

## Recommended Cross Sections and Optical Potential of Dy Isotopes for Neutron Induced Reactions at 14.0 MeV

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**ABSTRACT.** The evaluation is based mainly on the calculations of the nuclear optical model potential and the relevant parameters which are collected and selected from References Input Parameter Library (RIPL-3) which is being developed under the international project coordinated by the International Atomic Energy Agency (IAEA). The analyzing of a complete energy range has been done starting from threshold energy for each reaction. The cross sections are reproduced in fine steps of incident neutron energy with 0.01MeV intervals with their corresponding errors. The recommended cross sections for available experimental data taken from EXFOR library have been calculated for all the considered neutron induced reactions for Dy ( $Z=66$ ;  $A=162-164$ ) isotopes. The calculated results are analyzed and compared with the experimental data. The optimized optical potential model parameters give a very good agreement with the experimental data over the energy range 13.4-14.87MeV for neutron induced cross section reactions (n,p) for spherical Dy-162 target element, (n,2H), (n,d), (n,n+p), and (n,p) for spherical Dy-163 target element, and (n,2H) and (n,p) for spherical Dy-164 target element.

### 1. INTRODUCTION

The excitation functions in (n,p), (n,n+p), (n,d), (n,2H) reactions measured for Dy ( $Z=66$ ,  $A=162-164$ ) with the aid of EXFOR library have been evaluated in the present work for the exact estimation of the cross sections among different authors. This paper describes the standard optical model potential analyses of the spherical Dy ( $Z=66$ ,  $A=162-164$ ) target elements up to 14.0MeV. The present paper also describes the background of the References Input Parameter Library (RIPL-3) used for input parameters. These data are used in the real and imaginary part of optical model potential-special emphasis is placed in this study on the isotopes dependence of the optical model potential. The systematic of such reactions, neutron induced reactions was discussed in Junhua Luo et al. (2009) [1], Kannan and Ganesan (2010) [2], Kadenko (2013) and Koning (2013) [4]. The present work concerns the induced neutron cross section reactions. Recommended formulas for the evaluation of cross sections for these reactions were derived using EXFOR experimental data for different authors describing the emission or neutron capture in nuclear reactions. The parameters of formulas were fitted with minimum chi squared from the analysis of available experimental data. One the whole, the results of calculations of optical potential are in best agreement with experimental data.

### 2. RECOMMENDED CROSS SECTION

The available measured data from EXFOR library for the cross section of the above mentioned reactions measured for Dy ( $Z=66$ ,  $A=162-164$ ) have been plotted, interpolated and recalculated in different fine steps and for different energy ranges of incident neutron by using Matlab-8.1 in order to calculate the recommended cross section for each mentioned reaction. This can be described in the following steps:

1- The interpolations for the nearest data for each energy interval as a function of cross sections and their corresponding errors have been done using Matlab-8.1.

- 2- The sets of experimental cross sections data are collected for different authors and with different energy ranges. The cross sections with their corresponding errors for each value are re-arranged according to the energy interval 0.01MeV for available different energy range for each author.
- 3- The normalization for the statistical distribution of cross sections errors to the corresponding cross section values for each author has been done.
- 4- The interpolated values are calculated to obtain the recommended cross section which is based on the weighted average calculation according to the following expressions [5]:

$$\sigma_{w.a.} = \frac{\sum_{i=1}^n \frac{\sigma_i}{(\Delta\sigma_i)^2}}{\sum_{i=1}^n \frac{1}{(\Delta\sigma_i)^2}} \quad (1)$$

Where the standard deviation error is:

$$S.D. = \frac{1}{\sqrt{\sum_{i=1}^N \frac{1}{(\Delta\sigma_i)^2}}} \quad (2)$$

Where  $\sigma_i$  : is the cross section value.  $\Delta\sigma_i$  : is the corresponding error for each cross section value. Figs. 1 to 4 illustrate the recommended cross sections for the above mentioned reactions as calculated in the present work compared with EXFOR library. It is clear in the caption of each figure, the refry of authors name are arranged according to the year of measured data are listed with the present calculated recommended cross section. The results are in good agreement with the measured data.

### 3. BACKGROUND OF (RIPL-3)

The Reference Input Parameter Library (RIPL-3) is being developed under the international project coordinated by the International Atomic Energy Agency (IAEA). The practical use of nuclear reactions requires a considerable numerical input that describes properties of the nuclei and interactions involved. The (RIPL-3) represents a fairly comprehensive set of such parameters, collected and selected from sources all over the world. The (RIPL) contains input parameters for theoretical calculations of nuclear reaction cross sections. The library is targeted at users of nuclear reaction interested in nuclear applications [6].

### 4. OPTICAL MODEL POTENTIAL

In the frame of the optical model, all the interactions between the nucleons of the projectile and the nucleons of the target are replaced by an average and central interaction  $V(v)$  between the projectile and the target in their ground states. The nuclear optical model used to describe the interaction between two nuclei is inspired by the optical phenomenon. The nuclear medium diffracts one part of the incident wave which models the incident particle and another part of the wave is refracted [7].

As the nucleon-nucleon interaction is a short range interaction, the potential  $V_v \times f_v(r, r_v, a_v)$  which is approximately the sum of nucleon-nucleon interactions, has the same behavior. The nucleons in the core of the nucleus undergo only the interaction with their closest neighbors. Due to this saturation of the nuclear forces,  $V_v \times f_v(r, r_v, a_v)$  is uniform inside the nucleus and then decreases exponentially in the surface region [8]. The present evaluations are based mainly on the calculations of the optical model potential. A standard form of the optical model potential and relevant parameters used in the present work contains volume, surface, and spin-orbit parts, each having real and imaginary components. This potential can be written as follows [9,10,11]:

$$\begin{aligned}
V(r,E) = & -V_v \times f_v(r, r_v, a_v) \\
& + i \left\{ 4 \times a_{ws} \times W_s \times \left[ \frac{df_s(r, r_{ws}, a_{ws})}{dr} \right] - W_g \times \exp(-X_g^2) - W_v \times f_v(r, r_{wv}, a_{wv}) \right\} \\
& + \frac{\lambda_\pi^2}{r} \times \left\{ V_{so} \times \left[ \frac{df_{so}(r, r_{vso}, a_{vso})}{dr} \right] + i W_{so} \times \left[ \frac{df_{so}(r, r_{wso}, a_{wso})}{dr} \right] \right\} \times \left( \vec{\ell} \cdot \vec{s} \right)
\end{aligned} \quad (3)$$

In equation 3  $V_v$  and  $W_v$  are the real and imaginary volume potential well depths,  $W_s$  is the well depth for the surface derivative term,  $W_g$  is the well depth for the global nucleon-nucleon optical potential,  $V_{so}$  and  $W_{so}$  are the real and imaginary well depths for the spin-orbit potential, and  $\lambda_\pi^2$  is the pion Compton wavelength squared ( $\cong 2$ ). The quantity  $\vec{\ell} \cdot \vec{s}$  is the scalar product of the orbital and intrinsic angular momentum operators and is given by [9]:

$$\vec{\ell} \cdot \vec{s} = \ell \quad \text{for } j = \ell + \frac{1}{2} \quad (4)$$

$$\vec{\ell} \cdot \vec{s} = -(\ell + 1) \quad \text{for } j = \ell - \frac{1}{2} \quad (5)$$

The  $f_i(r, r_i, a_i)$  is radial-dependent form factors. The real potential, imaginary potential and form factors are defined below [9]:

**a. Real Potential:**  $V_v, V_{so}$  are the depths of real potential in (MeV) taken from (RIPL-3), as shown in Table 1. (Hint: We select the energy at maximum value of the obtained recommended cross section for different reactions for selected isotopes).

**b. Imaginary Potential:**  $W_s, W_v, W_g, W_{so}$  are the depths of imaginary potential in (MeV) taken from (RIPL-3), as shown in Table 1.

**c. Form Factor:** Wood–Saxon form factor is permitted for  $f_i(r, r_i, a_i)$  terms in equation 3 are as follows:

$$f_i(r, r_i, a_i) = \frac{1}{[1 + \exp(X_i)]} \quad ; \text{ With } i = v, s, g, so \text{ (Wood–Saxon form factor)} \quad (6)$$

$$\text{Where } X_i = (r - R_i) / a_i \quad ; \text{ With } i = v, s, g, so \quad (7)$$

$r$  is the radial distance in (fm) and  $a_i$  is the diffuseness.

The nuclear radius  $R_i$  is given by:

$$R_i = r_i \times A^{\frac{1}{3}} + r_c \quad (8)$$

Where:  $r_c$  is the coulomb radius;  $r_v, r_{ws}, r_{wv}, r_{vso}$  and  $r_{wso}$  are the geometry parameters of real and imaginary potentials in (fm) taken from (RIPL-3). The optical potential poten.m program has been built in the present work using Matlab-8.1. The aim of this program is to calculate the real and imaginary optical potential as a function of radial distance and the energy of induced neutron for spherical 66Dy target isotopes.

## 5. RESULTS AND DISCUSSION

The energy dependence of the neutron potential based on the dysprosium isotopes ( $Z=66, A=162-164$ ) is  $E=13.4-14.87\text{MeV}$  for spherical 66Dy isotopes nuclei, which are included in the present

calculations to cover the same energy range for the same targets charge and mass. The optical model potential (OMP) parameters are including in the (RIPL-3) optical file coordinated research project. The parameters for optical model potential used in this work are tabulated in Table 1, for spherical  $^{66}\text{Dy}$  target elements. The global potentials are calculated for systematic utilization of nuclear radial distance  $r=1$  to  $20\text{fm}$  as well as real and imaginary potentials.

This model represents the scattering in terms of a complex potential  $V(r,E)$ , see equation 3, where the functions  $V$  and  $W$  are selected to give the potential its proper radial dependence. The real part,  $V$ , is responsible for the elastic scattering; it describes the ordinary nuclear interaction between target and projectile and may therefore be very similar to a shell model potential. The imaginary part,  $W$ , is responsible for the absorption.

The usual optical potential for  $^{66}\text{Dy}$  isotopes has a real optical depth  $V_v$  of the order of  $41.9\text{MeV}$  with radius of the real depth  $r_v=1.27\text{fm}$  and diffuseness  $a_v=0.62$ , also the spin orbit potential  $V_{so}=6.4\text{MeV}$  with radius  $r_{vso}=1.27\text{fm}$  and diffuseness  $a_{vso}=0.62$ . The imaginary optical depths for these isotopes are  $W_s=10.8\text{MeV}$  and  $W_v=1.7\text{MeV}$  with radiuses  $r_{ws}=1.36\text{fm}$  and  $r_{wv}=1.27\text{fm}$  with diffuseness  $a_{ws}=0.5\text{fm}$  and  $a_{wv}=0.62\text{fm}$ , at  $14.0\text{MeV}$  incident neutron energy.

The radial distance is to be at most of the order of the  $r=1:20\text{fm}$  and the energy of incident neutrons have been taken at maximum value of the obtained recommended cross section. All parameters used in this work for optical model potential have been taken from (RIPL-3) library [10]. Table 1, shows these parameters for dysprosium ( $Z=66$ ,  $A=162-164$ ). Fig. 5 shows the optical model potential for dysprosium target element induced by neutrons, in which absorption  $W$  is relatively weaker than elastic scattering  $V$ . The absorptive part,  $W$ , at low energies must have a very different form.

Because of the exclusion principle, the tightly bound nucleons in the nuclear interior cannot participate in absorb the relatively low energy carried by the incident particle. The optical potential is thus often has the proper shape of being large only near the surface, as shown in Fig. 5. At higher energy, where the inner nucleons can also participate in absorption,  $W$ , may look more like  $V$ . A spin – orbit term is also included in this optical potential. It is also peaked near the surface, because the spin density of the inner nucleons vanishes. A Wood – Saxon form factor is also included. The calculation using the optical model potential, as described in this work, does not deal with where the absorbed particles actually go; they simply disappear from the elastic channel.

## 6. CONCLUSIONS

We have evaluated the neutron induced nuclear cross section data of spherical dysprosium isotopes for considerable energy ranges. The calculated recommended cross sections are in good agreement with experimental data. The reliability in this work is to estimate the global optical parameters chosen for the energy  $E=14.0\text{MeV}$  from RIPL-3 library for spherical  $^{66}\text{Dy}$  ( $A=162-164$ ) isotopes target elements of neutron induced reactions. The results confirm that the global optical potential parameters are appropriate for these calculations. Hence, the optical model potential is successful in accounting for neutron induced reactions and leads to an understanding of the nucleon-nucleon interactions.

## Acknowledgments

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Table 1 Optical potential parameters used for spherical dysprosium (A=162-164) from RIPL-3 Library, with energy range 0.001-20MeV. Hint:  $W_g = W_{so} = 0.00\text{MeV}$  and  $r_{wso} = r_c = a_{wso} = 0.00\text{fm}$  [10].

Energy (MeV)	$V_v$ (MeV)	$r_v$ (fm)	$a_v$ (fm)	$W_v$ (MeV)	$r_{wv}$ (fm)	$a_{wv}$ (fm)	$W_s$ (MeV)	$r_{ws}$ (fm)	$a_{ws}$ (fm)	$V_{so}$ (MeV)	$r_{vso}$ (fm)	$a_{vso}$ (fm)
0	46.0	1.27	0.62	0.0	1.27	0.62	14.0	1.36	0.5	7.0	1.27	0.62
1	45.7	1.27	0.62	0.1	1.27	0.62	13.8	1.36	0.5	7.0	1.27	0.62
2	45.4	1.27	0.62	0.3	1.27	0.62	13.5	1.36	0.5	6.9	1.27	0.62
3	45.1	1.27	0.62	0.4	1.27	0.62	13.3	1.36	0.5	6.9	1.27	0.62
4	44.8	1.27	0.62	0.5	1.27	0.62	13.1	1.36	0.5	6.8	1.27	0.62
5	44.5	1.27	0.62	0.6	1.27	0.62	12.8	1.36	0.5	6.8	1.27	0.62
6	44.2	1.27	0.62	0.7	1.27	0.62	12.6	1.36	0.5	6.7	1.27	0.62
7	43.9	1.27	0.62	0.9	1.27	0.62	12.4	1.36	0.5	6.7	1.27	0.62
8	43.6	1.27	0.62	1.0	1.27	0.62	12.1	1.36	0.5	6.6	1.27	0.62
9	43.3	1.27	0.62	1.1	1.27	0.62	11.9	1.36	0.5	6.6	1.27	0.62
10	43.0	1.27	0.62	1.2	1.27	0.62	11.7	1.36	0.5	6.5	1.27	0.62
11	42.7	1.27	0.62	1.4	1.27	0.62	11.4	1.36	0.5	6.5	1.27	0.62
12	42.4	1.27	0.62	1.5	1.27	0.62	11.2	1.36	0.5	6.5	1.27	0.62
13	42.1	1.27	0.62	1.6	1.27	0.62	11.0	1.36	0.5	6.4	1.27	0.62
14	41.9	1.27	0.62	1.7	1.27	0.62	10.8	1.36	0.5	6.4	1.27	0.62
15	41.6	1.27	0.62	1.8	1.27	0.62	10.6	1.36	0.5	6.3	1.27	0.62
16	41.3	1.27	0.62	1.9	1.27	0.62	10.3	1.36	0.5	6.3	1.27	0.62
17	41.0	1.27	0.62	2.1	1.27	0.62	10.1	1.36	0.5	6.2	1.27	0.62
18	40.7	1.27	0.62	2.2	1.27	0.62	9.9	1.36	0.5	6.2	1.27	0.62
19	40.5	1.27	0.62	2.3	1.27	0.62	9.7	1.36	0.5	6.2	1.27	0.62
20	40.2	1.27	0.62	2.4	1.27	0.62	9.5	1.36	0.5	6.1	1.27	0.62

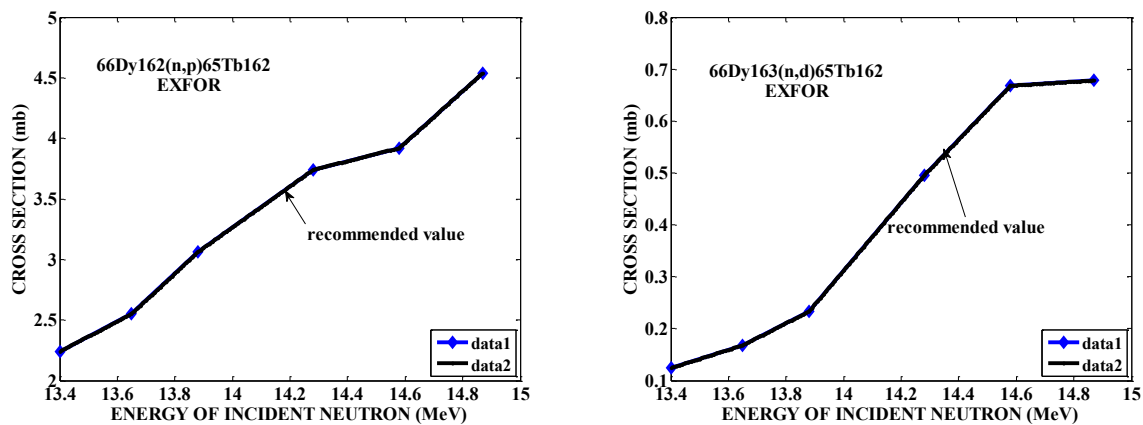


Fig. 1. Recommended cross section compared with EXFOR Library versus the energy of incident neutron. Left side: for  $^{162}\text{Dy}(n,p)^{162}\text{Tb}$  reaction; Data 1:[12]Sakane et al.(1997). Data 2: present work. Right side: for  $^{163}\text{Dy}(n,d)^{162}\text{Tb}$  reaction; Data 1: [13]Sakane et al.(1996). Data 2: present work.

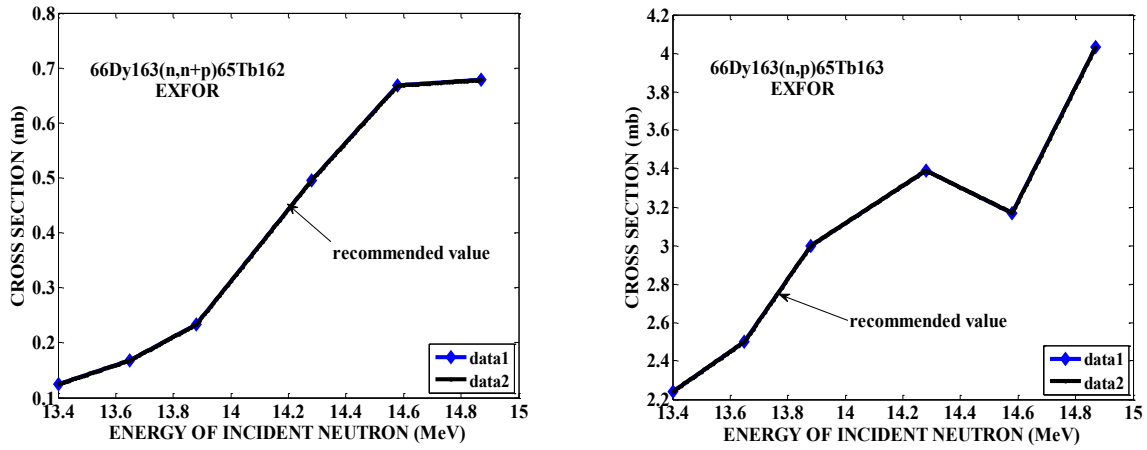


Fig. 2. Recommended cross section compared with EXFOR Library versus the energy of incident neutron. Left side: for  $^{163}\text{Dy}(n,n+p)^{162}\text{Tb}$  reaction; Data 1: [13] Sakane et al.(1996). Data 2: present work. Right side: for  $^{163}\text{Dy}(n,p)^{163}\text{Tb}$  reaction; Data 1: [12] Sakane et al.(1997). Data 2: present work.

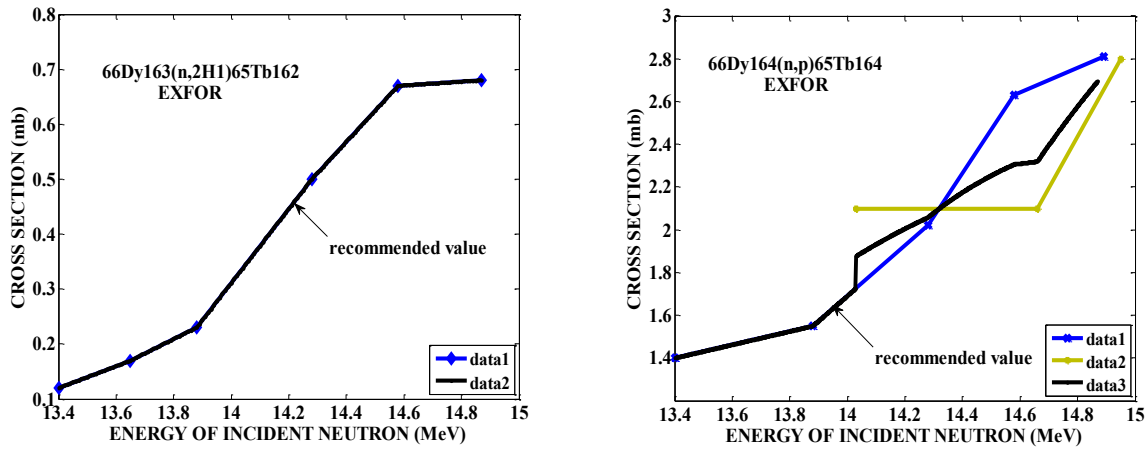


Fig. 3. Recommended cross section compared with EXFOR Library versus the energy of incident neutron. Left side: for  $^{163}\text{Dy}(n,2\text{H})^{162}\text{Tb}$  reaction; Data 1: [14] Skane et al.(2002). Data 2: present work. Right side: for  $^{66}\text{Dy}^{164}(n,p)^{65}\text{Tb}^{164}$  reaction; Data 1: [12] Sakane et al.(1997). Data 2: [15] Kasugai et al. (1997).Data 3: present work.

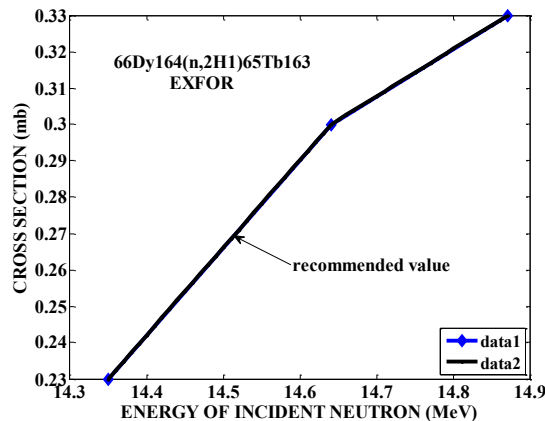
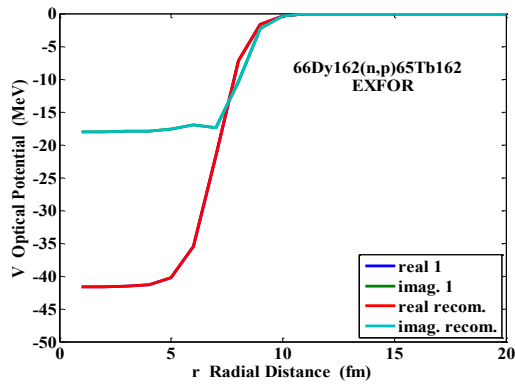
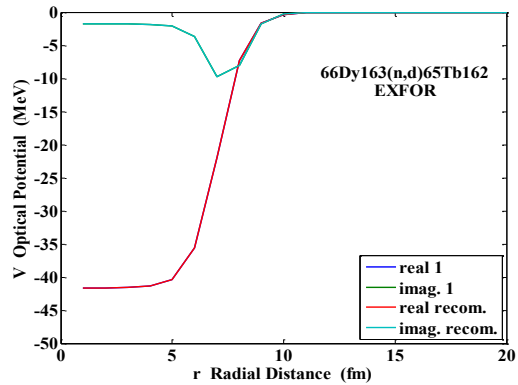


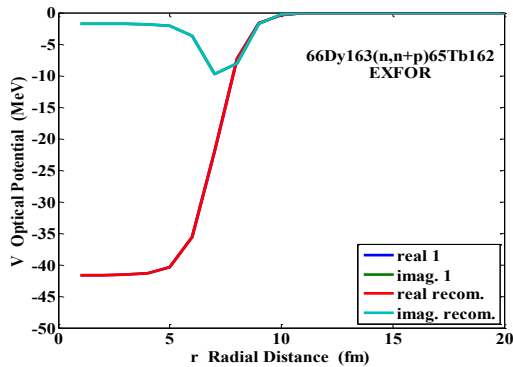
Fig. 4. Recommended cross section compared with EXFOR Library versus the energy of incident neutron, for  $^{164}\text{Dy}(n,2\text{H})^{163}\text{Tb}$  reaction; Data 1: [14] Sakane et al. (2002). Data 2: present work.



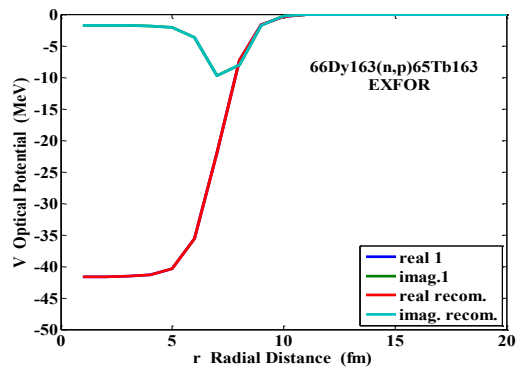
No.1 related to Data1 in the left side of Fig. 1.



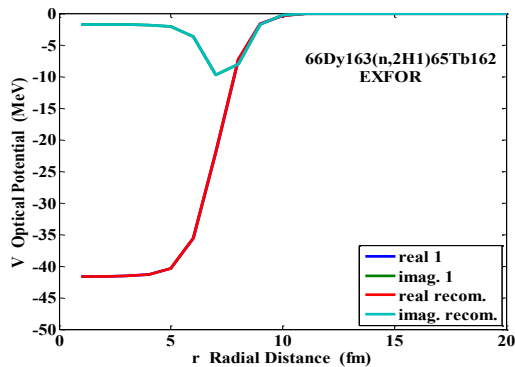
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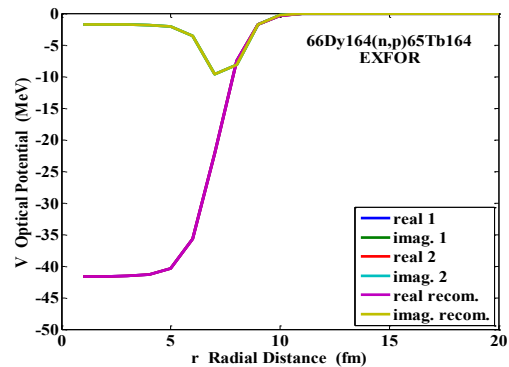
No.1 related to Data1 in the left side of Fig. 2.



No.1 related to Data1 in the right side of Fig. 2.

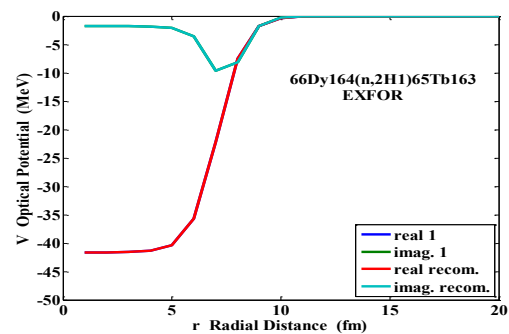


No.1 related to Data1 in the left side of Fig. 3.



No.1&2 related to Data1 & Data2 in the right side of Fig. 3.

Fig. 5. The Optical Model Potential of neutron induced reaction on spherical Dy ( $Z=66$ ,  $A=162-164$ ) calculated in the present work as a function of radial distance. Typical parameters chosen are taken for energy 14.0MeV (RIPLE-3 Library).



No.1 related to Data1 in Fig. 4.

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