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Calculation of photo-nuclear reaction cross sections for ^{16}O

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Abstract. Because of the high thermal expansion coefficient of uranium, the fuel used in nuclear power plants is usually in the form of UO_2 which has ceramic structure and small thermal expansion coefficient. UO_2 include one uranium atom and two oxygen atoms. After fission progress, total energy values of emitted gamma are about 14 MeV. This gamma energy may cause transmutation of ^{16}O isotopes. Transmutation of ^{16}O isotopes changes physical properties of nuclear fuel. Due to above explanations, it is very important to calculate photo-nuclear reaction cross sections of ^{16}O. In this study; for (γ,p), (γ,np), (γ,n) and (γ,2n) reactions of ^{16}O, photo-nuclear reaction cross-sections were calculated using different models for pre-equilibrium and equilibrium effects. Taking incident gamma energy values up to 40 MeV, Hybrid and Cascade Exciton Models were used for pre-equilibrium calculations and Weisskopf-Ewing (Equilibrium) Model was used for equilibrium model calculations. Calculation results were compared with experimental and theoretical data. While experimental results were obtained from EXFOR, TENDL-2013, JENDL/PD-2004 and ENDF/B VII.1 data base were used to get theoretical results.

1 Introduction

Nuclear fuel is basic element of reactor core and source of energy produced in nuclear reactor. The fuel used in nuclear reactor has to meet the physical criteria such as linear coefficient of expansion, thermal inductivity, heat capacity etc. [1-3]. Due to high linear thermal expansion coefficient of uranium ($\alpha=13.9\times10^{-6}$ m/(mK), t=25°C) [4], it can deform fuel sheath (envelope) at high temperature. So we can't use pure uranium at fuel rods. In general, UO_2 ($\alpha=7.69\times10^{-6}$ m/(mK), t=25°C) [5] having smaller linear thermal expansion coefficient is used as a fuel in Light Water Reactor (LWR), Pressurized Water Reactor (PWR), Boiling Water Reactor (BWR) etc...[6]

Nuclear transmutations and fission in fuel components change the physical properties of fuel rods. Gamma energies emitted after fission reaction is approximately 14 MeV. Two of three atoms of nuclear fuel are oxygen. Transmutations occur in ^{16}O due to photo-nuclear reactions and it will affect the physical properties of nuclear reactor fuel. Therefore calculations of photo-nuclear reaction cross sections of ^{16}O are very important.

In this study; for (γ,p), (γ,np), (γ,n) and (γ,2n) reactions of ^{16}O, photo-nuclear reaction cross-sections were calculated using different models for pre-equilibrium and equilibrium effects. Taking incident gamma energy values up to 40 MeV, Hybrid and Cascade Exciton Models were used for pre-equilibrium calculations and Weisskopf-Ewing (Equilibrium) Model was used for equilibrium model calculations. Calculation results were compared with experimental and theoretical data. While experimental results were obtained from EXFOR, TENDL-2013, JENDL/PD-2004 and ENDF/B VII.1 data base were used to get theoretical results.

2 Calculations of nuclear reactions

Statistical models can be applied to solve excitation functions. One of these models describes as above: Projectile particle was absorbed by target nucleus. Without emitting particles, compound nucleus reaches the equilibrium state. Weisskopf-Ewing (WE) model can be used to explain this case [7]. In this model, reaction cross section is given as following;

$$\sigma(a,b)=\sigma_a(\varepsilon)\frac{\Gamma_b}{\sum_{b'}\Gamma_{b'}} \tag{1}$$

In this formula, ε is the incident energy of particle and $\sigma_a(\varepsilon)$ is the cross section for the formation of a compound state. Γ_b is the emission probability per time for the particle b and given as [8]:

$$\Gamma_b=\frac{2s_b+1}{\pi^2\hbar^2}\mu_b\int d\varepsilon\,\sigma_b^{inv}(\varepsilon)\,\varepsilon\,\frac{\omega_1(U)}{\omega_1(E)} \tag{2}$$

In equilibrium, the probability of emitting particle is given as following:

$$W_b(\varepsilon)\propto(2s_b+1)\,\mu_b\,\varepsilon\,\sigma_b^{inv}(\varepsilon)\frac{\omega_1(U)}{\omega_1(E)} \tag{3}$$

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where s_b is spin, μ_b is reduced mass, ε is energy of emitted particle, σ_b^{inv} is the inverse reaction cross section, $\omega_1(U)$ is the nuclear level density of the nucleus, $\omega_1(E)$ is the nuclear level density of the nucleus emitting b particle, U is the excitation energy of residual nucleus and E is the excitation energy of the emitting nucleus [9].

One of the other reaction models is Cascade Exciton Model (CEM) which assumed to occur in three steps:

I. Intra-nuclear Cascade
II. Pre-equilibrium
III. Equilibrium

In INC stage, secondary particles were created by either incident particle was absorbed by nucleus or projectile particle consumed its total energy. The next stage is the state where compound nuclear reaction model is applied. Cascade particles define in which exciton state compound nucleus has been emitted. In the last stage, nucleus is in equilibrium and particle emission will occur through either evaporation or fission [10].

In general, these three steps contribute values obtained as experimentally. According to this, particle spectra equation is following as;

$$\sigma(p)dp = \sigma_{in}\left\{N^{cas}(p) + N^{prq}(p) + N^{eq}(p)\right\} \qquad (4)$$

where p is the linear momentum and σ_{in} is inelastic cross sections calculated within cascade model [11].

3 Results and discussions

In this study, to calculate (γ,p), (γ,np), (γ,n) and (γ,2n) nuclear reaction cross-sections of ^{16}O pre-equilibrium and equilibrium models were used with the incident gamma energies up to 40 MeV. For equilibrium and pre-equilibrium effects, Weisskopf Ewing Model and Cascade Exciton Model (CEM) have been used, respectively. Equilibrium model calculations have been prepared by using PCROSS and ALICE-2011 computer codes. CEM calculations have been performed by CEM-03.01 computer code. The results of comparisons between cross section calculations of this study, experimental data and evaluated ones taken from literature are as following:

In Fig. 1 the results of (γ,p) reaction calculations are in agreement with experimental data and evaluated results up to 20 MeV. At higher energies, results of CEM and WE models are coherent with ENDF/B VII.1 while those of equilibrium model calculations are in agreement with TENDL-2013 data.

While equilibrium and CEM calculation results are smaller than experimental and evaluated data in Fig. 2, WE model calculations are in good agreement for (γ,np) reaction cross-section calculations. At higher energies, nuclear model calculations are coherent with experimental data.

In Fig. 3 for (γ,n) reaction cross-section calculations below 25 MeV; all nuclear models are in good agreement with experimental and evaluated data. In 25-40 MeV energy region; equilibrium model results are in agreement with TENDL-2013 and JENDL/PD-2004 although experimental data are greater than them. The other models are in very good agreement with experimental data.

The calculation results of (γ,2n) reactions in Fig. 4 are below experimental data while they are in agreement with evaluated results.

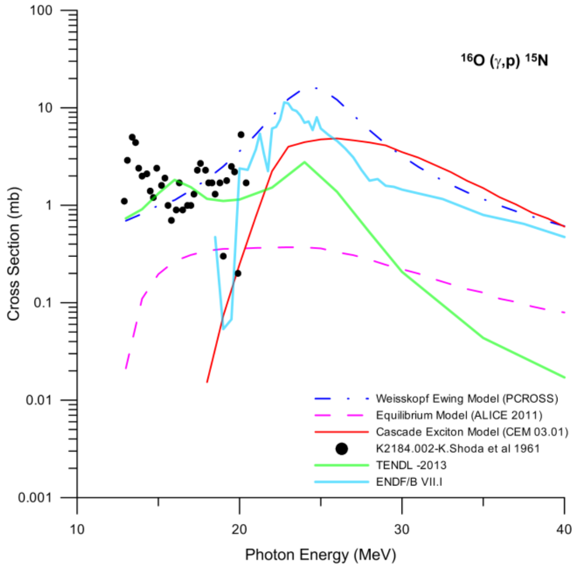

Figure 1. Comparison of cross section calculations of ^{16}O(γ,p)^{15}N reaction between given nuclear reaction models, experimental data and evaluated data library [13,14].

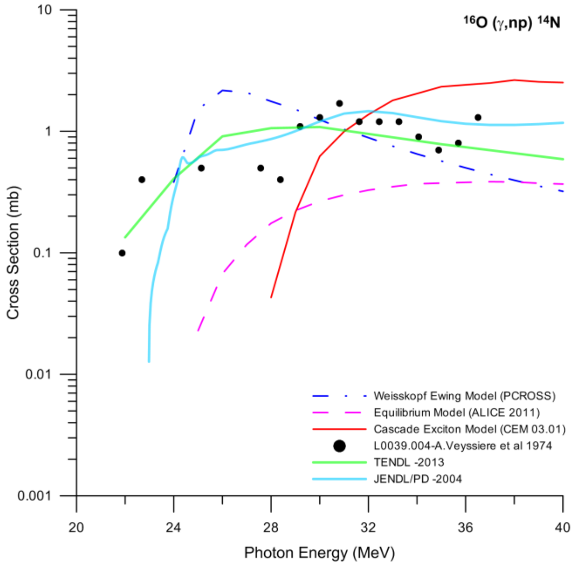

Figure 2. Comparison of cross section calculations of ^{16}O(γ,np)^{14}N reaction between given nuclear reaction models, experimental data and evaluated data library [13,14].

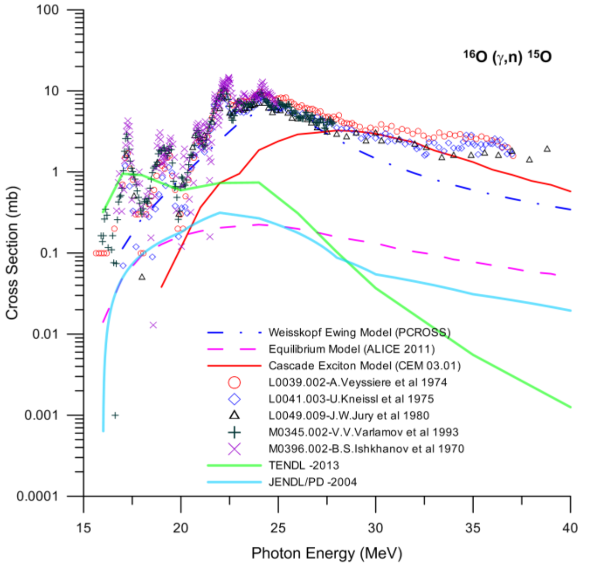

Figure 3. Comparison of cross section calculations of $^{16}O(\gamma,n)^{15}O$ reaction between given nuclear reaction models, experimental data and evaluated data library [13,14].

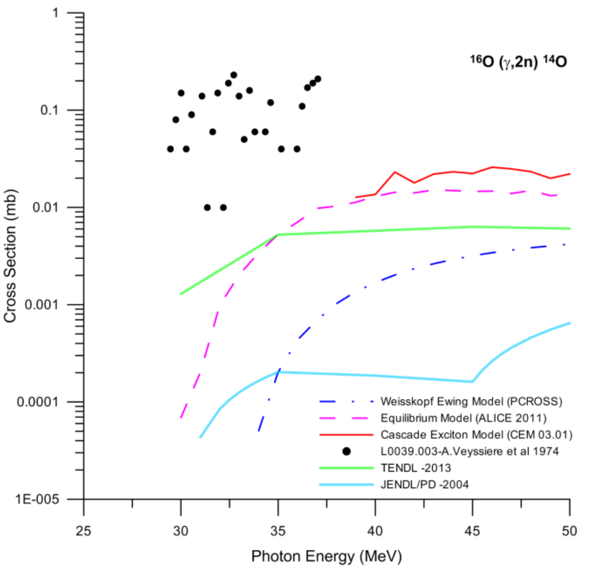

Figure 4. Comparison of cross section calculations of $^{16}O(\gamma,2n)^{14}O$ reaction between given nuclear reaction models, experimental data and evaluated data library [13,14].

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