Continuum Spectra Analysis of (p, d) and (n, d) Reactions on Bi in Several tens of MeV Energy Region

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Abstract

Theoretical analyses of the double differential cross sections for proton and neutron induced deuteron pickup reactions on ^{209}Bi are described. Neutron induced reaction cross-section data were analyzed at incident energies from about 41 MeV to 65 MeV and at 20^0 laboratory angle, while proton induced reaction cross-section data were analyzed at the incident energy of 42 MeV and at 25^0 laboratory angle. Spectrum regions are treated in the direct reaction scheme, i.e., several tens of MeV energy region. The double differential cross section - energy spectra were analyzed using the DWBA-based cross sections and the asymmetric Lorentzian form strength response function having energy dependent spreading width. Both the (n,d) and (p,d) spectra are fairly well reproduced by the theoretical calculations in the tens of MeV energy region.

I. Introduction

The nuclear data for neutron induced reactions are required in many fields of science, for accelerator driven transmutation system of nuclear waste, for nuclear heating of reactor, for clinical radiotherapy, for radiation effects in environment etc. However, this type of nuclear data at incident energies above 20 MeV or so are rather scarce because there are only a few experimental facilities having intense neutron sources suitable for the measurement.

From the above points of view, it is indispensable to devlop theoretical model for a compilation of a new nuclear data library. The code GNASH is one of the most powerful tools to estimate particle production cross sections of nucleon-induced reactions at the medium energy range that is from tens of MeV up to 100 MeV. However, since this code is based on the exciton model, it is not applicable to the particle productions via the direct reactions such as pickup and stripping reactions. The highest energy range of spectra is governed by the direct reactions. 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 Syafarudin et al. [2] firstly adopted this model to (p,d) reactions, and demonstrated its reasonable predictive ability. As a second step, it was extended to neutron-induced reactions. With a small modifications, (n,d) spectra were well reproduced.

In the present work, we investigate the applicability of the model for heavy target nuclei, since it was tested only medium mass nuclei [3]. Deuteron spectra from (n,d) and (p,d) reactions on ^{209}Bi are analyzed with the present model and compared with experimental data. In addition, we discuss the dependence of resultant spectra on the optical model potentials [4, 5, 6] used in the DWBA calculation. Since a single-step model is valid in the excitation energy range up to about tens of MeV, we confined ourselves to the highest of 10 MeV energy domain of particle production spectra. At the lower energy range, where the multistep is the dominant, is out of the scope of this work.

II. Analyses

1. Experimental Data

(1) (p, d) reactions

The experiments were 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. 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. Details of the experimental procedure and the results have been reported in ref [7].

(2) (n, d) reactions

The experiments were performed at the fast neutron facility of the Louvain-la-Neuve cyclotron(CYCLONE). Details of the experimental procedure and the results have been reported in ref [8].

2. Theoretical Calculations

The ^{209}Bi(n,d)^{208}Pb double differential cross section has been analyzed with the direct reaction model. To obtain the DDX for the (n,d) reaction we have made some slight changes in the theoretical calculations given in ref. [2].

Theoretical methods of calculating direct reactions are generally used to predict the excitation of a state having known spin-parities and existing shells of the related nucleons. To calculate spectra in the direct reaction scheme, methods are proposed by Lewis [9] and the authors' group [10, 11]. Details of our mathematical calculations for direct reaction model are given below.

Double differential cross sections for pickup reactions are assumed to be given by an incoherent sum of DWBA calculations and expressed as below

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

and the spectroscopic factor is as

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

where $d\sigma/d\sigma|^{DW}_{l,j}(E)$ is the cross-section calculated by the DWBA code DWUCK4 [12] and $\sum C^2 S_{l,j}$ is the sum of the spectroscopic factors of all the possible states.

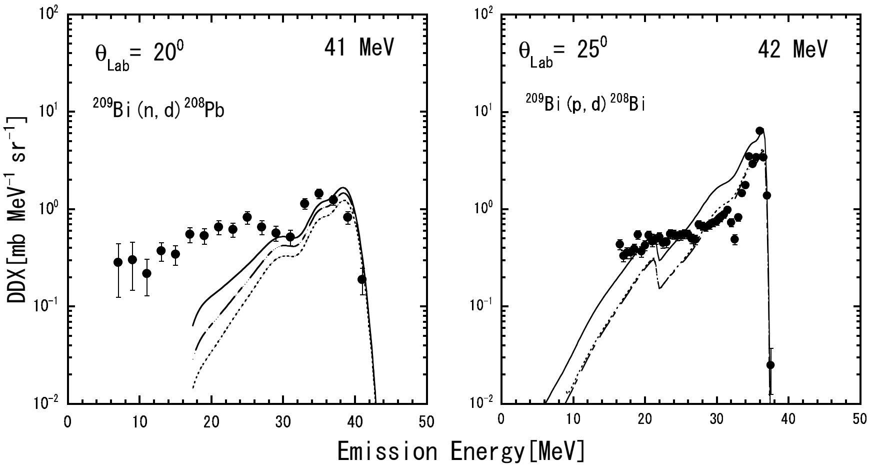

Fig. 1 The ^{209}Bi(n, d) double differential cross section (DDX) data (left) and ^{209}Bi(p, d) double differential cross section (DDX) data (right) at 41 MeV and 42 MeV respectively. Closed circles show experimental data. Solid, dot-dashed and dotted curves refer to the prediction due to present work using Koning, Menet and Becchetti potentials respectively.

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]

$$\sum C^2 S_{l,j} = \begin{cases} n_n(l,j) - \dfrac{n_p(l,j)}{2T+1} & \text{for} \quad T_< = T - \frac{1}{2} \\ \dfrac{n_p(l,j)}{2T+1} & \text{for} \quad T_> = T + \frac{1}{2} \end{cases} \tag{3}$$

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 the (p, d) reaction but for the (n, d) reaction, we considered the sum rule equation given by

$$\sum C^2 S_{l,j} = \frac{n_{p(l,j)}}{2T+1} \tag{4}$$

This is because here only the normal states are populated and not the analog states.

The strength function $f_{l,j}$ over the spectra is predicted by using a modified Lorentzian function [10, 11, 14] as follows

$$f_{l,j} = \frac{n_0}{2\pi} \frac{\Gamma(E)}{\left(|E - E_F| - E_{l,j}\right)^2 + \Gamma^2(E)/4} \tag{5}$$

and

$$\int_0^\alpha f_{l,j}(E)dE = 1 \tag{6}$$

where $E_{l,j}$ is the calculated energy of the single-particle state which varies with the spreading width Γ(E),and n_0 is the renormalization constant deduced from shell model calculations. The sum-rule fraction of spectroscopic factors $C^2 S_{l,j}$ and the centroid energies for $J = l \pm \frac{1}{2}$ shell-orbits are estimated by using the BCS theory, and single particle energies are calculated based on a prescription shown in ref [15]. The energy variable is taken as E-E$_F$ in consistency with the work of Hisamochi et al. in ref. [16].

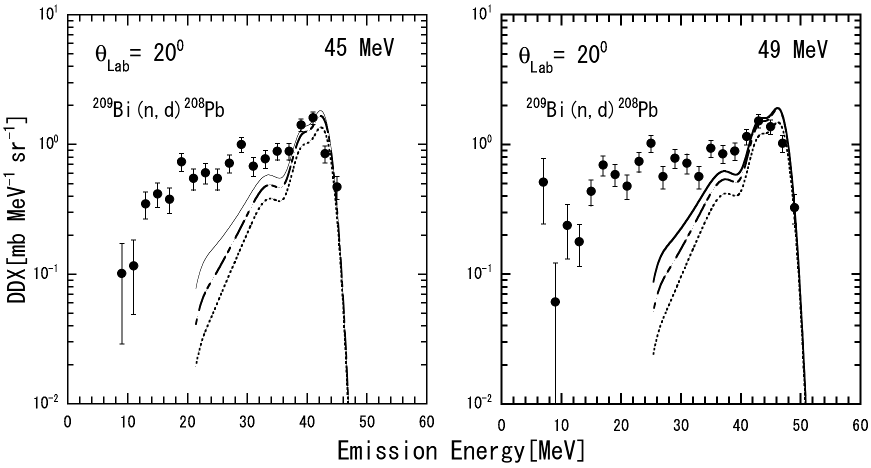

Fig. 2 Same as fig.1 but for ^{209}Bi(n, d) reaction at 45 and 49 MeV respectively.

The spreading width is fairly well expressed with a function proposed by Brown and Rho [17] and Mahaux and Sartor [14], as

$$\Gamma(E) = \frac{\epsilon_0 \left(E - E_F\right)^2}{\left(E - E_F\right)^2 + E_0^2} + \frac{\epsilon_1 \left(E - E_F\right)^2}{\left(E - E_F\right)^2 + E_1^2} \tag{7}$$

where ϵ_0, ϵ_1, E_0 and E_1 are constants which express the effects of nuclear damping in the nucleus [10]. The estimated parameters [10] are

$$\begin{array}{ll} \epsilon_0 = 19.4\,\text{(MeV)}, & E_0 = 18.4\,\text{(MeV)}, \\ \epsilon_1 = 1.40\,\text{(MeV)}, & E_1 = 1.60\,\text{(MeV)}. \end{array} \tag{8}$$

III. Results and Discussion

We applied the present method to Bi(n,d)Pb reaction data at 41-65 MeV and Bi(p,d)Bi reaction data at 42 MeV, as shown in figs. 1-3. The experimental and theoretical DDX are given by the closed circles and lines respectively.

For proton, the global optical model potentials of Becchetti and Greenlees [4], Menet et al. [5] and Koning and Delaroche [6] were used, whereas, for deuterons, the adiabatic potential constructed with the proton and neutron parameters of those three [4, 5, 6] optical model potentials were used. The results for the cross-sections are consistent with one another and presented by dotted, short-long- dashed and solid line for Becchetti and Greenlees [4], Menet et al. [5] and Koning and Delaroche [6] potentials respectively.

From fig. 1, we can see that theoretical results are in fair agreement with the experimental data for the (n,d) reaction, while for the (p,d) reaction, in the case of potential of Becchetti and Greenlees [4], it overstimates a little, may be because of using global potentials, not best fit potentials. However, in fig. 2, for the (n,d) reaction with the Koning potential, the spectrum at 45 and 49 MeV incident energies and the theoretical ones are in close agreement to each other. Again, in fig. 3, at 53.5 MeV incident energy, for potentials of Menet and Koning, the calculated energy spectra are overstimated, may be for the same reason as described for fig. 1 for the (p,d) reaction, i.e., due to not using the best fit potentials. It should be noted from figs. 1-3 that at all incident energies both for the (n,d) and (p,d) reactions the double differential cross sections, the calculated specta agree with experimental data only above tens of MeV incident energies, because our calculated energy spectrum regions are treated in direct reaction scheme.

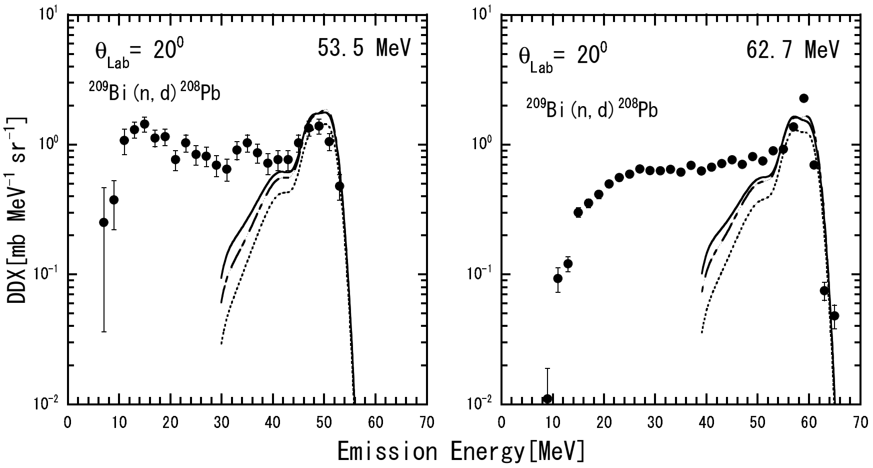

Fig. 3 Same as fig.1 but for ^{209}Bi(n, d) reaction at 53.5 and 62.7 MeV respectively.

IV. Conclusion

The double differential cross sections for neutron and proton induced reactions on ^{209}Bi have been analyzed here. The bombarding energy range for neutron induced reaction is about 40 MeV$\leq$ E$_n$$\leq$65 MeV and at 20^0 Laboratory angle, while for proton it is at 42 MeV and at 25^0 Laboratory angle. The spectra of continuum region have been analyzed consistently with direct reaction model. The overall strengths are reproduced well using asymmetrical Lorentzian form response functions having energy-dependent spreading widths. The calculated DDXs show an overall good agreement with the experimental data both in magnitude and shape.

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