

EVALUATION OF ANGULAR DISTRIBUTION OF TRANSFER REACTION IN EVEN-EVEN NUCLEI FOR ASTROPHYSICAL APPLICATIONS

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ABSTRACT

Angular distribution of transfer reactions of ^{12}C and ^{24}Mg at incident deuteron energies of 28.5MeV and 30MeV has been investigated, using Nucleon transfer reactions specifically within the Distorted Wave Born Approximation (DWBA) which was implemented with the DWUCK 5 source code. This code used optical model parameter(OPM) as one global parameter set and is based on direct reactions model, was used to calculate the differential cross section and spectroscopic factors with stripping reaction as transferred particles(d,p). Global Woods-Saxon volume and surface for the entrance and exit potential is been used. Bound state energies of ^{12}C (d,p) ^{13}C and ^{24}Mg (d,p) ^{25}Mg reactions in the exit channels -4.946MeV and -7.331MeV and spin at $2p_{3/2}^+$. The result of differential cross sections and spectroscopic factors for the reactions ^{12}C are 5.10mb and 0.695, with uncertainty of 26%, then 4.58mb and 0.678 with uncertainty of 21%. The result ^{12}C (d,p) ^{13}C appear to evaluate with fair agreement between the theory and experiment for validating the theoretical model. Also ^{24}Mg are 1.60mb and 0.291 with uncertainty of 4% , than 1.28mb and 0.250 with uncertainty of 4%. The result ^{24}Mg (d,p) ^{25}Mg appear to show disagreement between the theory and experiment for validating the theoretical model.

Keywords: Angular distribution, DWBA, Differential Cross Section, Spectroscopic Factors, Transfer Reactions.

1.0 INTRODUCTION

Transfer reactions in which one nucleon or a cluster of nucleons are exchanged between the target and the projectile are often used in nuclear structure studies to determine the energy, position and the orbital occupation of the excited states of many nuclei. Likewise,[1] it is widely used in nuclear astrophysics to determine the partial decay widths of nuclear states involved in resonant reactions, and to evaluate the direct capture cross-section.[2] It is apparent from the foregoing that a model of the reaction process is essential if we wish to obtain nuclear structure information from direct reaction data.[3] The reaction models are Distorted wave Born Approximation (DWBA), Adiabatic model, Coupled Channels Born Approximation (CCBA) and Coupled reaction channels (CRC).[4]It was first demonstrated by Butler in 1950 that the measured angular distributions of the differential cross section ($d\sigma/d\Omega$) of the $^AZ(d, p)^{A+1}Z$ transfer reaction depend sensitively on L , the angular momentum of the transferred neutron with respect to the core. Nucleus AZ , thus enabling L to be determined by a comparison of the measured angular distribution with the one calculated by a suitable model of the reaction. Although $^{12}\text{C}(d, p)$ and ^{24}Mg has been studied extensively over the deuteron energy range from 0.4 to 80.2 MeV.[5] angular distributions in transfer reactions are a powerful tool for probing the structure and dynamics of even-even nuclei. They help in determining nuclear spins and parities, understanding the nuclear shell structure, revealing transition strengths, and providing insights into the reaction mechanisms and nuclear deformations[6].

Angular distribution and excitation function measurements of $^{12}\text{C}(\text{d}, \text{p})$ reaction were carried out at the 350 kV Accelerator of the Energy Research Laboratory, King Fahd University of Petroleum and Minerals, Dhahran. The result of this study, excitations and the differential cross-sections of $^{12}\text{C}(\text{d}, \text{p})$ reaction are measured for the first time below 400 keV. This data could be used to test the existing DWBA theory for $^{12}\text{C}(\text{d}, \text{p})$ reaction at very low deuteron energies.[5] Existing measurements of the angular distributions of the ground-state to ground-state transitions of the $^{12}\text{C}(\text{d}, \text{p})^{13}\text{C}$ and $^{13}\text{C}(\text{p}, \text{d})^{12}\text{C}$ neutron-transfer reactions have been analyzed systematically using the Johnson- Soper adiabatic and distorted-wave theories. The present analysis provides an important reference point from which to assess the requirements of future spectroscopic analyses of transfer reactions measured in inverse kinematics using rare nuclei.[3]

The research focused on calculating the differential cross sections and spectroscopic factors for the reactions involving ^{12}C and ^{24}Mg at deuteron energies of 28.5 MeV and 30 MeV, respectively. To compare the results of analyzed reaction model (DWBA), global Woods-Saxon volume and surface for the entrance and exit potential is been used with experimental results in order to validating the theoretical model.

2.0 THEORETICAL BACKGROUND

The Nuclear Reaction Video (NRV) knowledge base provides the web service (dialog) to set the input parameters for calculation of nucleon transfer cross sections within the DWBA. The parameters are as follow; Reaction, Potentials, Bound states or Experimental data.[7]

2.1 Dwba Calculations

The most commonly used theoretical model to describe direct transfer reaction cross-sections is the Distorted Wave Born Approximation (DWBA) which relies on the following assumptions.

The entrance and exit channels processes are dominated by the elastic scattering, the transfer process is weak enough to be treated as a first order perturbation, the nucleon(s) transfer occurs directly between the two active channels $a + A$ and $c + C$ and the transferred nucleon(s) is directly deposited on the final state with no rearrangement of the core configuration.[8]

2.2 Transfer Reactions

The transfer reaction cross-section is proportional to the square of the transition amplitude which in case of the DWBA model, and in the post representation that is The transition amplitudes can be given in either a post or prior form depending on whether it is based on the interactions in the exit or entrance channel, respectively,[9] is given by

$$T_{fi}^{\alpha(\beta)} = J \iint d^3r_b d^3r_a x_{kf}^{(-)*}(r_b) \langle bB | \Delta V_{\alpha(\beta)} | aA \rangle x_{kf}^{(+)}(r_a) \quad (1)$$

where $x_{kf}^{(-)}$ and $x_{kf}^{(+)}$ are the distorted waves, ra and rb are the relative coordinates for the systems (a, A) and (b, B) respectively, and J is the Jacobean for the transformation to these coordinates is given by transformation equation [10] and

$$J = \left(\frac{m_a m_b}{m_a m_b - m_b m_a} \right)^3 \quad (2)$$

Where m_a is mass of deuteron, m_b is the mass of proton, m_A is the mass of target and m_B is the mass of target like. The quantity $\langle bB | \Delta V_{\alpha(\beta)} | aA \rangle$ is the form factor for the transfer reaction that couples the bound states in the entrance and exit channels.[8]

The asymptotic of the distorted waves $x_{kf}^{(\pm)}(r)$ $kf(r)$ is the combination of the plane wave with the momentum k and the outgoing (or incoming) spherical scattered wave without the Coulomb potential I[11]

2.3 Differential Cross Section

Differential cross-section is defined as the ratio of the intensity of radiant energy scattered in a given direction to the incident irradiance and thus has dimensions of area per unit solid angle, $d\Omega$ [12]The spectroscopic factor S_{xA} expresses the overlap probability between the $x + A$ wave-function and the final bound-state configuration C . It can be extracted from the ratio of the measured differential cross- section to the one calculated by the DWBA for the relevant single-particle or cluster transfer:[8]

$$\left(\frac{d\sigma}{d\Omega}\right)_{exp} = S_{xA} S_{xC} \left(\frac{d\sigma}{d\Omega}\right)_{DWBA} \quad (3)$$

where $\left(\frac{d\sigma}{d\Omega}\right)_{exp}$ and $\left(\frac{d\sigma}{d\Omega}\right)_{DWBA}$

Are the experimental and DWBA differential cross sections.

The product of the spectroscopic factors corresponding to the configuration of the $x + A$ bound state (S_{xA}) and of the projectile (S_{xC}) is involved in the previous expression. Hence, by knowing one of the spectroscopic factors it is possible to extract the other one. Therefore the light projectile in transfer reaction is usually chosen to have a strong cluster configuration, e.g., $S_{xC} \approx 1$, as in the case of the (d, p) reaction.[8]

2.4 Optical Model

The optical model potential is defined as the potential which furnishes the energy-averaged scattering amplitudes. These are characterized by a real part and an imaginary part,[8]

$$U(r) = V(r) + iW(r) \quad (4)$$

The imaginary part takes into account the flux that leaves the elastic channel and is not explicitly described by the model. These potentials have volume, surface, and spin-orbit parts that are characterized by a Woods-Saxon shape or derivatives of a Woods-Saxon shape. According to [13]. If we consider

$$V(r) = \frac{V_o}{1 + \exp\left(\frac{r - R_o}{a_o}\right)} \quad (5)$$

and

$$W(r) = \frac{W_o}{1 + \exp\left(\frac{r - R_o}{a_o}\right)} \quad (6)$$

for the volume terms, there are six free parameters in the fit. In this parameterization, $R_i = r_i A^{1/3}$ where A is mass number and the fitted parameter is r_i . The surface term is defined by the derivative of a Woods- Saxon shape and is typically purely imaginary.

3.0 METHOD

After downloading the NRV Browser source code from (link : <http://nrv.iinr.ru/nrv/>) or *Installation Guide Documentation* for Nuclear Reactions Video and extracting together with the data libraries with the set of components. In order to do the simulation, the geometry should be defining first using nuclear reactions.[7] Plate 1 below is the front page of NRV web where we are going to select the nuclear transfer reaction that will take us to plate 2 for modification of parameters . If all parameters are set from table 1 together with deuteron energies, the cross section calculation may be started by pressing the Calculate button. In this case the input data as well as the entered experimental data are sent to the NRV server and stored in the user folder. On the basis of these parameters the NRV server prepares the input file and runs the DWUCK5 code on the server side. DWUCK5 is designed to calculate the differential cross-sections and other observables for direct nuclear reactions particularly transfer reactions. It uses the Distorted Wave Born Approximation (DWBA) framework to model these reactions.[14] After the calculation the server passes the results to the Java applet located on the left side of the web dialog. The results are shown by the solid curve together with the experimental data. The integrated transfer reaction cross section is also shown in the plot. The user may open an additional Java window with the differential cross section by clicking the corresponding Java applet. This window is shown in plate 1. The plot in this window is the same as the plot in the web dialog, but provides additional options allowing processing the data using the menu items. [13]

Table 1: List of Woods Saxon optical model parameters used in DWBA calculation for the entrance and exit channels.

particals	V MeV	r_o fm	a_o fm	W_D MeV	r_w fm	a_w fm	$V_{s.o}$ MeV	$a_{s.o}$ fm	r_c fm
D	-107	1.05	0.85	-13.25	1.43	0.7	0	0.75	1.3
P	-55.67	1.17	0.75	-10.35	1.35	0.57	-6.2	0.75	1.25



Plate 1: selection of nuclear transfer reaction.

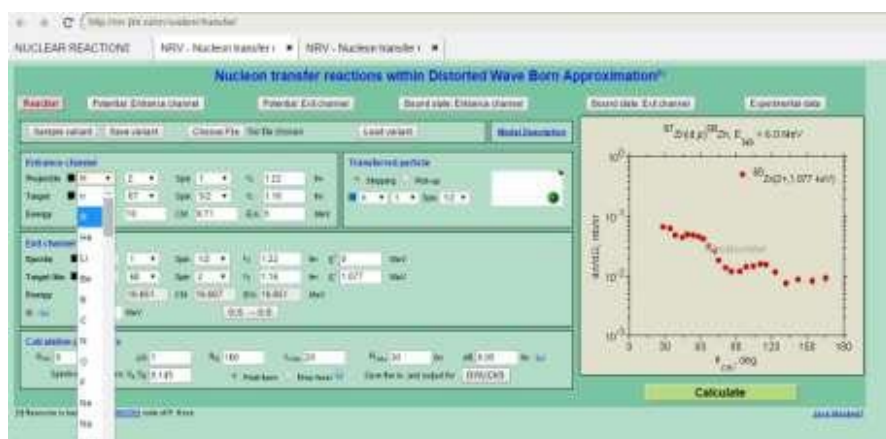


Plate 2: Modification of parameters.

3.1 Data Analysis

The data of this work has been arranged in orders and organized by using tabulation method. DWBA is a theoretical approach used to analyze scattering processes, particularly in nuclear physics. It involves approximating the interaction between a projectile and a target nucleus using distorted wave functions. The first step in data analysis is to set up the theoretical model based on DWBA principles, defining the potential and interaction parameters. Collect experimental data from scattering experiments. This might include cross-sections, angular distributions, and other observables that provide insight into the interaction between particles. Compute the distorted waves for both the incoming and outgoing particles. These waves account for the interactions between the particles and the nucleus, incorporating the effects of the potential that distorts the waves compared to free-particle behavior. Use the DWBA model to calculate theoretical cross-sections and angular distributions based on the distorted wave functions. This involves solving the Schrödinger equation with the appropriate boundary conditions and interaction potentials. Compare the theoretical predictions from DWBA with the experimental data. This step involves fitting the model to the data to determine the best set of parameters, such as potential strengths and angular momentum couplings. Extract meaningful parameters from the comparison. These might include spectroscopic factors information, interaction potentials, and coupling constants. This step helps in understanding the underlying physical processes and properties of the nuclei involved. Assess the uncertainties and reliability of the extracted parameters. This involves examining how sensitive the results are to changes in the model parameters and assessing the quality of the fit. Finally, the user may save the data in the text or graphics formats, plot the cross section vs. scattering angle in c.m. or lab. System. and described graphically with the help of spreadsheet (Microsoft Excel) or *SciDAvis*.

4.0 RESULTS AND DISCUSSIONS

The results of Bound state energy, calculated theoretical and experimental cross-sections obtained through DWBA simulation for (d,p) transferred particles with various selected target materials accompanied by the corresponding deuteron incident energies.

Table 2: Reaction parameters: The below table give the result of the transfer reaction of ^{12}C (d,p) ^{13}C at the deuteron energies of 28.5MeV and 30MeV. The excitation energy at ground state (g.s) is zero and target like spin at $3/2^+$. However; the energies between entrance and exits channels are changes due reaction processes.

Reaction	$^{12}\text{C} (d,p) ^{13}\text{C}$			
Channels	Entrance channels	Exits channels	Entrance channels	Exits channels
Projectile/Ejectile	^2H	^1H	^2H	^1H
Target/T/like	^{12}C	^{13}C	^{12}C	^{13}C
E_{lab} MeV	28.5	29.239	30	30.624
$E_{\text{c.m}}$ MeV	24	26.722	25.714	28.436
E/A MeV	14.25	29.239	15	30.624
Q-value MeV	-	2.722	-	2.722
E^* MeV	-	0	-	0
Target/T/like spin	2	3/2	2	3/2

Table 3: Bound State: Particles transferred in the entrance and exit channels together with wave function in every state and interaction potential.

Reaction	Entrance channel: Transferred particles: $^2\text{H}_{(1)} \rightarrow ^1\text{H}_{(1/2)} + n_{(1/2)}$			Exit channels: Transferred particles: $^{13}\text{C}_{(3/2)} \rightarrow ^{12}\text{C}_{(2)} + n_{(1/2)}$		
Wave function	state	Interaction potential (Gaussian)		state	Interaction potential (W.S Volume)	
J_{tr}	$\frac{1}{2}$	V_0 MeV	-55.39	$3/2+$	V_0 MeV	-105.936
L_{tr}	0	r_v fm	1.75	1	r_v fm	1.25
S_{tr}	$\frac{1}{2}$	R_v fm	1.75	$\frac{1}{2}$	R_v fm/ a_v fm	2.862/0.65
N_{tr}	1	r_c fm	1.25	2	r_c fm	1.25
E_{bound} MeV	-2.225	R_c fm	1.25	-4.946	R_c fm	2.862

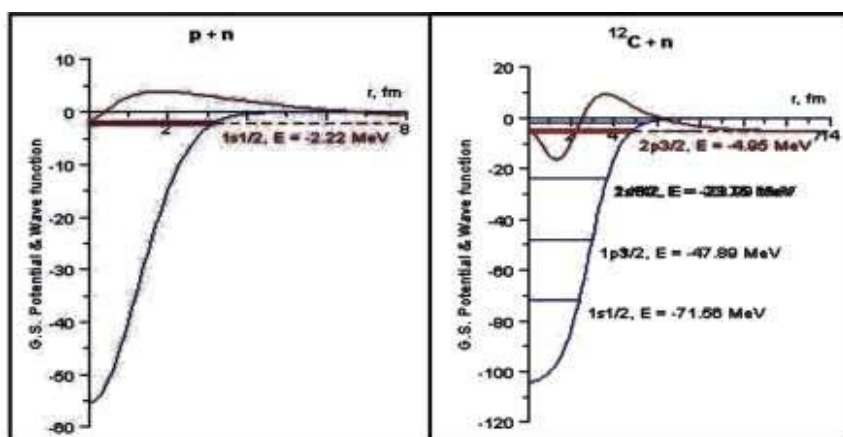


Fig. 1: Graph of bound state energies of entrance and exit channels for the particle transferred.

The transferred particle of deuteron that gives $p + n$ produce E_{bound} of -2.22MeV at the shell models of $1s_{1/2}$ in the entrance channels while ^{13}C gives $^{12}\text{C} + n$ with E_{bound} of -4.95MeV at the shell models of $2p_{3/2}$ in the exit channels.

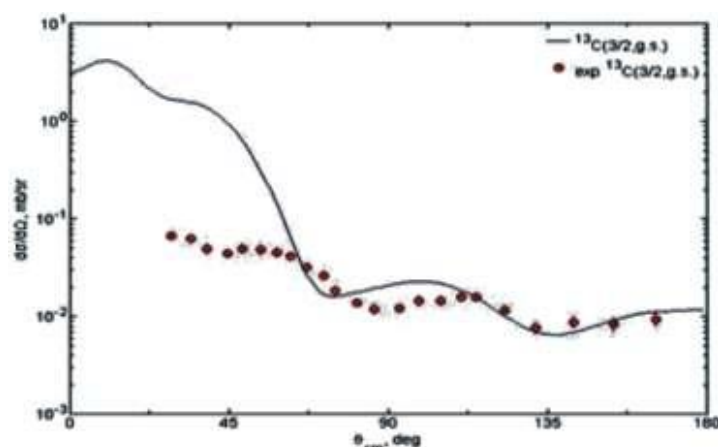


Fig. 2: Experimental (scatter points) and calculated angular distributions of the $^{12}\text{C}(\text{d},\text{p})^{13}\text{C}$ (3/2 g.s) at E_{lab} of 28.5MeV. The solid curves refer to the theoretical cross section of finite-range DWBA calculation.

Figure 2 show $^{12}\text{C}(\text{d},\text{p})^{13}\text{C}$ at 28.5MeV reaction. The experimental and theoretical transfer reactions produce the same Ejectile, target like spin and excitation energy at ground state of ^{13}C (3/2,0.0 MeV). After calculation both experimental and theoretical reactions provided differential cross sections and scattering angle(emitting angle of the detected particle measured) as shown above, the experimental (scatter point) and theoretical (solid curve) cross section of finite range DWBA calculation are compared. The overlap between experimental and theoretical transfer reaction initially at angle 66° with uncertainty 26% which yield the total cross section (σ_{tr}) of 4.37mb and spectroscopy factors of 0.695. All things considered, an uncertainty of the order of $\pm 30\%$ in the value of an absolute spectroscopic factor is not unreasonable[15] and appears to evaluate with fair agreement between the theory and experiment for validating the theoretical model.

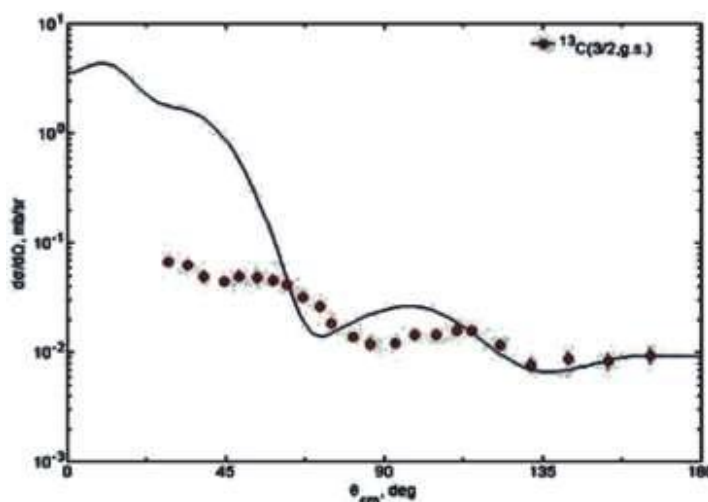


Fig.3: Experimental (scatter points) and calculated angular distributions of the $^{12}\text{C}(\text{d},\text{p})^{13}\text{C}$ (3/2 g.s) at E_{lab} of 30MeV. The solid curves refer to the theoretical cross section of finite-range DWBA calculation.

Figure 3 show $^{12}\text{C}(\text{d},\text{p})^{13}\text{C}$ at 30MeV reaction. The experimental and theoretical transfer reactions produce the same Ejectile, target like spin and excitation energy at ground state

of ^{13}C (3/2,0.0 MeV). After calculation both experimental and theoretical reactions provided differential cross sections and scattering angle (emitting angle of the detected particle measured) as shown above, the experimental (scatter point) and theoretical (solid curve) cross section of finite range DWBA calculation are compared. The overlap between experimental and theoretical transfer reaction initially at angle 62° with uncertainty of 21% which yield the total cross section (δ_{tr}) of 4.58mb and spectroscopy factors of 0.678. All things considered, an uncertainty of the order of $\pm 30\%$ in the value of an absolute spectroscopic factor is not unreasonable[15] and appears to evaluate with fair agreement between the theory and experiment for validating the theoretical model.

Table 4: Reaction parameters The below table give the result of the transfer reaction of $^{24}\text{Mg}(\text{d,p})^{25}\text{Mg}$ at the deuteron energies of 28.5MeV and 30MeV. The excitation energy at ground state (g.s) also zero and target like spin at $3/2^+$. However; the energies between entrance and exits channels are changes due reaction processes.

Reaction	$^{24}\text{Mg}(\text{d,p})^{25}\text{Mg}$			
Channels	Entrance channels	Exits channels	Entrance channels	Exits channels
Projectile/Ejectile	^2H	^1H	^2H	^1H
Target/T/like	^{24}Mg	^{25}Mg	^{24}Mg	^{25}Mg
E_{lab} Mev	28.5	32.67	30	34.11
$E_{c.m}$ Mev	26.308	31.414	27.692	32.798
E/A Mev	14.25	32.67	15	34.11
Q-value Mev	-	5.106	-	5.106
E^* MeV	-	0	-	0
Target /T/like spin	2	3/2	2	3/2

Table 4: Bound State: Particles transferred in the entrance and exit channels together with wave function in every state and interaction potential.

Reaction	Entrance channel: Transferred particles: $^2\text{H}_{(1)} \rightarrow ^1\text{H}_{(1/2)} + n_{(1/2)}$			Exit channels: Transferred particles: $^{25}\text{Mg}_{(3/2)} \rightarrow ^{24}\text{Mg}_{(2)} + n_{(1/2)}$		
Wave function	state	Interaction potential (Gaussian)		state	Interaction potential (W.S Volume)	
J_{tr}	$1/2$	V_o MeV	-55.39	$3/2^+$	V_o MeV	-76.726
L_{tr}	0	r_v fm	1.75	1	r_v fm	1.25
S_{tr}	$1/2$	R_v fm	1.75	$1/2$	R_v fm/ a_v fm	3.606/0.65
N_{tr}	1	r_c fm	1.25	2	r_c fm	1.25
E_{bound} MeV	-2.225	R_c fm	1.25	-7.331	R_c fm	3.606

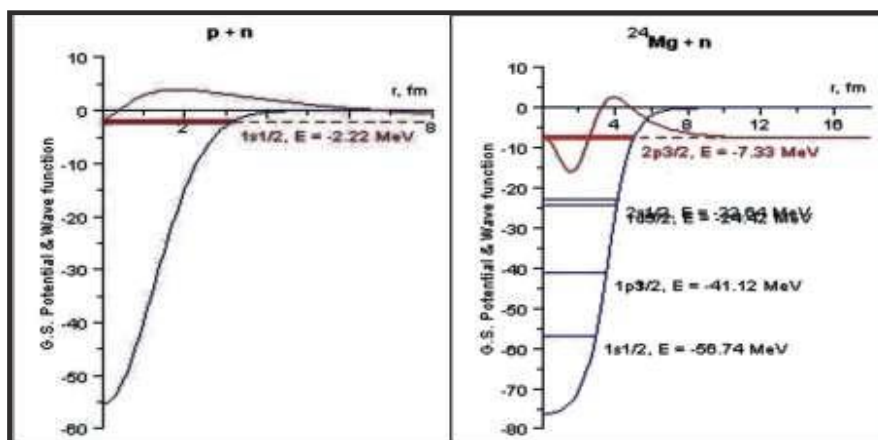


Fig. 4: Graph of bound state energies of ground state potential and wave function over radius $r(\text{fm})$ at entrance and exit channels for the particle transferred.

The transferred particle of deuteron that gives $p + n$ produce E_{bound} of -2.22MeV at the shell models of $1s_{1/2}$ in the entrance channels while ^{25}Mg gives $^{24}\text{Mg} + n$ with E_{bound} of -7.33MeV at the shell models of $2p_{3/2}$ in the exit channels.

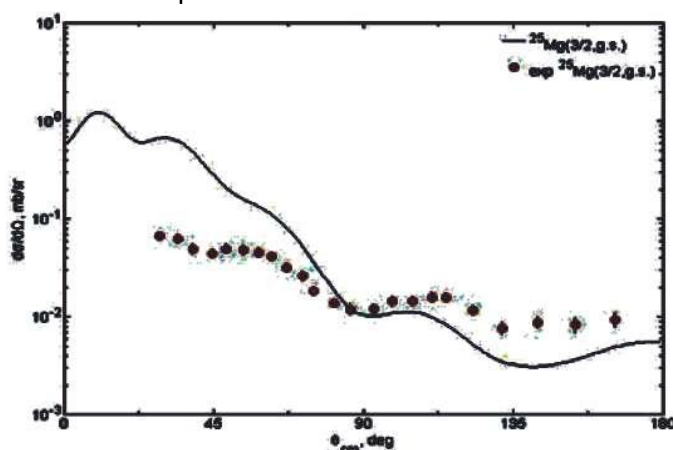


Fig. 5: Experimental (scatter points) and calculated angular distributions of the $^{24}\text{Mg}(d,p)^{25}\text{Mg}$ ($3/2 \text{ g.s.}$) at the E_{lab} of 28.5MeV . The solid curves refer to the theoretical cross section of finite-range DWBA calculation.

Figure 5 show $^{24}\text{Mg}(d,p)^{25}\text{Mg}$ at 28.5MeV reaction. The experimental and theoretical transfer reactions produce the same Ejectile, target like spin and excitation energy at ground state of $^{25}\text{Mg}(3/2, 0.0 \text{ MeV})$. After calculation both experimental and theoretical reactions provided differential cross sections and scattering angle (emitting angle of the detected particle measured) as shown above, the experimental (scatter point) and theoretical (solid curve) cross section of finite range DWBA calculation are compared. The overlap between experimental and theoretical transfer reaction initially at angle 86° with uncertainty of 4% which yield the cross section (δ_{tr}) of 1.60mb and spectroscopic factors of 0.291 . All things considered, an uncertainty of the order of $\pm 30\%$ in the value of an absolute spectroscopic factor is not unreasonable[15] and appear to show disagreement between the theory and experiment for validating the theoretical model.

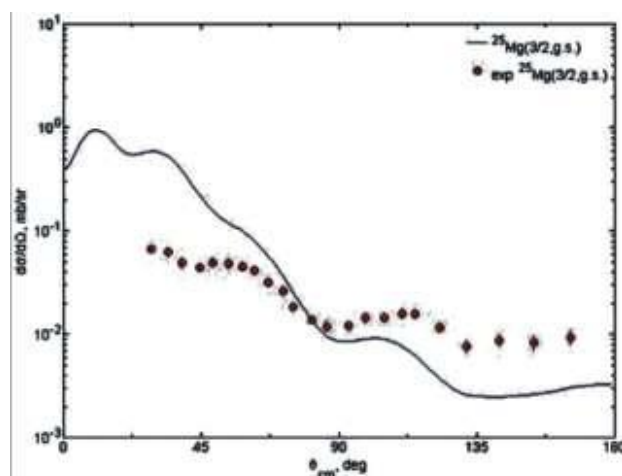


Fig 6: Experimental (scatter points) and calculated angular distributions of the $^{24}\text{Mg}(d,p)^{25}\text{Mg}$ (3/2 g.s) at the E_{lab} of 30MeV. The solid curves refer to the theoretical cross section of finite-range DWBA calculation.

Figure 6 show $^{24}\text{Mg}(d,p)^{25}\text{Mg}$ at 30MeV reaction. The experimental and theoretical transfer reactions produce the same Ejectile, target like spin and excitation energy at ground state of $^{25}\text{Mg}(3/2,0.0 \text{ MeV})$. After calculation both experimental and theoretical reactions provided differential cross sections and emitting angle of the detected particle measured as shown above, the experimental (scatter point) and theoretical (solid curve) cross section of finite range DWBA calculation are compared. The overlap between experimental and theoretical transfer reaction at angle 81° with uncertainty of 4% which yield the total cross section (σ_{tr}) of 1.28mb and spectroscopic factors of 0.250 All things considered, an uncertainty of the order of $\pm 30\%$ in the value of an absolute spectroscopic factor is not unreasonable[15] and appear to show disagreement between the theory and experiment for validating the theoretical model.

4.2 CONCLUSION

The research focused on calculating the differential cross sections and spectroscopic factors for the reactions involving ^{12}C and ^{24}Mg at deuteron energies of 28.5 MeV and 30 MeV, respectively. The analyzed reaction model (DWBA) and experimental have been compared. The differential cross sections and spectroscopic factors for the reactions ^{12}C are 5.10mb and 0.695, with uncertainty of 26%, then 4.58mb and 0.678 with uncertainty of 21%. The result $^{12}\text{C}(d,p)^{13}\text{C}$ appear to evaluate with fair agreement between the theory and experiment for validating the theoretical model. In the case of ^{24}Mg are 1.60mb and 0.291 with uncertainty of 4% , than 1.28mb and 0.250 with uncertainty of 4%. The result $^{24}\text{Mg}(d,p)^{25}\text{Mg}$ appear to show disagreement between the theory and experiment for validating the theoretical model. In conclusion the future research will be obtained the differential cross sections and spectroscopic factors of ^{24}Mg at the E_{lab} of 28.5 and 30MeV with appropriate direct reaction models.

4.3 CONTRIBUTION TO THE KNOWLEDGE

Researchers often use such comparisons to validate theoretical models and gain insights into the nuclear structure and dynamics involved in specific reactions, contributing to our understanding of nuclear physics

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