BALKAN PHYSICS LETTERS

10 February 2010
BPL, **18**, 181013, pp. 97-107 (2010)

CROSS SECTION CALCULATIONS ON SOME NUCLEAR REACTIONS IN ASTROPHYSICS

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Abstract. - Big Bang assumes that light nuclei have been occurred by Big Bang Nucleosynthesis in earlier universe model, then the heavier elements have been occurred with nuclear reactions which happen in stars, supernovae and novae. Nuclei occurred at the end of the nuclear reactions give us very important knowledges about forming the heavier nuclei and abundance magnitude of these elements.

In this work, transfer reactions which play very important role in nuclear astrophysics have been analyzed by DWBA models. The cross sections of $^{18}F(d,p)^{19}F$ and $^{40}Ca(d,p)^{41}Ca$ nuclear reactions happened in nova and supernova explosions, respectively, have been determined for different potential values. It is observed that the cross sections have been significantly changed by depending on potential values. The results of calculations are compatible with the experimental data.

1. Introduction

Nuclear astrophysics describe where and how was the matter shaped and indicate that there is a direct similarity in the universe between evolution of the macroscobic object such as stars, galaxies and physical behavior of microscobic object such as protons, neutrons and electrons [1].

Stripping reactions are important reactions in terms of nuclear physics. We can understand what degree a given residual nuclear state looks like the target ground state with the simple addition of one neutron in a particular shell model orbit via a deuteron stripping (d, p) reaction [2]. This gives us important information about the validity of the shell-model and it can provide tests of calculated shell model wave functions [3].

Potential sets which explain experimental scattering and reaction cross section data are obtained using a computer code. Distorted-wave Born approximation (DWBA) is the effective model in analyzing the transfer reactions, so it is widely used in the analysis and interpretation of stripping reactions and other direct process as pick-up [4, 5, 6], knock-out [7] reactions. This model can also be performed for transfer reactions by heavy ions [8, 9] and multi-nucleon transfer reactions [10, 11]. DWBA yields results about the reaction ratios [12], the shell-model [13, 14] and the astrophysical implications [15]. The DWBA code DWUCK consists of two part; Zero Range Born Approximation (DWUCK4) and Finite range Born Approximation (DWUCK5). The DWBA code DWUCK is used to compute the angular distributions with angles.

In this paper, $^{18}F(d,p)^{19}F$ and $^{40}Ca(d,p)^{41}Ca$ reactions are analyzed with the DWUCK4 and DWUCK5. Our purpose is to show that the experimental data have been analyzed within the framework of the zero range and finite range DWBA for $^{18}F(d,p)^{19}F$ and $^{40}Ca(d,p)^{41}Ca$ reactions and to compare these methods with together.

2. Model

A scattering occurs when the projectile particle with high energy produced in laboratory bombards a fixed target nucleus. An interaction between projectile and target is related to the cross section of nuclear reaction. The cross section is a probability of measured nuclear reactions that occured per couple of particles [2]. It is used to compute reaction ratios and can be determined with the experiments at laboratories. It is a major factor that the interaction potential between projectile and target effects the angular distributions and energies of scattered particles.

When the nuclear reaction models were analyzed, it was appeared that the essential problem was to find potential sets which give the best fit for the experimental data. So, the potentials should be determined in that process. There is not only one interaction between projectile and target nucleus, so the interactions around these particles are not represented by only one potential. This potential should be an optical potential which consists of real and imaginary parts. Because, optical model is successful in explaining elastic and inelastic scattering about understanding nuclear interactions. The optical potential is shown as:

$$V_{op}(r) = V(r) + iW(r), \tag{1}$$

where i is the complex unit, *V(r)* and *W(r)* are real and imaginary parts of the potential, respectively. Nuclear potentials change as depending on energies. When the energy of the projectile increases, the number of the excited channels increase. Therefore, the intensity of the imaginary potential which describes this interaction also rises.

In this paper, the single particle transfer, which is the neutron, have been analyzed with the stripping process. Due to the fact that all particles are represented by the wave functions in quantum mechanics, this single particle also has the wave functions generated in a Woods-Saxon potential. The programme uses the Woods-Saxon potential volume and surface absorption terms with including spin-orbit interaction in distorting potentials. This potential is generally given as:

$$V(r) = -\frac{V_0}{1 + exp\frac{(r-R)}{a}}, \tag{2}$$

where V_0 represents the potential well depth, a is the surface thickness of the nucleus, r is the distance from the center of nucleus and $R = r_0 A^{1/3}$. The programme uses volumetric and surface Woods-Saxon potentials, which are shown below, respectively.

$$V(r) = V_R f(x_R) + iV_I f(x_I) \tag{3}$$

and

$$V(r) = V_R g(x_R) + iV_I g(x_I) \tag{4}$$

$$g(x) = \frac{df(x)}{dx} \tag{5}$$

where i is the type of used potential and f_i is the function of the potential.

$$f(x_i) = \frac{1}{1 + exp(x_i)} \tag{6}$$

$$x_i = \frac{r - R_i}{a_i}. \tag{7}$$

These notations are similar to formula 2.

In this work, it is chosen a real-volume Woods-Saxon and an imaginary-surface Woods-Saxon forms. This paper uses zero range and finite range DWBA to calculate $^{18}F(d,p)^{19}F$ and $^{40}Ca(d,p)^{41}Ca$ reactions' cross sections and investigate the applicability of this method. The cross sections of deuteron stripping reactions can be explained by single nucleon capture into the target nucleus. This process can be described with a great success by DWBA.

3. $^{18}F(d,p)^{19}F$ Reaction

The $^{18}F(d,p)^{19}F$ reaction has been investigated in theoretical form and its experimental results have been obtained at Oak Ridge National Laboratory (ORNL) previously. Our purpose is to compare the consistency between the produced experimental results and theoretical results by using the codes DWUCK for different potential sets. This reaction has been studied extensively in Ref. [16]. *(p,α)* and *(p,γ)* reactions, which are important in terms of astrophysics, generate crucial reactions for the decaying nucleus of ^{18}F [17]. For example, the detailed information can be obtained about the nuclear structures with resonance similarities and the energy levels on the mirror nuclei ^{19}Ne and ^{19}F between $^{18}F(p,\gamma)^{19}Ne$ and $^{18}F(d,p)^{19}F$ reactions [18, 19]. Briefly, it is well understood the astrophysical events and structure of some nuclei by examining $^{18}F(d,p)^{19}F$ reaction for the nova explosions.

The nucleus ^{19}F has the ground state and two excited states; $2s_{1/2}$ ground, $1p_{1/2}$ (110 keV) first excited and $1d_{5/2}$ (197 keV) second excited states. Angular distributions for the $^{18}F(d,p)^{19}F$ reaction to the ground state and two excited states of ^{19}F at a deuteron energy of 12.1 MeV have been analyzed by using a conventional DWBA models. These three states have been analyzed by fixing all potential parameters other than the potential depth and the differential cross sections have been measured over a narrow angular range. The optical model parameters are shown in Table 1.

Table 1. Optical potential parameters used in the DWBA analysis for $^{2}H(^{18}F,p)^{19}F$ reaction [16].

Particle	$V_R(MeV)$	r_R(fm)	a_R(fm)	$4V_1(MeV)$	r_I(fm)	a_I(fm)	r_C(fm)
d	109.0	1.35	0.70	58.8	1.39	0.60	1.39
p	52.4	1.36	1.01	10.4	1.47	0.64	1.39
n	-	1.46	0.73	-	-	-	-

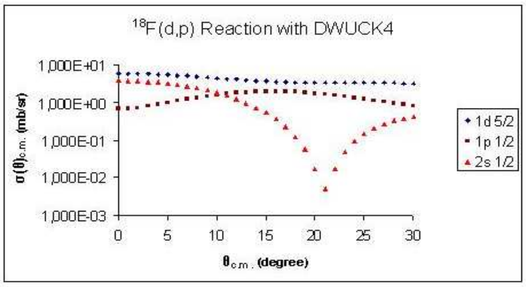

Figure 1. The results of DWUCK4 analysis for three states of ^{19}F at $^{18}F(d,p)^{19}F$ reaction with the same potential values.

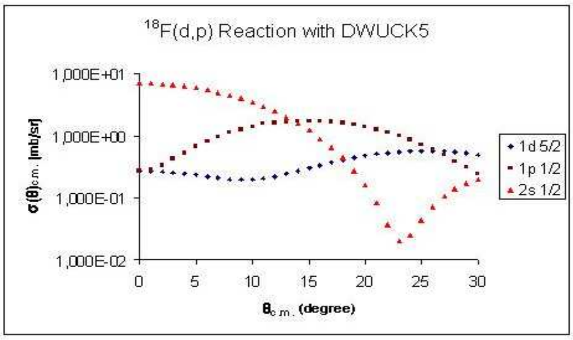

Figure 2. The results of DWUCK5 analysis for three states of ^{19}F at $^{18}F(d,p)^{19}F$ reaction with the same potential values.

As shown above, the DWBA analysis have been performed with the code DWUCK for the nucleus ^{19}F. Two figures are different from each other. The magnitudes of cross sections for the various final states in ^{19}F are determined from the DWBA and these results can be compared by the predictions of some nuclear models. The code DWUCK5 analysis is compatible with the experimental results [16]. The total cross sections of these states are follows as:

Table 2. Total cross sections produced with the DWUCK4 code for the same potential values.

The States	**Total Cross Section (mb)**
$1d_{5/2}$	1.5389E+01
$1p_{1/2}$	6.6803E+00
$2s_{1/2}$	2.3791E+00

Table 3. Total cross sections produced with the DWUCK5 code for the same potential values.

The States	**Total Cross Section (mb)**
$1d_{5/2}$	1.0120E+00
$1p_{1/2}$	2.2961E+00
$2s_{1/2}$	1.7920E+00

It is clear that there are some differences between two codes, and it can be understood that the finite range DWBA is a good approach. We'll show the effect on total cross section with different potential values for only one state. For instance; let $1p_{1/2}$ be an excited state. When we analyze this state with the potential depth less than %50 and more than %50 respectively, angular distributions obtained as shown in figure 3.

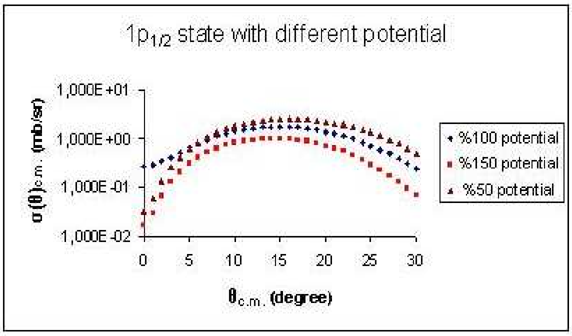

Figure 3. The state $1p_{1/2}$ of ^{19}F for the different potential values with DWUCK5 code.

Table 4. The total cross sections for the state $1p_{1/2}$ of ^{19}F for the different potential values with DWUCK5 code.

The State	**Total Cross Section (mb)**
%100 potential	2.2961E+00
%150 potential	9.6396E-01
%50 potential	2.5409E+00

Here, it is shown that the cross sections depend on potential values. If the potential intensity rises, the total cross section values decrease. That is, the total cross sections are proportional potential intensities reversely. As a consequence, the finite range DWBA calculations are more consistent and give good fits to data only if the deuteron potential with the real well depth of $V_R \approx 110MeV$ has been used.

4. $^{40}Ca(d,p)^{41}Ca$ Reaction

The $^{40}Ca(d,p)^{41}Ca$ reaction has also been studied previously and the experimental results have been obtained for both codes. This reaction is very important in terms of forming heavier elements, and it has been occurred with the energetic supernova explosions like $^{40}Ca(\alpha,\gamma)^{44}Ti$ reaction [20]. It is clear that both the temperature and pressure of medium and the abundance of target nucleus are a great factor for producing elements. If the nucleus ^{40}Ca is too much in the medium, the production of heavier nucleus ^{44}Ti also increase [21]. So, the product nucleus can begin nuclear reactions for occurring heavier elements.

Table 5. Optical potential parameters used in the DWBA analysis for $^{40}Ca(d,p)^{41}Ca$ reaction [22].

Particle	$V_R(MeV)$	r_R(fm)	a_R(fm)	$4V_1(MeV)$	r_I(fm)	a_I(fm)	r_C(fm)
d	97.40	1.112	0.875	70.0	1.562	0.477	1.25
p	49.47	1.18	0.70	24.2	1.180	0.70	1.25
n	1	1.18	0.70	-	-	-	-

Although the nucleus ^{41}Ca have a lot of states, $1f_{7/2}$ ground state is handled in this study.

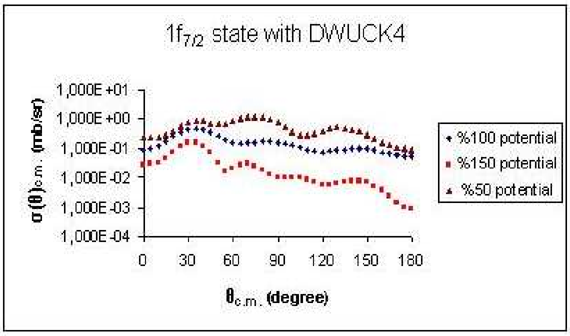

Figure 4. The results of DWUCK4 analysis for $^{40}Ca(d,p)^{41}Ca$ reaction with the different potential values.

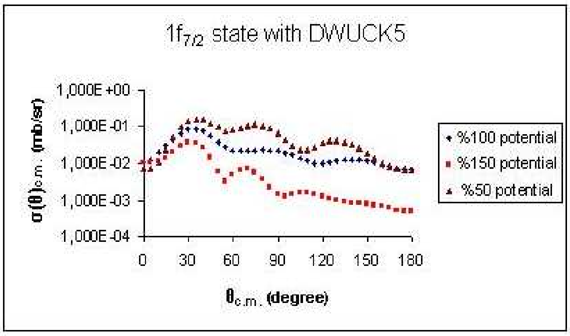

Figure 5. The results of DWUCK5 analysis for $^{40}Ca(d,p)^{41}Ca$ reaction with the different potential values.

The experimental data of previous paper [23] are here analyzed by using the DWBA codes.

Table 6. Total cross sections are produced with DWUCK4 code for the different potential values for the $^{40}Ca(d,p)^{41}Ca$ reaction.

The State	**Total Cross Section (mb)**
%100 potential	2.0847E+00
%150 potential	3.5545E-01
%50 potential	7.7755E+00

Table 7. Total cross sections are produced with DWUCK5 code for the different potential values for the $^{40}Ca(d,p)^{41}Ca$ reaction.

The State	**Total Cross Section (mb)**
%100 potential	3.0207E-01
%150 potential	7.5761E-02
%50 potential	7.9607E-01

As seen above, the total cross sections are different with regard to intensities of the applied potential for the $^{40}Ca(d,p)^{41}Ca$ reaction on DWUCK4 and DWUCK5 processes. Differential cross sections have been measured for the $^{40}Ca(d,p)^{41}Ca$ reaction at the deuteron bombarding energy of 12 MeV. Differential cross sections have been measured over a wide angular range. It is observed that the first pics on graphics are over the degree of 30^o and total cross section values decrease stably. It has also understood that the best fits to stripping angular distributions in this process by using zero range DWBA calculations has been given by deuteron wave functions generated by an optical potential with $V_R \approx 100$ MeV.

Besides, it is also compared two codes with each other. When it is performed with the same potential values for this reaction, the results of DWUCK4, DWUCK5 analysis are obtained as:

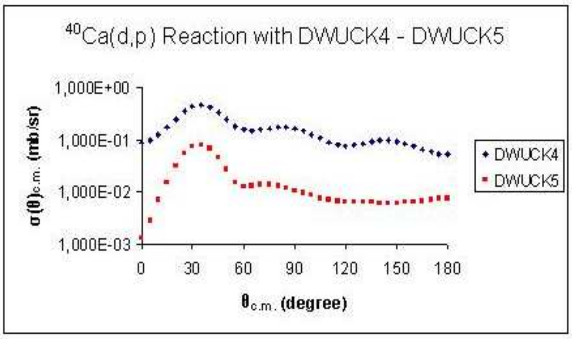

Figure 6. The results of DWUCK4-DWUCK5 analysis for $^{40}Ca(d,p)^{41}Ca$ reaction with the same potential values.

Table 8. Total cross sections are produced with DWUCK4-DWUCK5 codes for the same potential values for the $^{40}Ca(d,p)^{41}Ca$ reaction.

The Codes	Total Cross Section (mb)
DWUCK4	2.0847E+00
DWUCK5	3.0207E-01

5. Conclusions and Results

DWBA is an important model for nuclear astrophysics. In this work, some nuclear reactions occured in stellar explosive have been analyzed by the DWBA codes and total cross sections related to reactions have been computed.

We have considered the case of *(d,p)* reactions in this model. The calculations for $^{18}F(d,p)^{19}F$ and $^{40}Ca(d,p)^{41}Ca$ reactions are computed by the DWBA. There are some changes for total cross sections of these reactions graphics, which depends upon applied potential parameters. Total cross sections have changed by changing real and imaginary parts of potential. This result suggets that the potential is a very important factor. With increasing and decreasing potential intensities, the total cross sections fall off and rise, respectively.

DWBA has been used as one impact model for the analysis of direct nuclear reactions. Nuclear reactions, which are important for astrophysics, can also been operated without DWBA. These reactions are good examples to test the DWBA theory for understanding nuclear models and structures. Single nucleon stripping reactions at an incident energy less than 50 MeV have been successfully analyzed within the context of DWBA [12]. In this study, Zero Range Born Approximation (DWUCK4) and Finite Range Born Approximation (DWUCK5) codes that includes DWBA have been performed how to calculate. There are some similarities and disparities between DWUCK4 and DWUCK5 codes. In other words, the difference between DWUCK4 and DWUCK5 codes is another important evidence. Besides, DWUCK5 code have some alternatives with respect to DWUCK4. That is, the finite range DWBA gives us much information about the nuclear structure.

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