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The Study on ^{27}Al(p,d)^{26}Al Reaction at 68 MeV Proton Energy

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Abstract

The ^{27}Al(p,d)^{26}Al reaction has been studied with 68 MeV protons for the laboratory angles of 25°, 30°, 35° and 45°. Energy spectra have been estimated here as an incoherent sum of many shell-orbits constituents based on the distorted-wave Born approximation (DWBA). An asymmetric Lorentzian form strength response function having energy dependent spreading width is adopted in this analysis. The calculated deuteron energy spectrum is reasonably well reproduced obviously in the direct reaction region. A comparison between the experimental and the calculated values is described in the direct reaction region.

Keywords: Double differential cross section, ^{27}Al(p,d)^{26}Al, Nuclear reaction, Direct reaction model, DWBA analysis

1. Introduction

The development of modern nuclear technologies requires a large amount of nuclear data to supply needs for the conceptual design of different fields of applications: the technology of radioactive waste transmutation and power production, radiotherapy, shielding problems and so on [1].

Nuclear data are quantitative results of scientific investigations of the nuclear properties of matter. They cover the areas of nuclear reaction, nuclear structure and nuclear decay data, importantly describe properties of atomic nuclei and fundamental physical relationship governing their interactions, thereby characterizing the physical process underlying all nuclear technologies [2, 3]. So, nuclear data are always in demand in the field of nuclear science and technology.

Theoretical models for producing nuclear data are always appreciable in the perspective of theoretical based data production and also for the eligibility of producing unlimited data. Ideally, nuclear data are expected to be collected experimentally for nucleons at various incident energies and for all kinds of emitted particles of all over the energy and the emission angles. However, it is not possible in reality to have all required nuclear data experimentally as desired for its' high cost and all kinds of preparation for the experiment. Hence developing theoretical model that can produce nuclear data is always indispensable.

The models available to study the continuum spectra for one nucleon transfer reaction cannot reproduce well the experimental data [4, 5]. Therefore, Matoba et al. [6, 7] in agreement with Lewis [8] had advanced an analysis using an asymmetric Lorentzian shaped strength function having energy-dependent spreading widths and DWBA cross sections for the production of double differential cross-sections in the direct reaction model. It was also suggested that the approach proposed by Lewis [8] to be employed, in parallel with the prediction models described by Crawley [9] and Gales et al. [10]. This model has been successfully applied for the (p,d) reactions [11-16], then applied for the (n, d) reaction [17-19] in the direct reaction model with a slight modification and demonstrates its reasonable ability.

In the present work, the continuum spectra for the ^{27}Al(p, d)^{26}Al reaction have been analyzed by the same method of calculation. Here, the laboratory angles are 25°, 30°, 35° and 45° and the incident energy is 68 MeV. Earlier, another work was also done at various scattering angles and for the same reaction but at different incident energy [42 MeV] to make this method of calculation as a global one over a wide range of scattering angles [20]. With the same method of calculation, the application of seniority scheme to the present model for odd target nucleus i.e. ^{27}Al(p, d)^{26}Al makes this model more feasible. The calculated results are compared here with the experimental ones in the direct reaction region.

The experiment was performed at 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. [21].

2. Theoretical Calculations

2.1 Direct Reaction Calculations

In this method, the theoretical calculation of the double differential cross-sections has been done by considering a direct reaction model as an incoherent sum of the direct reaction components, which is based on DWBA predictions and expressed as follows:

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

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

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

The distribution of strength function over the spectra is predicted by using an asymmetric Lorentzian function [6, 7, 23]

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

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and

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

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 by Hisamochi et al. [24]. The sum rule of spectroscopic factors and the centroid energies ($E_{l,j}$) calculation for $J = l \pm \frac{1}{2}$ shell orbits have been done by using a BCS calculation [25]. In this calculation, we need single particle energies to calculate the centroid energy, where single particle energies are calculated by the prescription of Bohr and Motelson [26]. Spreading width (Γ) is expressed by a function proposed by Brown and Rho [27] as well as by Mahaux and Sartor [23] as

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

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

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

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

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 [28]

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

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 target isospin.

2.2 Seniority Scheme

Calculation of spectroscopic factor for odd target nucleus in continuum spectrum for direct reaction model

2.2.1 Direct reaction model calculation

In that case use the reaction equation (1)

2.2.2 Coefficient of fractional parentage in seniority scheme

Seniority scheme

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

Spectroscopic factor for one nucleon separation from n particles in a shell

$$C^2S = n$$

for even particle system in a shell

$$C^2S = \frac{2j+2-n}{2j+1}$$

for odd particle system in a shell (8)

The present estimation

We calculate C^2S from the BCS equation [25]. It is proper to multiply a constant to the strength function as follows,

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

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

(9)

3. Results and Discussion

Double differential cross-sections (DDXs) for the ^{27}Al(p,d)^{26}Al reaction have been obtained at 68 MeV, as shown in Figs. 1, 2, 3 and 4 for the laboratory angles of 25°, 30°, 35° and 45°. The measured spectra correspond to the deuteron energy regions of about 0-58 MeV. Experimental and theoretical results are represented by the circles and lines respectively, whereas, the solid and dashed lines represent the DDX with seniority scheme and without seniority scheme. Koning and Delaroche [29] potential has been used here for protons and the corresponding potentials for deuteron in the analysis of data and shown in Table 1.

The DDX is reproduced fairly well at all angles with the application of seniority scheme in the deuteron energy region above 50 MeV. The best result of theoretical values has been found at 30° angle while for the other three (25°, 35° and 45°), it is a bit underestimated. However, for the deuteron energy region below 50 MeV, the calculated values are underestimated compared to experimental values. This is because the calculation 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 less than it. It should be noted here that no renormalization is required in this method for the theoretical calculation to make good matching with the absolute values of the experimental one.

As a whole, a fair agreement is found in this work between the theoretical and experimental values. The reaction is analyzed here with the direct reaction model; so, the calculated double differential cross sections agree with experimental data as far as ~ 12 MeV deuteron excitation energies.

Table 1. Optical model parameters used in the DWBA calculations for the $^{27}Al(p,d)^{26}Al$ reaction at 68 MeV

Koning and Delarohe potential [29]

At 68 MeV

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	32.93	1.17	0.67	1.33	7.50	3.09	1.30	0.54	4.43	0.97	0.59
Deuteron	a	1.17	0.67	1.33	a	a	1.30	0.54	a	0.97	0.59
Neutron	b	1.25	0.65	-	-	-	-	-	-	-	-

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

For all potentials nonlocality, 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	λ= 25
Neutron	0.85 fm	0.621 fm	-
Deuteron	0.54 fm	-	-

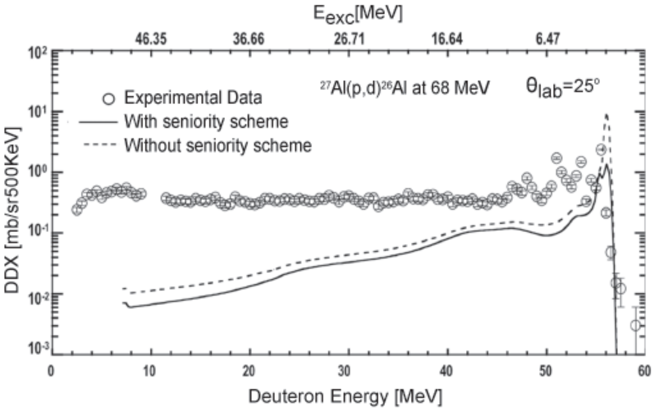

Fig. 1: Double differential cross sections for the $^{27}Al(p,d)^{26}Al$ reaction at 68 MeV for 25°angle

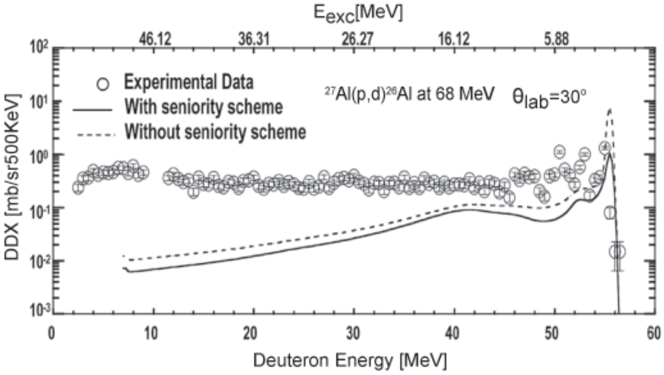

Fig. 2: Double differential cross sections for the $^{27}Al(p,d)^{26}Al$ reaction at 68 MeV for 30°angle

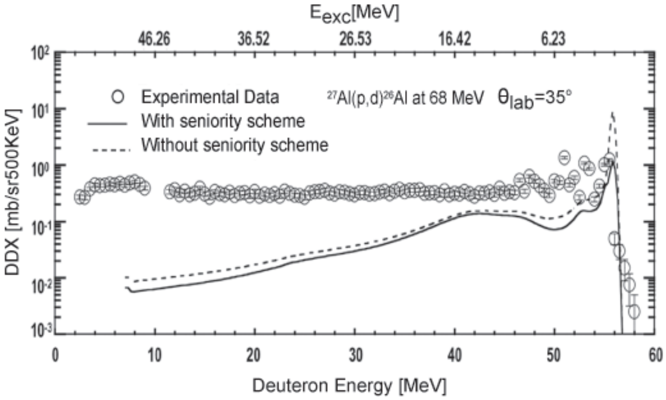

Fig. 3: Double differential cross sections for the $^{27}Al(p,d)^{26}Al$ reaction at 68 MeV for 35°angle

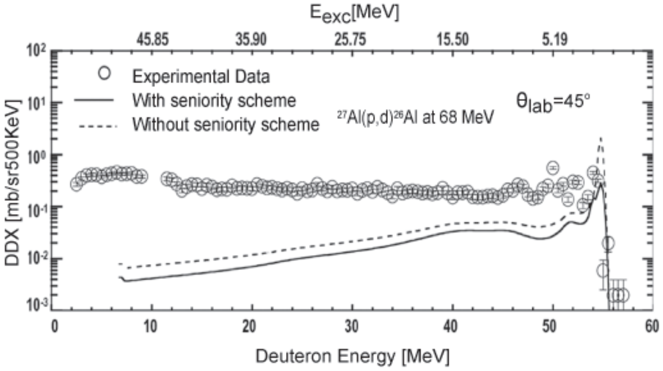

Fig. 4: Double differential cross sections for the $^{27}Al(p,d)^{26}Al$ reaction at 68 MeV for 45°angle

4. Conclusion

In this paper, the DDXs of the $^{27}Al(p,d)^{26}Al$ reaction have been calculated. The incident energy is 68 MeV and the laboratory angles are 25°, 30°, 35° and 45°. Here, the spectra of the $^{27}Al(p,d)^{26}Al$ reaction have been analyzed consistently with the direct reaction model. The overall strengths are reproduced well using the asymmetric Lorentzian form response function having energy dependent spreading width.

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