(n,α) Reaction Cross Sections and Angular Distributions for Several MeV Neutrons

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In this work from the unified viewpoint using the TALYS code we analyzed the experimental (n,α) cross sections, angular distributions of 39K and 64Zn, and the ratio of forward/backward cross-sections of ^{95}Mo, ^{143}Nd, ^{147}Sm and ^{149}Sm isotopes at the 4.0-6.5MeV energies of neutrons.

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I. INTRODUCTION

In our previous work [1] the experimental total (n,α) cross sections for 11 nuclei from ^{39}K to ^{95}Mo as well as the angular distribution of emitted alpha particle for some isotopes in the several MeV energy range of neutrons were compared to existing other experimental data, evaluated nuclear data libraries and TALYS-1.6 [2] calculations with "default" optical potential parameters. From these results some disagreements between the experimental data and the TALYS-1.6 calculation with the default parameters were observed. In our last paper [3] it is mentioned that there is a possible way to reduce the disagreement by changing the optical model parameters that implemented in last version of the TALYS code.

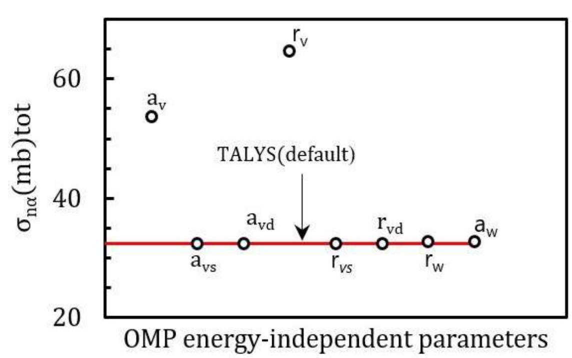
In this paper, firstly we studied the influence of the TALYS-1.8 code optical parameters on the final results. The most sensitive parameter "r_v" was found by fitting of TALYS-1.8 calculation to the experimental (n,α) cross sections and angular distributions simultaneously for ^{39}K and ^{64}Zn isotopes, as examples. In addition, we analyzed the total (n,α) cross sections and the ratio of a forward/backward ratio at the 4.0-6.5 MeV energies of neutrons for ^{95}Mo, ^{143}Nd, ^{147}Sm and ^{149}Sm isotopes.

II. THE SENSITIVITY OF OPTICAL MODEL PARAMETERS IN TALYS CODE

For a process of nuclear reaction, the interaction of a nucleon with a nucleus can be imagined that some parts of the incident particles on a nucleus are scattered and others are absorbed by the nucleus. It is analogous to the reflecting and absorption of light by a semi-transparent body. This is a main physical principle of the optical model in the nuclear reaction. The optical model can be represented by a nuclear complex potential with parameters that are adjusted to fit the experimental data. The local and global parameterizations of Koning and Delaroche are used as the default optical model potentials (OMP) in the TALYS code. The phenomenological OMP for nucleon-nucleus scattering, U[2], is defined as:

$$U(r,E) = -V_V(r,E) - iW_V(r,E) - iW_D(r,E) + V_{SO}(r,E).1. + iW_{SO}(r,E).1. + V_C(r,E) \quad (1)$$

where $V_{V,SO,C}$ and $W_{V,D,SO}$ are the real and imaginary components of the volume-central (V), surface-central (D), spin-orbit (SO) and Coulomb (C) potentials, respectively. E is the LAB energy of the incident particle in MeV. All components are separated in energy-dependent well depths, V_V, W_V, W_D, V_{SO}, and W_{SO}, and energy-independent radial parts $f(r, R_i, a_i)$ that used the Saxon-Woods form. Energy–independent (radial) 8 parameters: a_v, r_v, a_d, r_d, a_w, r_w, a_{SO} and r_{SO} and energy-dependent 13 parameters: $d_1, d_2, d_3, v_1, v_2, v_3, v_4, v_{SO1}, v_{SO2}, w_1, w_2, w_{SO1}$ and w_{SO2} there are. In the TALYS code, all these parameters are used as default values for each isotope or can be adjusted in the region of 0.1-10. To investigate the influence of above parameters on the final results, we calculated the (n,α) reaction cross-sections firstly using the default values of these parameters, then they one by one changed in certain range for each parameters. Our results of calculation for total cross sections of the ^{64}Zn(n,α)^{61}Ni reaction at 4 MeV of neutron energy are shown in Fig.1, as example



a)

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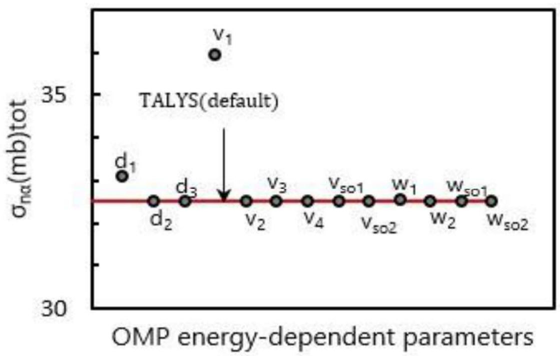


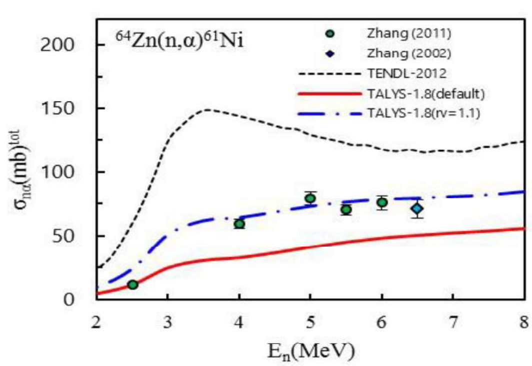
b)

FIG.1. Comparison of the calculated by the TALYS-1.8 total cross sections of the ^{64}Zn (n,α)^{61}Ni reaction at E_{inc}=4 MeV with the default and the adjusted values of OMP parameters

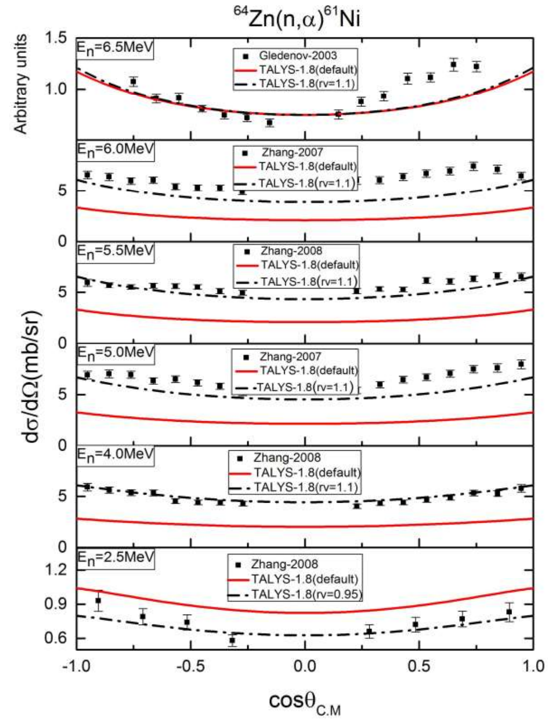
In this case the total cross-section of ^{64}Zn(n,α)^{61}Ni reaction at 4 MeV of neutron energy is 32.5mb by TALYS-1.8 with default parameters. After that, an adjusted calculation is sequentially executed by changing 'default' values into1.1 for each OMP parameters. From Fig.1 it can be seen that more sensitive parameters are r_v, a_v, v_1 and d_1. The biggest changing of the ^{64}Zn(n,α)^{61}Ni reaction cross section at 4 MeV was observed for r_v parameter.

III. RESULTS AND DISCUSSION

We used the adjusted parameter, r_v, which is the most sensitive one among the OMP parameters, to fit TALYS calculation to the experimental data. The total cross-sections and the angular distributions of (n,α) reactions for ^{39}K and ^{64}Zn isotopes, calculated by the TALYS-1.8 with the defaults and adjusted parameter r_v as well as values by TENDL are compared with the experimental data in the Figs.2 and 3. All the experimental data were taken from Ref.[4].



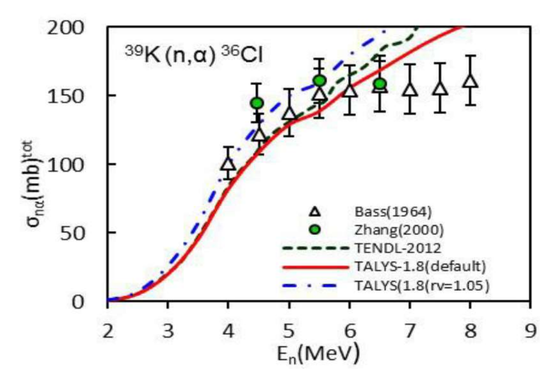
a) Total cross sections



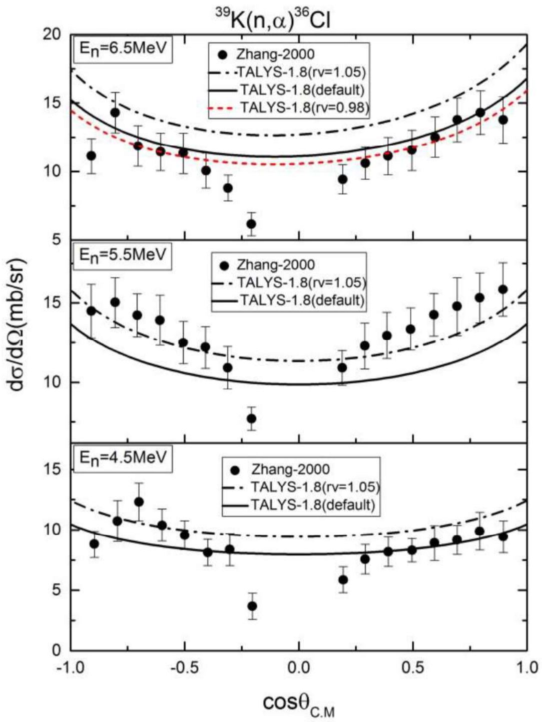
b) Angular distributions

FIG.2. Comparison of TALYS-1.8 calculation with default and adjusted OMP parameters for the $^{64}Zn(n,\alpha)^{61}Ni$ reaction at several MeV energy range.

^{64}Zn(n,α)^{61}Ni. From the FIG.2a it can be concluded that the calculated total cross-sections of this reaction by TALYS-1.8 with the default parameters were in disagreement with the experimental data, especially in the region of 4 to 7 MeV. Also, a big difference between calculated by the TENDL values and the experimental data in this case was observed. For the adjusted parameter r_v=1.1 the calculated and experimental (n,α) cross-sections were satisfactorily in agreement except for 2.5 MeV.



a)Total cross sections



b) Angular distributions

FIG.3. The same as in FIG.2 for the $^{39}K(n,\alpha)^{31}C$ reaction.

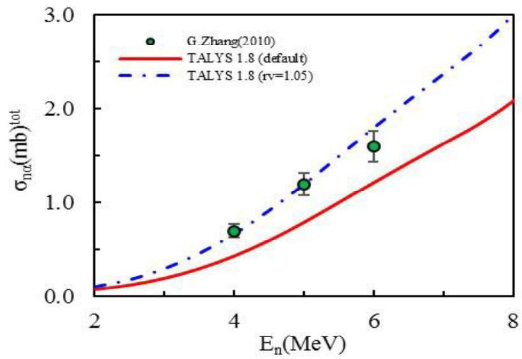
From the FIG.2b it is seen that for angular distributions of the $^{64}Zn(n,\alpha)^{61}Ni$ reaction satisfactory agreement between the calculated by TALYS-1.8 values and experimental data was obtained with the parameter r_v =1.1 for neutron energy of E_n=4.0, 5.0, 5.5, 6.0 and 6.5 MeV. For neutron energy E_n=2.5 MeV best agreement between the calculated results with parameter r_v=0.95 and experimental data was reached. As to neutron energy point E_n=6.5 MeV where angular distribution is given in arbitrary units the calculated values were normalized to experimental data at $\theta_{c.m}=90^\circ$

$^{39}K(n,\alpha)^{36}Cl$. For the total cross-section, FIG.3a shows that, a small difference between two existing experimental data in region 4-6 MeV was observed. The results of the TENDL and TALYS-1.8 with default parameters calculations are in agreement within the error limits of the experimental data for neutron energy range of E_n=4÷6.5 MeV. In addition, the results of TALYS-1.8 calculation can be improved by changing the parameter r_v =1.05. Nevertheless, it should be noted that an essential disagreement between the TALYS-1.8 calculation and experimental values in the region above 7 MeV was obtained.

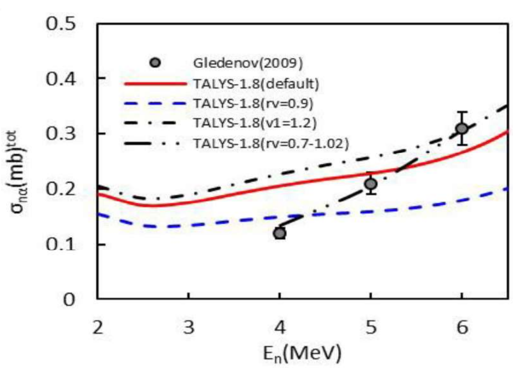
For the angular distribution of this reaction FIG.3b shows that, the results of TALYS-1.8 calculation with default parameters are in satisfactory agreement with the experimental data at 4.5 MeV. But, at 5.5 and 6.5 MeV, calculated values and experimental data are in disagreement. So, good agreement between the calculated and experimental values at 5.5 MeV was reached using parameter r_v=1.05 as in the case of the total cross-section. At the same time the parameter r_v=1.05 gives worse results than default parameter at 6.5 MeV. But, in this case r_v=0.98 gives better results than other ones.

IV. THE TOTAL CROSS-SECTION FOR HEAVY ISOTOPES

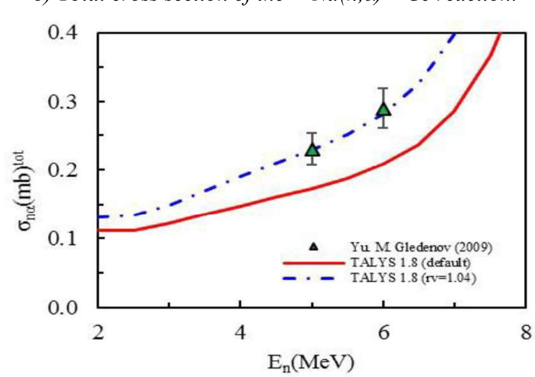
Comparison of calculated results by TALYS-1.8 with the default and adjusted parameters for the total cross-sections of (n,α) reactions of the ^{95}Mo, ^{143}Nd, ^{147}Sm and ^{149}Sm heavy isotopes are shown in Fig.4.



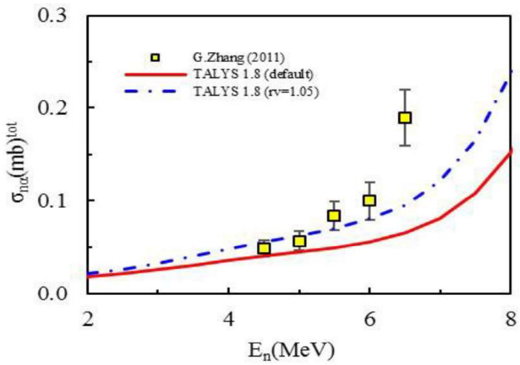
1. Total cross section of the $^{95}Mo(n,\alpha)^{92}Zr$ reaction.



b) Total cross section of the $^{143}Nd(n,\alpha)^{140}Ce$ reaction.



c) Total cross section of the $^{147}Sm(n,\alpha)^{144}Nd$ reaction.



d) Total cross section of the $^{149}Sm(n,\alpha)^{146}Nd$ reaction.

FIG.4. The comparison of the results of TALYS-1.8 calculation with default and adjusted parameters for the total cross-sections of (n,α) reactions of 95Mo, 143Nd, 147Sm and 149Sm.

$^{95}Mo(n,\alpha)^{92}Zr$. FIG.4.a shows that the result of TALYS-1.8 calculation with default parameters is in disagreement with experimental data. So, by taking the parameter $r_v = 1.05$, the agreeable results in within the error limits of the experimental data were obtained.

$^{143}Nd(n,\alpha)\ ^{140}Ce$. From FIG.4.b it is seen that result of TALYS-1.8 calculation with default parameters is in disagreement with experimental data in region E_n=4-6 MeV. Then by trying to change the OMP any parameters, we could not reach fitted results in this region. Therefore, we considered different values of the parameter r_v for each incident neutron energy. These values were obtained in the range of r_v=0.70-1.02 for E_n=4-6 MeV.

$^{147}Sm(n,\alpha)^{144}Nd$. In this case the agreement between the calculated and experimental cross sections was obtained at the parameter $r_v = 1.04$.

$^{149}Sm(n,\alpha)^{146}Nd$. From FIG.4.d the disagreement between the experimental and calculated TALYS-1.8 with default parameters was seen. So, it can also be improved by changing the parameter $r_v = 1.05$. However, in the region above 6.0 MeV, by changing any parameters of OMP to reduce the disagreement between the TALYS calculation and the experimental data was not gotten.

V. FORWARD/BACKWARD RATIO FOR HEAVY ISOTOPES

In the laboratory system, the angular distribution of emitted particles from heavy nuclei for the compound mechanism of the nuclear reaction has the isotropic tendency. At the same time for the pre-equilibrium and direct reaction mechanisms forward peaked form is dominant. The forward/backward ratios of alpha particle from (n,α) reaction were calculated by TALYS code for ^{95}Mo, ^{143}Nd, ^{147}Sm and ^{149}Sm isotopes. These results and experimental data are given in Table.1.

Table.1. Calculated and measured forward/ backward ratios of heavy isotopes.

		$^{95}Mo(n,\alpha)^{92}Zr$			
Energy (MэB)	Measured Ref [5]	TALYS-1.0 (default)	TALYS-1.0 (r_d=0.5)	TALYS-1.8 (default)	TALYS-1.8 (direct)
4.0	1.10±0.14	1.21	1.21	1.00	1.93
5.0	1.24±0.14	1.40	1.40	1.01	2.06
6.0	1.37±0.14	1.65	1.64	1.01	2.20
	Ref [6]	$^{143}Nd(n,\alpha)^{140}Ce$			
4.0	1.25±0.12	1.22	1.20	1.00	1.92
5.0	1.78±0.18	1.54	1.51	1.01	2.08
6.0	2.50±0.25	1.90	1.89	1.05	2.23
	Ref [6]	$^{147}Sm(n,\alpha)^{144}Nd$			
5.0	1.65±0.23	1.73	1.71	1.01	2.05
6.0	2.49±0.32	2.02	2.02	1.05	2.20
	Ref [7]	$^{149}Sm(n,\alpha)^{146}Nd$			
4.5	1.40±0.40	1.64	1.61	1.01	2.03
5.0	1.60±0.40	1.81	1.79	1.01	2.09
5.5	1.90±0.50	1.96	1.95	1.02	2.17
6.0	2.20±0.60	2.09	1.99	1.03	2.24
6.5	2.70±0.70	2.20	2.20	1.05	2.32

The measured forward/backward ratio, is increased with the growing the incident particle energy. This fact is perhaps explained by the increasing the contribution from direct and pre-equilibrium mechanisms when the projectile energy increases.

In our calculations were used two versions of TALYS-1.0 and 1.8 codes. In the TALYS-1.0 version, above-mentioned growing tendency of forward/backward ratio is being kept. In addition, the results of TALYS-1.0 with adjusted the OMP parameter, r_d, are shown in Table.1 that gives the same values as calculation with the default parameters. It means that TALYS-1.0 calculation with adjusted OMP parameters leads to the same changed values for forward and backward directions.

The TALYS-1.8 version gives different results from the experimental data. From the analysis by the TALYS-1.8 version it was observed that the contribution of the compound mechanism is one-order more than direct mechanism. Therefore, calculated by TALYS-1.8 version forward/backward ratio is close to 1.0 value. Also, we calculated the forward/backward ratio by only direct reaction mechanism for TALYS-1.8 version (see the sixth column in table.1, titled as TALYS - 1.8(direct)). These calculations gave the growing tendency of the forward/backward ratio with increasing the neutron energy.

VI. CONCLUSIONS

1. The total (n,α) cross section for ^{64}Zn at neutron energy of 4 MeV was calculated using TALYS code with different OMP parameters to investigate the influence of these parameters on the final results. It was obtained that the radial parameter r_v is the most important one.
2. It was shown that changing the radial parameter r_v in the acceptable range satisfactorily agreement between the calculated results and experimental data of the total cross sections, angular distributions of the emitted α-particles and forward/backward ratios for the fast neutron induced (n,α) reactions on the some medium mass and heavy isotopes were reached.

VII. REFERENCE

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