuclear data. According to U.S. Department of Energy [1], "Reliable nuclear structure and reaction data represent the fundamental building blocks of nuclear physics and astrophysics research, and are also of importance in many applications". The reliability of nuclear data is established by evaluating or analyzing and validating.

A number of analyses have been successfully performed on the reaction mechanism in the lower excitation energy region, using Distorted Wave Born Approximation (DWBA). However, the continuum spectra which appear just above the discrete excitation levels are still under study [2]. Therefore, an approach such as proposed by Lewis [3] is suggested to be employed, in parallel with the prediction models described by Crawley [4] and Gales et al. [5] for analyzing the continuum spectrum in the direct reaction region, i.e., several tens of MeV energy region. In agreement with Lewis [3], Matoba et al. [6, 7] have advanced an analysis using an asymmetric Lorentzian shaped strength function having energy-dependent spreading widths and DWBA cross-sections. The experimental data that are used in this article had been obtained from the TIARA facility of JAERI. A proton beam of 68 MeV from the AVF cyclotron was led to the HB-1 beam line. Details of the experimental procedure and the results have been reported in ref. [8].

The present work is concerned with the continuum spectra for the ^{90}Zr(p,d)^{89}Zr reaction at 68 MeV at four different laboratory angles, namely 25°, 30°, 35°and 45°. This model has been successfully applied for the (p,d) reactions [2, 9-15] and then applied for the (n,d) reaction [16-21] with a slight modification and thus demonstrates its reasonable ability. From the above circumstances, we can say that, this work has a certain value both for theoretical nuclear physics and for an application to nuclear technology.

2. Theoretical Calculations

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:

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

Where $d\sigma / d\Omega\big|_{l,j}^{DW}(E)$ is the cross-section calculated by the DWBA code, DWUCK-4 [22] and $C^2 S_{l,j}(E)$, the spectroscopic factor expressed as

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

Where $\sum C^2 S_{l,j}$ 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, 23]

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

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 [24]. The sums of spectroscopic factors and the centroid energies ($E_{l,j}$) for $J = l \pm \frac{1}{2}$ shell orbits

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*Corresponding author: *sadia_afroze@yahoo.com* have been estimated by using the “Bardeen, Cooper and Schrieffer” (BCS) calculations. In these calculations, single particle energies required to calculate the centroid energy are calculated by the prescription of Bohr and Mottelson [25]. Spreading width (Γ) is expressed by a function proposed by Brown and Rho [26] and by Mahaux and Sartor [23] as

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

where $\varepsilon_0, \varepsilon_1$, E_0 and E_1 are constants which express the effects of nuclear damping in the nucleus [6]. The estimated parameters [6] are

$$\varepsilon_0 = 19.4 \text{ MeV}, \quad E_0 = 18.4 \text{ MeV}$$

$$\varepsilon_1 = 1.40 \text{ MeV}, \quad E_1 = 1.60 \text{ MeV} \tag{6}$$

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 [27] as given by

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

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

3. Results and Discussion

In this study, the continuum spectra of ^{90}Zr(p, d)^{89}Zr reaction are analyzed by overlapping the DWBA predictions as described earlier in Sec. 2. DDXs were obtained for the ^{90}Zr(p, d)^{89}Zr reaction at 68 MeV for laboratory angles of 25°, 30°, 35° and 45°as shown in Figs. 1-4. The measured spectra correspond to the deuteron energy regions of about 0-58 MeV. Three global potentials [28-30] were used here for protons, while for deuteron an adiabatic potential [28-30] 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 [28], Koning and Delaroche [29] and Menet et al. [30] potentials respectively. The reaction is analyzed here with the direct reaction model; this is why, the calculated double differential cross sections agree with experimental data as far as ~ 12 MeV deuteron excitation energies.

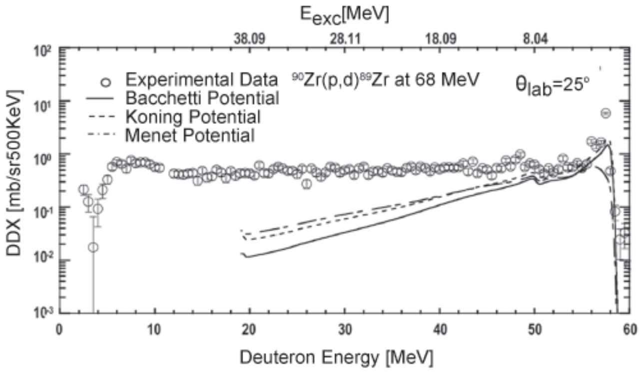

Fig. 1: Double differential cross sections for the ^{90}Zr(p, d)^{89}Zr reaction at 68 MeV for 25°angle

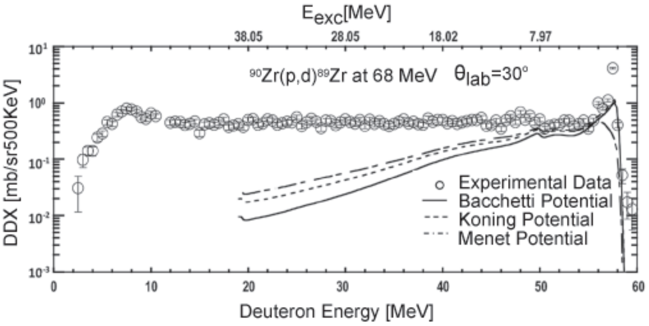

Fig. 2: Double differential cross sections for the ^{90}Zr(p, d)^{89}Zr reaction at 68 MeV for 30°angle

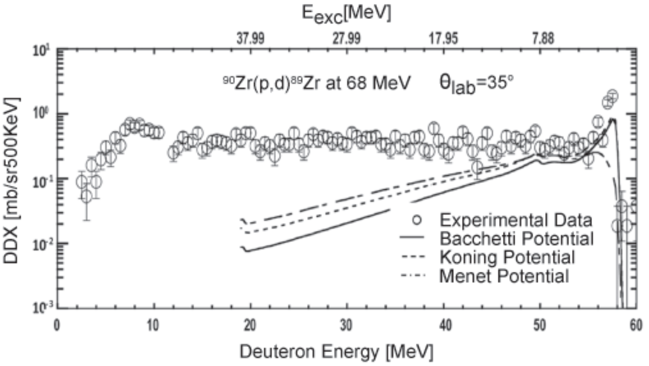

Fig. 3: Double differential cross sections for the ^{90}Zr(p, d)^{89}Zr reaction at 68 MeV for 35° angle

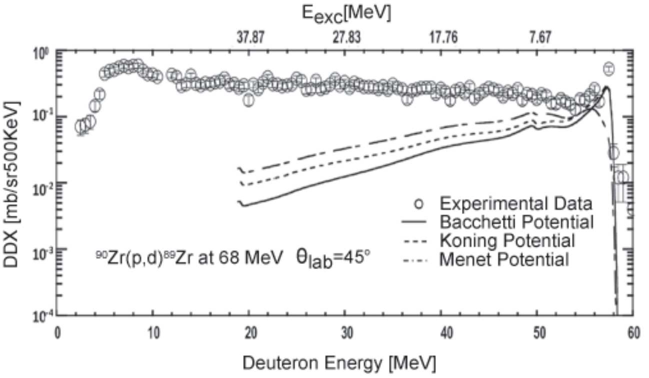

Fig. 4: Double differential cross sections for the^{90}Zr(p, d)^{89}Zr reaction at 68 MeV for 45°angle

Table 1: Optical model parameters used in the DWBA calculations for the ^{90}Zr(p, d)^{89}Zr reaction at 68 MeV Becchetti and Greenlees potential [28]

Particle	V	r	a	r_c	W_v	W_s	r′	a′	V_{so}	r_{so}	a_{so}
	(MeV)	(fm)	(fm)	(fm)	(MeV)	(MeV)	(fm)	(fm)	(MeV)	(fm)	(fm)
Proton	38.48	1.17	0.75	1.25	12.26	0.00	1.32	0.59	6.20	1.01	0.75
Deuteron	a	1.17	0.78	1.25	b	b	1.29	0.61	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 deuteron kinetic energy, [c]Well depth adjusted to fit the separation energy

Koning and Delaroche potential [29]

Particle	V	r	a	r_c	W_v	W_s	r′	a′	V_{so}	r_{so}	a_{so}
	(MeV)	(fm)	(fm)	(fm)	(MeV)	(MeV)	(fm)	(fm)	(MeV)	(fm)	(fm)
Proton	32.20	1.21	0.66	1.24	7.22	3.37	1.27	0.53	4.58	1.04	0.59
Deuteron	a	1.21	0.66	1.24	a	a	1.27	0.55	a	1.04	0.59
Neutron	b	1.25	0.65	-	-	-	-	-	-	-	-

[a]Adiabatic potentials [29], [b]Well depth adjusted to fit the separation energy

Menet potential [30]

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	41.44	1.16	0.75	1.25	7.32	2.52	1.37	0.31	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 deuteron kinetic energy, [c]$a' = 0.74 - 0.008(E_d/2) + 1.0(N-Z)/2A$, [d]Well depth adjusted to fit the separation energy

For all potentials non locality, finite-range parameters and spin-orbit term are shown below

Particle	Nonlocality parameters	Finite-range parameter	Thomas-Fermi spin orbit term
Proton	0.85 fm	0.621 fm	$\lambda = 25$
Neutron	0.85 fm	0.621 fm	-
Deuteron	0.54 fm	-	-

From Figs. 1 and 2, we can see that for the peak production, the calculated DDX value fits well for Beccheti and Greenlees potential [28] for the 25° and 30° angles but the agreement for the experimental data with Koning and Delaroche [29] and Menet et al. [30] potentials was reasonable. For the same Figs, in the case of overall DDX production, Koning and Delaroche [29] and Menet et al. [30] potentials give better agreement with experimental DDX than that of Beccheti and Greenlees potential [28].

From the Figs. 3 and 4, we can see that for Beccheti and Greenlees [28] and Koning and Delaroche [29] potentials, the theoretical result of DDX are in good agreement with experimental results for the 35° and 45° angles but for Menet et al. [30] potential, it is a bit under estimated. It should be mentioned here that 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 the direct reaction scheme.

As we mentioned before, in this research the analysis has been done only for direct reaction process and not for pre-equilibrium and evaporation processes, i.e., it covers the deuteron energy region above 50 MeV and not below it. So, it is noticeable that the measured DDX values of ^{90}Zr(p,d)^{89}Zr reaction are in good agreement with the experimental values for all angles (25°, 30°, 35° and 45° angles) in the deuteron energy region above 50 MeV, however, they are underestimated compared to experimental values for the deuteron energy region below 50 MeV.From Figs 1 to 4, we can see the discrepancies between the theoretical and experimental values in the direct reaction region are not noticeable. Finally, we can say that the use of more appropriate global potential in the DWBA calculations may even more improve the theoretical results.

4. Conclusion

In this work, double differential cross sections have been measured at 68 MeV proton-induced reactions on the^{90}Zr target. Values have been extracted over 4 angular positions (25°, 30°, 35° and 45° angles). As a confirmation of our theoretical model, three global potentials are used for proton and deuteron for the DWUCK-4 calculations. The overall strengths are reproduced well using the asymmetric Lorentzian form response function having energy-dependent spreading width. The calculated results again indicate that this method is successful in the calculations of the double-differential cross-section for the direct reaction region over the range of the target nucleus from ^{27}Al to ^{209}Bi.

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