Cross Section Evaluation of the *(n,α)* Reaction with Fast Neutrons on ^{64}Zn and ^{147}Sm Using the Hauser Feshbach Approach

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Abstract. In the (n,α) reactions induced by neutrons with energy about some *MeV* the experimental data are very poor due to the difficulty of the measurement of the cross section. In this energy region of the incident neutrons the cross section is of order of tens *mb* or lower for emission of charged particles. It is supposed for both nuclei that the nuclear reaction is going by formation of an intermediate compound nucleus and this is suggested by the differential cross section experimental data. For the theoretical evaluation it was used the Hauser - Feshbach approach. In this approach it is important to obtain the penetrability for neutron in the entrance channel and for charged particles (proton, alpha) in the exit channels. We have obtained the penetrability starting from quantum mechanical considerations and after that using them for obtaining the cross section. For this purpose we realized computer programs where it was implemented the regular an irregular functions in the integral form without any approximation. The theoretical and experimental evaluations of the ^{64}Zn and ^{147}Sm are important from theoretical point of view, nuclear reactor materials studies and astrophysical researches. Experimental data were measured using a double gridded ionization chambers at electrostatic generators of LNF - JINR Dubna and Institute of Heavy Ions Physics from Pekin University.

INTRODUCTION.

The cross section evaluation in the (n,α) reaction with fast neutrons on the medium and heavy nuclei is important from practical point of view and also from theoretical one.

Due to the (n,p) and (n,α) reactions with fast neutrons in the nuclear reactor takes place an accumulation of Hydrogen and Helium in the walls of the building and vessels. This process depends on these cross sections and will affect the physical properties of the walls and in time will change their mechanical resistance.

The evaluation of the cross sections in the reactions with fast neutrons gives us new information and data about nuclear structure and reaction mechanisms participating in the energy region for incident neutrons.

The knowledge of the fast neutrons cross sections is also important in the astrophysical questions on the generation, concentration and distribution of the elements from Mendeleev Periodical Table in the Universe.

BASICS OF THE HAUSER FESHBACH FORMALISM (HF).

For the evaluation of the cross section in the (n,α) reaction on the ^{64}Zn and ^{147}Sm nuclei with fast neutrons we made the supposition that the reactions are going by formation of a compound nucleus in the frame of the statistical model of the nuclear reaction [1]. Some of the statistical assumptions are: 1) the potential well act in a finite and is zero outside of this range 2) the reaction is going by formation of a compound nucleus (CN), 3) the compound nucleus is characterized by many states as well as the residual nucleus, 4) the compound nucleus has a time of life much greater than the time necessary to the incident particle to pass the nucleus, etc.

Some important consequences of these assumptions are: 1) no interferences in the cross section, 2) the differential cross section is symmetrical around $\theta = 90^0$ ($\theta =$ the polar angle).

A simple comparison between the incident neutron wavelength and the radius of the target nucleus shows us that the neutrons wavelength is greater than the radius of the analyzed nuclei and in the cross section we have contributions only from neutrons with $l=0, 1$.

All mentioned above allows us to use the HF formalism [2]. The cross section in the HF formalism has the expression:

$$\sigma_{n\alpha} = \pi \lambda\!\!\!^{-}{}_n^2 \frac{T_n T_\alpha}{\sum_c T_c} F_{n\alpha}^{fluct} \tag{1}$$

The terms are:

$\lambda\!\!\!^{-}{}_n =$ neutron reduced wave length, $T =$ penetrability coefficient for different particles (PC), $F_{n\alpha}^{fluct}$ = widths correction fluctuation factor (WCF), $c =$ channel.

The penetrability coefficient represents the probability of a particle to pass a potential barrier. In this approach the determination of the penetrability is very important for the particles in the incident channel and for all possible outgoing channels. The summation in (1) is realized over the incident channel and all possible open outgoing channels.

Expression (1) is called the improved HF formula because first time this relation was determined without the WCF factor. In the CN mechanism, according with the Bohr hypothesis the CN “forget” how is formed and therefore the correlation between incident and outgoing channels is zero. However the experience shows that is not always true and WCF factor indicates this correlation. If there is no correlation between the incident and one emergent channel the WFC factor is equal to 1. If some degree of correlation between these channels exits then the WFC factor is less than unity. In the (n,α) reaction induced by fast neutrons, after our evaluation, the WFC factor is practically equal to *1* around *1 MeV* and slowly decreases to *0.8 – 0.7* values for neutrons with *5-6 MeV*.

The PC were determined using the quantum mechanical approach based on the reflection factor (U_l) described in [3].

$$T(l,E) = 1 - \left|U_l(E)\right|^2 \tag{2}$$

$$U_l = \left\{ \frac{D_l - R\left[\frac{1}{W_l^-}\frac{dW_l^-}{dr}\right]}{D_l - R\left[\frac{1}{W_l^+}\frac{dW_l^+}{dr}\right]} \frac{W_l^-}{W_l^+} \right\}_{r=R} \tag{3}$$

The terms in the expression (3) are: D_l = derivative logarithm, R = the channel radius, W^+, W^- = the ingoing and outgoing functions.

From (2) results that the PC is less than *1* every time for any incident neutrons energy. The ingoing and outgoing functions are a linear combination of regular and irregular functions for neutral and the Coulombian functions for charged particles [3], [4]. For neutral particles the calculation of the regular and irregular functions is easy in comparison with the Coulombian functions in the integral form [4] for charged particles.

For our evaluation the WCF was taken from [5] and has a quite complication form determined by Monte Carlo method.

$$F_{ab}^{fluct} = \left(1+\frac{2\delta_{ab}}{\nu_a}\right)\int_0^\infty \prod_c \left(1+\frac{2T_c x}{\nu_c \sum_i T_i}\right)^{-\left(\delta_{aqc}+\delta_{bc}+\frac{\nu_c}{2}\right)} \tag{4}$$

$$\nu_a = 1.78 + \left(T_a^{1.212} - 0.78\right)\cdot e^{-0.228\sum_c T_c}$$

RESULTS.

Were evaluated the cross section in the *(n,α)* reactions on ^{64}Zn and ^{147}Sm with fast incident neutrons with orbital momentum *l = 0, 1* in the entrance channel. In the exit channels were taken into account α particles with all possible orbital momentum and the contributions of others open channels.

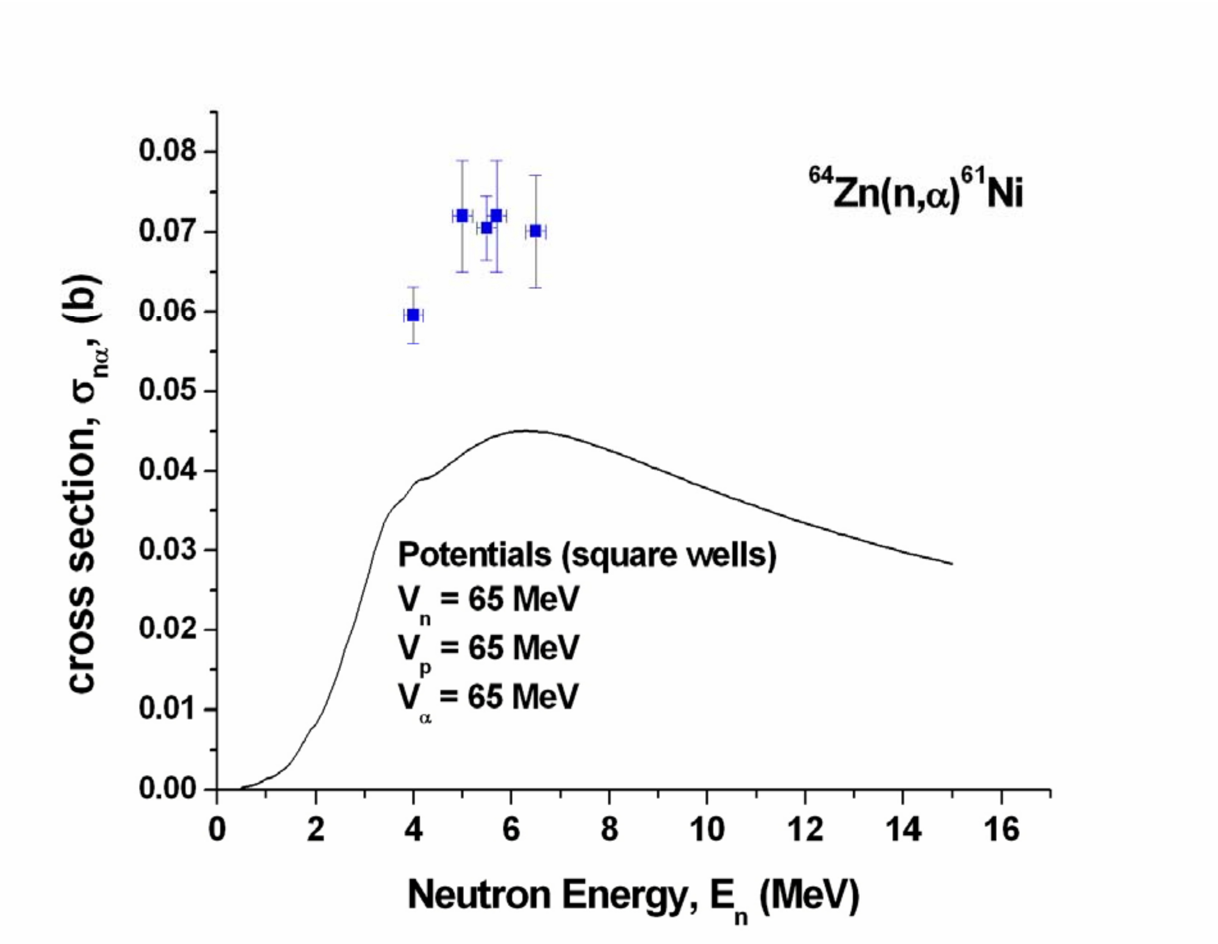

Fig. 1. The $^{64}Zn(n,\alpha)$ cross section. The HF evaluation (continuous line) is compared with experimental data [6].

For the evaluation of the cross the HF formalism was implemented in some computer programs. These programs are able to evaluate also the PC coefficients, to fit future experimental data (and to extract the potential depth, the channels radius), to represent the energetic dependences of the cross section, PC and WCF, to save the appropriate necessary ASCII files.

These programs can be easily adapted for other types of reactions and target nuclei with no major changes.

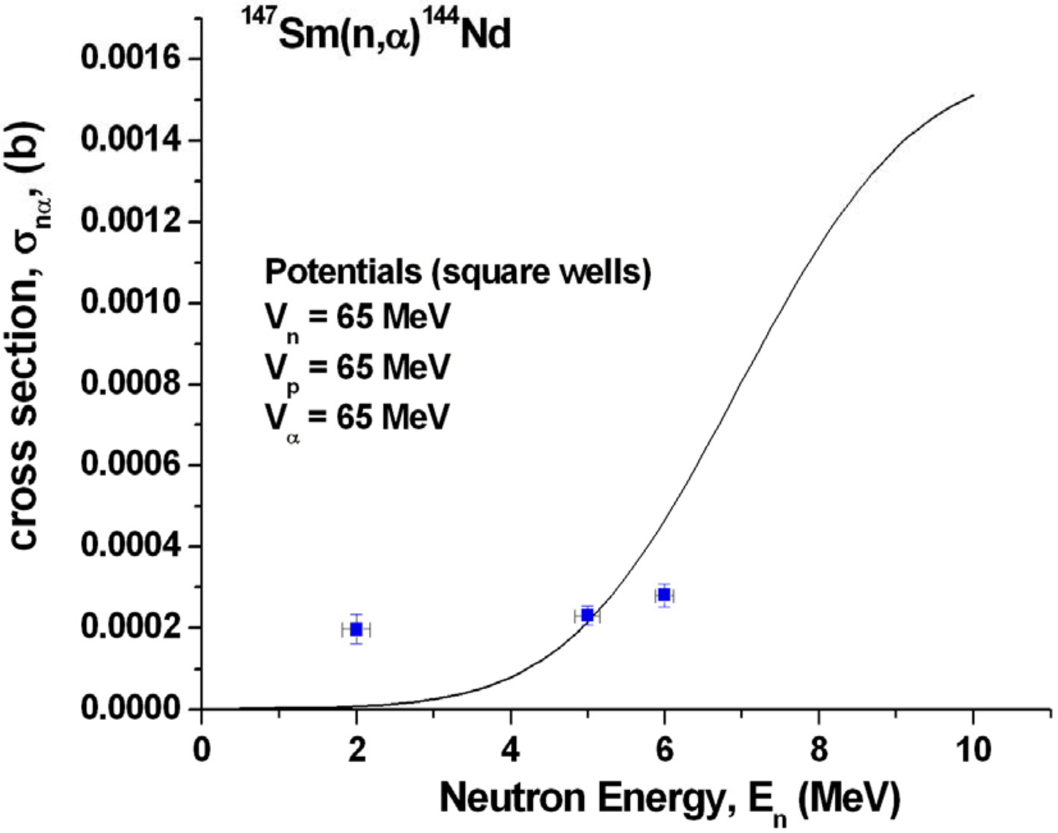

Fig. 2. The $^{147}Sm(n,\alpha)$ cross section. The HF evaluation (continuous line) is compared with experimental data [7].

DISCUSSIONS.

In our evaluation the nuclear potential has the simplest form, a potential well with no imaginary part. Then the internal wave function has an exponential form [3] and the calculation of expressions (2), (3) is faster. In future we plan to choose other type of nuclear potential like potential well with imaginary part, Wood Saxon potential and also to take into account the spin orbital interaction etc. In these cases in expression (3) the internal wave function can be determined only numerically by solving the necessary differential equations, increasing in this way the time of calculation.

The regular and irregular Coulombian functions were taken in their integral form and were not used approximate functions as is usually suggested and realized in other paper. These functions are necessary to evaluate the PC and these coefficients are evaluated using a quantum mechanical approach for the entrance channel and all possible open outgoing channels. All these enlarge the general character of the applicability of our calculation.

The depth of nuclear potential and the nuclear radius were suggested in the Talys software (http://www.talys.eu).

In the light of all above mentioned we consider that the agreement between theoretical evaluation and experimental data is good especially for ^{64}Zn nucleus.

We plan in the future to try other nuclear potentials and radius channels. Further new more experimental data on cross sections (and differential cross section) are necessary in a wide energy interval to obtain new values for nuclear potential parameters by fitting.

Our theoretical evaluation for both reactions usually is lower than the experimental data and this can indicate the presence of other nuclear reaction mechanism. If we consider that the experimental data and theoretical evaluation are well then it is necessary to analyze the contribution of other nuclear reactions mechanism (direct mechanism, pre - equilibrium mechanism).

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