Analysis of Continuum Spectra for Proton Induced Reactions on ^{27}Al, ^{58}Ni, ^{90}Zr, ^{197}Au and ^{209}Bi at Incident energies 42 and 68 MeV-Direct Reaction Model Analysis.

S.A. Sultana[1], T. Kin[2], G. Wakabayashi[2],
Y. Uozumi[2], N. Ikeda[2], M. Matoba[3] and Y. Watanabe[2]
e-mail: sadia_afroze@yahoo.com

1. Bangladesh Open University, Gazipur 1705, Bangladesh
2. Kyushu University, Fukuoka, 812-8581, Japan
3. Kyushu Sangyo University, Fukuoka 813-8503, Japan

Abstract

Theoretical analyses of the double differential cross sections for proton induced deuteron pickup reactions are described in this paper. Differential cross sections have been measured in the direct reaction region for various nuclei of mass number from 27-209 (^{27}Al -^{209}Bi) at incident energies e.g. 42 and 68 MeV (for ^{197}Au, only at 68 MeV and for ^{209}Bi, only at 42 MeV), using an approach based on the DWBA and an asymmetry Lorentzian function having energy-dependent spreading width. The values of the calculated double differential cross sections have been compared with the experimental ones and are in good agreement.

I. Introduction

Nuclear data from several tens of MeV to a few GeV are recently required for some applications, such as, transmutation of nuclear waste, energy production, space development, cancer therapy, etc. Again Accelerator Driven System (ADS) is used for the purpose of transmutation of nuclear waste, energy production, etc. and as for the ADS, for example, proton beam of 1.5 GeV is injected into the sub-critical reactor core, and various kinds of nuclear reactions are induced in the process of proton degradation. So the precise simulation of nuclear reactions is required for the engineering design work. Nuclear reaction data in the energy region from several tens of MeV to a few GeV are the basis of such simulation code and eagerly wanted. However, experimental data for differential cross sections are very scarce and discrepant if data exist.

When experimental data are limited, the calculation code based on the theoretical models becomes a useful tool for evaluating the cross sections. However, the models available for nuclear data analysis are not so well established as those used in the direct reaction regions, i.e., in higher emission energy region because the continuum spectrum in the direct reaction region is not possible to analyse so easily. Theoretical methods to calculate direct reactions are generally to predict excitation of a state having known spin-parities and existing shells of the related nucleons. Therefore, we have developed a new theoretical model, which is based on the first order DWBA model with a strength function of an asymmetric Lorentzian form. Hirowatari et al. [1] and Syafaruddin et al. [2] adopted this model to (p,d) reactions, then applied to both for proton and neutron induced reactions by Sultana et al. [3, 4] and demonstrated its reasonable predictive ability.

This paper is concerned with the analysis of continuum spectra for (p,d) reactions on ^{27}Al, ^{58}Ni and ^{90}Zr, at 42 and 68 MeV, on ^{197}Au at 68 MeV and on ^{209}Bi at 42 MeV incident energies by the same method of calculation with some modifications, i.e. the application of seniority scheme to the present model for odd target nucleus makes this model more feasible. Finally, there is an increasing interest to see whether this present model can successfully analyse the cross sections data in a wide range of mass number, i.e., from ^{27}Al to ^{209}Bi. The experimental data that used at the analyses in this paper were measured at the TIARA facility of JAERI [5].

II. Analyses

1. Theoretical Calculations

(1) Direct Reaction 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 DWBA predictions and expressed as below:

$$\frac{d^2\sigma}{d\Omega dE} = 2.30\sum_{\ell,j}\left[\frac{C^2S_{\ell,j}(E)}{2j+1}\times\left(\left.\frac{d\sigma}{d\Omega}\right|_{\ell,j}^{DW}(E)\right)\right] \tag{1}$$

where $d\sigma/d\Omega|_{l,j}^{DW}(E)$ is the cross-section calculated by the DWBA code DWUCK4 [6] and $C^2S_{l,j}(E)$, the spectroscopic factor expressed as

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

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 [7–9]

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

and

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

where n_0 is the renormalization constant and E_F the Fermi energy. The Fermi energy can be calculated by using an empirical formula given in [10]. The sums of spectroscopic factors and the centroid energies ($E_{l,j}$) for $J = l\pm\frac{1}{2}$ 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 Motelson [11]. Spreading width (Γ) is expressed by a function proposed by Brown and Rho [12] and by Mahaux and Sartor [9], as,

$$\Gamma(E) = \frac{\epsilon_0\left(E-E_F\right)^2}{\left(E-E_F\right)^2+E_0^2}+\frac{\epsilon_1\left(E-E_F\right)^2}{\left(E-E_F\right)^2+E_1^2} \tag{5}$$

where ϵ_0, ϵ_1, E_0 and E_1 are constants which express the effects of nuclear damping in the nucleus [8]. The estimated parameters [8] are

$$\begin{array}{ll} \epsilon_0 = 19.4\ \text{(MeV)}, & E_0 = 18.4\ \text{(MeV)}, \\ \epsilon_1 = 1.40\ \text{(MeV)}, & E_1 = 1.60\ \text{(MeV)}. \end{array} \tag{6}$$

The sum rule of the spectroscopic factors of nucleon orbits for $T\pm\frac{1}{2}$ isospin states above a closed shell core is estimated with a simple shell model prescription [13]

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

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.

(2) Seniority Scheme:

Calculation of Spectroscopic Factor for Odd Target Nucleus in Continuum Spectrum for Direct Reaction Model.

1. Direct reaction model calculation

$$\frac{d^2\sigma}{d\Omega dE} = 2.30\sum_{\ell,j}\left[\frac{C^2S_{\ell,j}(E)}{2j+1}\times\left(\left.\frac{d\sigma}{d\Omega}\right|_{\ell,j}^{DW}(E)\right)\right] \tag{8}$$

2. Coefficient of fractional parentage in seniority scheme

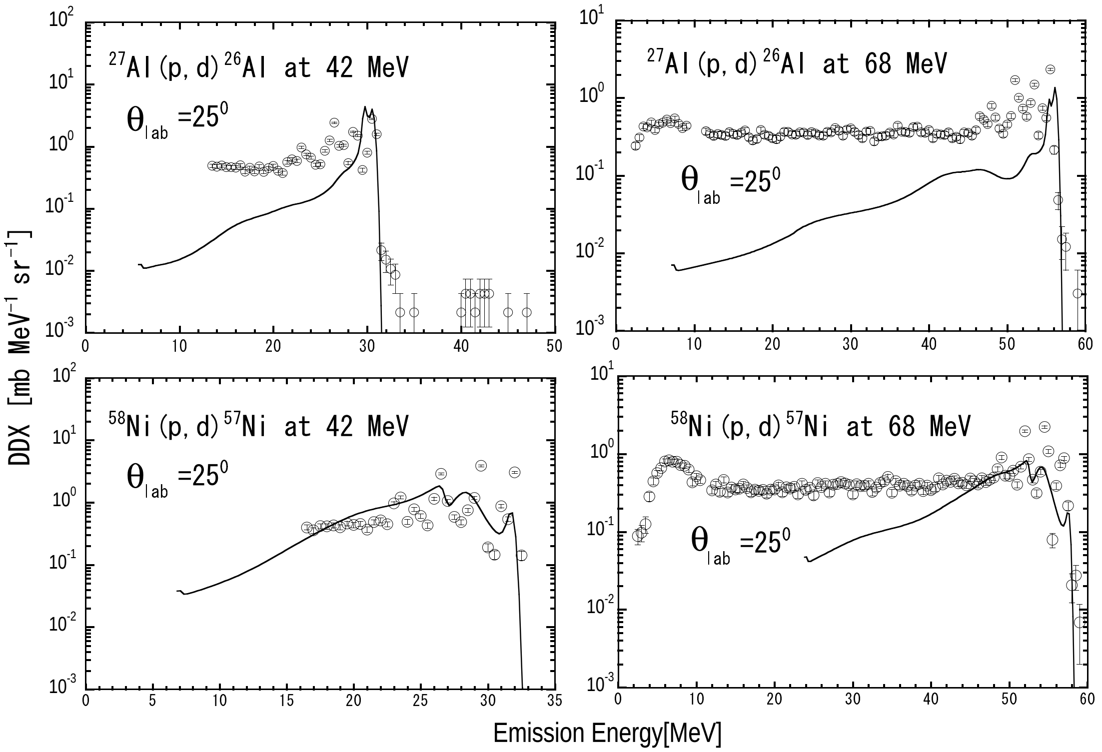

Fig. 1 ^{27}Al(p,d) and ^{58}Ni(p,d) double differential cross section (DDX) data at 42 and 68 MeV incident energies for 25^0 Laboratory angle are shown in this fig. The open circles show the result of experimental data. Solid curves refer to the prediction due to present work.

1) Seniority scheme:

Generally two identical particles connect each other as a pair. Seniority is defined as number of nucleons appeared from breakdown of nucleon pairing.

2) Spectroscopic factor for one nucleon separation from n paricles in a shell

$$\begin{array}{ll} C^2S = n & \text{for even paricle system in a shell} \\ C^2S = \frac{2j+2-n}{2j+1} & \text{for odd particle system in a shel} \end{array} \tag{9}$$

3) Our estimation:

We calculate C^2S from BCS equation. It is proper to multiply a constant to the strength function as follows,

The C^2S for the ground state and low lying states resulted from n particle system can be estimated by multiplying a constant (χ) as

$$\chi = \frac{\frac{2j+2-n}{2j+1}}{n} \tag{10}$$

III. Results and Discussion

This present work is concerned with the (p,d) reactions on ^{27}Al, ^{58}Ni,^{90}Zr at 42 and 68 MeV, on ^{197}Au at 68 MeV and on ^{209}Bi at 42 MeV. The comparisons between the theoretical and experimental double differential cross sections are presented in Figs.1-2. Solid lines and circles stand for the calculated results and for the experimental ones respectively. No theoretical data of the above mentioned nucleus in the direct reaction region are available for comparison with the data calculated by our model. Koning and Delaroche [14] potential is used here for protons and the corresponding adiabatic potentials for deuterons to analyze the double differential cross section spectra.

From figs. 1 and 2, we can see that the theoretical results are in good agreement with the experimental data for ^{90}Zr, ^{197}Au and ^{209}Bi, while for the ^{27}Al and ^{58}Ni, are in fair agreement as in these cases the theoretical results

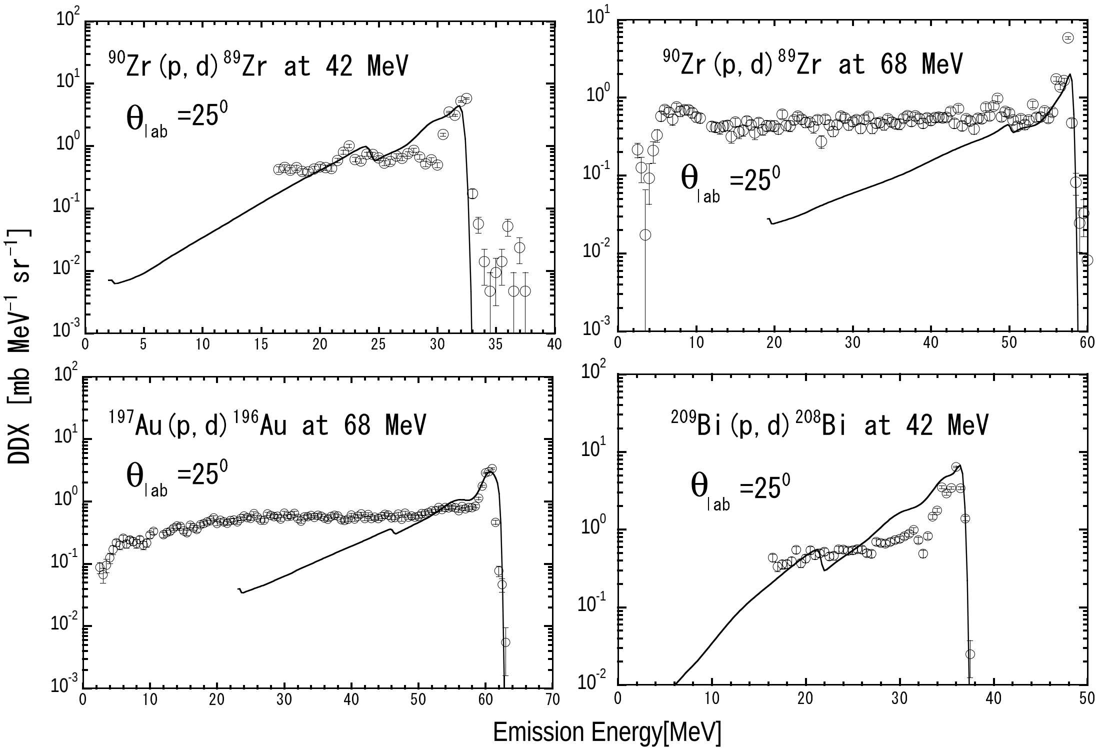

Fig. 2 ^{90}Zr(p,d) double differential cross section (DDX) data at 42 and 68 MeV incident energies, ^{197}Au(p,d) DDX data at 68 MeV incident energy and ^{209}Zr(p,d) DDX data at 42 MeV for 25^0 Laboratory angle are shown in this fig. The open circles show the result of experimental data. Solid curves refer to the prediction due to present work.

are little underestimated. The use of different optical model potentials may solve the problem of underestimation because the absolute values of the spectroscopic factors have systematic errors arising, for example, from the optical model parameters for DWBA analysis. It should be noted from Figs. 1-2 that for all spectra from ^{27}Al to ^{209}Bi at 42 and 68 MeV , the calculated spectra agree with experimental data only above tens of MeV incident energies, because our calculated energy spectrum regions are treated in direct reaction scheme.

IV. Conclusion

Proton induced reactions on ^{27}Al, ^{58}Ni, ^{90}Zr, ^{197}Au and ^{209}Bi have been analyzed here. The incident energies are 42 and 68 for ^{27}Al, ^{58}Ni and ^{90}Zr while for ^{197}Au, it is 68 MeV and for ^{209}Bi, it is 42 MeV at 25^0 Laboratory angle. The application of seniority scheme to the present model for odd target nucleus makes this model more feasible. The calculated DDXs show an overall good agreement with the experimental data both in magnitude and shape. Successful application of this model on a wide range of mass nuclei, e.g. from ^{27}Al to ^{209}Bi proves the suitability of the present model as a reliable one.

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