Analysis of Continuum Spectra of (n,d) Reactions with Direct Reaction Model

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Abstract

Higher energy deuteron emission spectra in the continuum region in nucleon induced reactions, i.e. (p,d) and (n,d) reactions, are not reproduced well by the usual pre-equilibrium reaction model. The one-step direct pick-up reaction model gives better predictions for the (p,d) reactions at incident energies of several tens MeV region. The present study aims to establish a method to analyze the continuum spectra of both the (p,d) and (n,d) reactions in the direct reaction scheme.

Introduction

There have been many works on one-nucleon transfer reactions. However, works on the (n,d) reaction have been yet scarce. As the (n,d) reaction data are not easy to be measured experimentally, it is desired to prepare a model which gives a reliable theoretical prediction, and to use it as a substitute of experimental results.

For the (p,d) reaction continuum spectra, we adopted an approach suggested by Lewis [1]. Here continuum spectra is assumed as an incoherent sum of all shell contribution and an asymmetric lorentzian form for the response function is adopted in DWBA-based cross sections calculation [2]. Similar procedure is used here to analyze the (n,d) reaction data with global optical potentials. The present work for the (n,d) reactions is an extension of the (p,d) reaction analyses . In this paper, we analyze the ^{58}Ni(p,d)^{57}Ni and ^{nat}Fe(n,d) ^{nat}Mn reactions in ensemble by this model.

Experimental Data

(p,d) reactions:

The data were referred from the report [3] of the experiments performed at the TIARA facility of JAERI. A proton beam of 68 MeV from the AVF cyclotron was lead to the HB-1 beam line. Energy distributions of light ions emitted from the target were measured using a ΔE-E counter telescope, which consisted of two thin silicon ΔE- detectors and a CsI(Tl) E- detector with photo-diode readout.

(n,d) reactions:

The data were referred from the report [4] of the experiments performed at the ^{7}Li(p,n) neutron source of the TIARA facility of JAERI. A spectrometer was used, which consisted of three counter telescopes mounted on a vacuum chamber to reduce the energy loss of secondary particles and charged particles in the air.

Theoretical Analysis

Theoretical Analysis

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:

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

where $d\sigma/d\Omega|_{l,j}^{DW}(E)$ is the cross-section calculated by a DWBA code DWUCK [5] and $C^2S_{l,j}(E)$, the spectroscopic factor expressed as

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

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 [6-8]

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

and

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

where n_0 is the renormalization constant and E_F the Fermi energy. The Fermi energy can

Table I. Optical model parameters used in the DWBA calculation for ^{58}Ni(p,d)^{57}Ni and ^{Nat}Fe(n,d)Mn

^{58}Ni(p,d)^{57}Ni:

	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	32.11	1.20	0.67	1.26	7.36	3.11	1.28	0.54	4.51	1.02	0.59
Deuteron	a	1.20	0.67	1.26	b	c	1.28	0.54	d	1.02	0.59
Neutron	e	1.25	0.65								

^{54}Fe(n,d)^{53}Mn:

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)
Neutron	30.04	1.20	0.67		7.11	2.38	1.28	0.54	4.33	1.01	0.59
Deuteron	a	1.20	0.67	1.26	b	c	1.28	0.54	d	1.01	0.59
Proton	e	1.25	0.65	1.26							

^{56}Fe(n,d)^{55}Mn:

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}
Neutron	29.65	1.20	0.67		7.11	2.30	1.28	0.54	4.34	1.02	0.59
Deuteron	a	1.20	0.67	1.26	b	c	1.28	0.54	d	1.02	0.59
Proton	e	1.25	0.65	1.26							

^{57}Fe(n,d)^{56}Mn

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)
Neutron	29.46	1.20	0.67		7.11	2.26	1.28	0.54	4.34	1.02	0.59
Deuteron	a	1.20	0.67	1.26	b	c	1.28	0.54	d	1.02	0.59
Proton	e	1.25	0.65	1.26							

^{58}Fe(n,d)^{57}Mn:

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)
Neutron	29.28	1.20	0.67		7.11	2.22	1.28	0.54	4.34	1.02	0.59
Deuteron	a	1.20	0.67	1.26	b	c	1.28	0.54	d	1.02	0.59
Proton	e	1.25	0.65	1.26							

	Nonlocality parameters	Finite-range parameter
Proton	0.85fm	0.621
Neutron	0.85fm	0.621
Deuteron	0.54fm	

$\lambda = 25$

[a]V = V(proton)+V(neutron), See ref. [13] for V(proton) and V(neutron).

[b]$W_v = W_v$ (proton)+ W_v (neutron), See ref. [13] for W_v (proton) and W_v (neutron).

[c]$W_s = W_s$ (proton)+ W_s (neutron), See ref. [13] for W_s (proton) and W_s (neutron).

[d]$V_{so} = V_{so}$(proton)+ V_{so} (neutron), See ref. [13] for V_{so} (proton) and V_{so} (neutron).

[e] Well depth adjusted to fit the separation energy.

be calculated by using an empirical formula given in [9]. 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 [10]. Spreading width (Γ) is expressed by a function proposed by Brown and Rho [11] and by Mahaux and Sartor [8], as,

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

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

ε_0 =19.4 (MeV), E_0 =18.4 (MeV)

ε_1 = 1.40 (MeV), E_1 =1.60 (MeV).

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 [12]

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

where $n_n(l, j)$ 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.

This sum rule of each orbit is suitable for (p,d) reaction but for (n,d) reaction we consider no contribution for $n_n(l, j)$ i.e. no contribution for IAS in the spectrum. So we apply 100% contribution for the spectra only for $n_p(l, j)$ and do some modification of the above sum rule equation i.e.

$$C^2 S_{l,j} = \frac{n_{p(l,j)}}{2T+1}$$

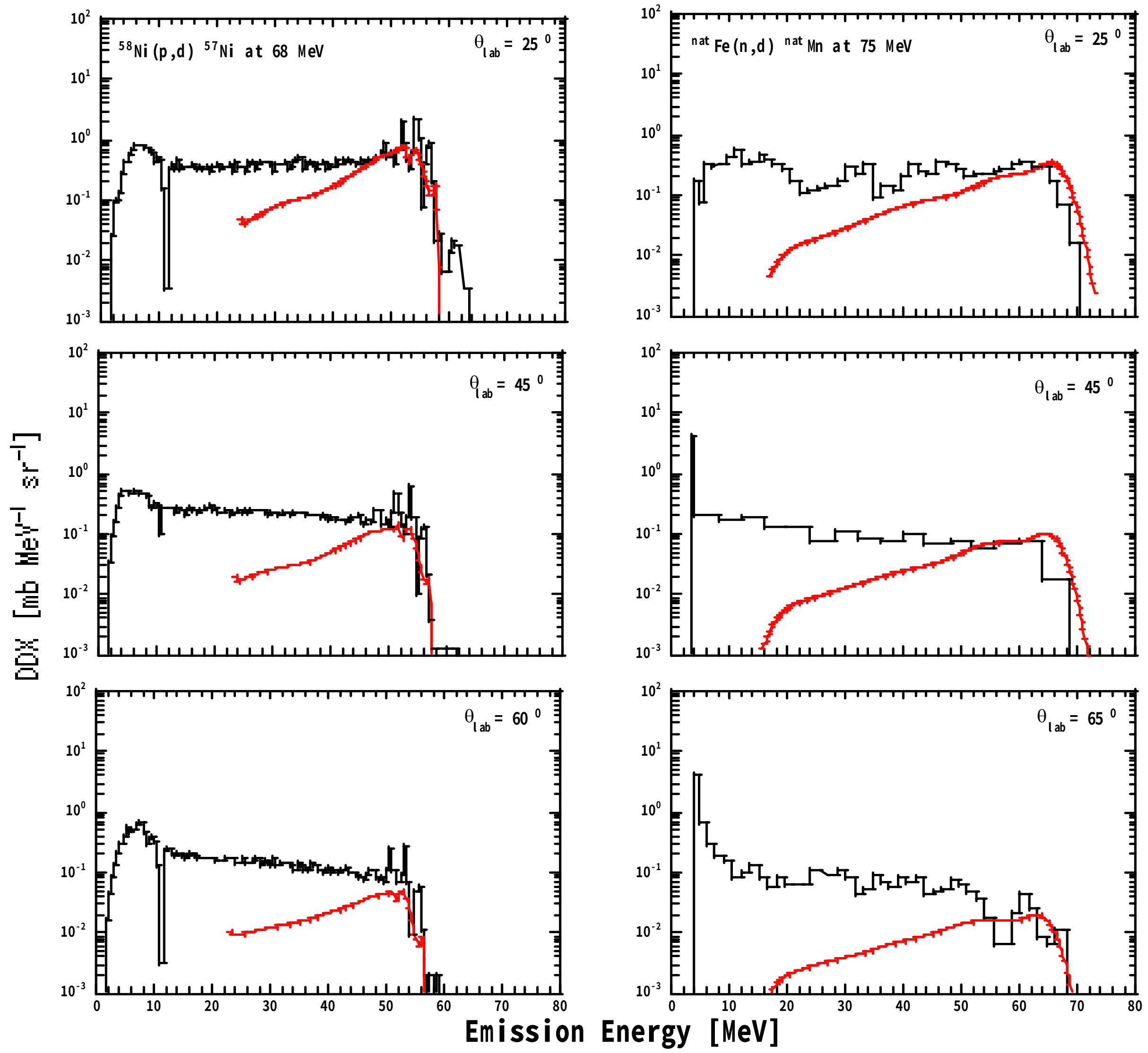
Discussions

Experimental and Theoretical double differential cross-sections for the $^{58}Ni(p,d)^{57}Ni$ and the $^{nat}Fe(n,d)Mn$ reactions at 68 MeV and 75 MeV, respectively are shown in Fig I. Table I shows the optical model parameters used in the DWBA calculations for the $^{58}Ni(p,d)^{57}Ni$ and $^{nat}Fe(n,d)\,^{nat}Mn$ reactions. In Fig. I, histograms represent the experimental spectra and solid lines the theoretical ones. The calculated spectra of both the (p,d) and (n,d) reactions obtained from the same method of calculation are in good agreement with the experimental ones in the higher energy region. To compensate the experimental energy resolutions for the (p,d) and (n,d) reactions, a convolution integration was applied to the theoretical cross-section with experimental resolution.

Fig.I ^{58}Ni(p,d) DDX data(left) ^{Nat}Fe(n,d) DDX data(right) at 68 MeV and 75 MeV respectively.

Histogram Experimental Data

Theoretical Prediction



Conclusion

The ^{58}Ni(p,d)^{57}Ni and ^{nat}Fe(n,d)^{nat}Mn reactions data have been studied here with the same method of calculations.

The theoretical calculations can reproduce well experimental spectra of forward angles (25^0,45^0), at high outgoing energies. But for the spectra at backward angles (60^0 for ^{58}Ni and 65^0 for ^{nat}Fe), the calculated results are somewhat underestimated. It is thus possible that for the backward angles there may be some contribution from the pre-equilibrium reaction process.

As a whole, a fairly good overall agreement is found between the theoretical and experimental spectra in both the magnitude and shape of double-differential cross-section. So from all the above consideration, we can conclude that this theoretical method is suitable not only for the (p,d) but also for (n,d) reactions.

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