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A STUDY OF PHOTONEUTRON REACTIONS USING STATISTICAL ANALYSIS[†]

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The well-known inputs for determining the reaction cross section are nuclear level density (NLD) and γ-ray strength functions. In this work, effects of γ-ray strength functions and NLD models on photoneutron reactions of ^{76,77,78}Se isotopes are analyzed by using the latest version of TALYS computer code. For γ-ray strength functions, macroscopic and microscopic options which are available in the TALYS, are used in the calculations. Kopecky-Uhl and Brink Axel γ-ray strength function models as macroscopic options, Hartree-Fock BCS tables, Hartree-Fock Bogolyubov tables and Goriely's hybrid model as microscopic options are preferred. The statistical analysis is carried out to determine the γ-ray strength function that reproduces the experimental data quite well. And then, calculations of photoneutron cross section are redone by using the determined γ-ray strength function via the NLD models. The Constant Temperature Model (CTM), Back Shifted Fermi Gas Model (BSFGM) and Generalized Superfluid Model (GSM) are preferred to use in NLD calculations. The predictions are compared with each other and the available experimental data. EXFOR library is used to take all experimental data.
Keywords: Nuclear level density models; Cross section; γ-ray strength functions; Photoneutron reactions; TALYS
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The proton induced reactions are commonly used in variety of applications from astrophysics to transmutation of nuclear waste and can give beneficial knowledge about the data estimation of nuclear reactions. The most important channel of these reactions is gamma emission channel, which is defined by gamma ray strength functions. This channel can be observable in all other reactions and can called as universal channel. Therefore, it has a great importance to describe this channel. The well-known and useful inputs for theoretical calculations of the photon induced reactions are NLD and γ-ray strength functions. These functions can be selected as an optional input in the computer codes [1,2]. There are many theoretical [3-6] and experimental [7-10] works for photon induced reactions in the literature using these codes.

In the photon induced reactions, giant dipole resonance (GDR) is dominant at energies below 30 MeV. It is observable in the energy range 10−15 MeV, and 20−25 MeV for heavy and light nuclei, respectively. In GDR energies, maximum photoabsorption and cross section of other photonuclear reactions are observed. The aim of the work is to study the effect of the nuclear level density and γ-ray strength function on cross section of photoneutron reactions. To analyze these effects, best known computer code TALYS is used for the theoretical calculations [11-19]. This code is widely used code in the reaction analysis. The effect of γ-ray strength function is investigated by using Kopecky-Uhl generalized Lorentzian, Brink-Axel Lorentzian, Hartree-Fock BCS table, Hartree-Fock Bogolyubov tables and Goriely's hybrid models. The γ-ray strength function which give the closest result to the experimental data, is determined with the statistical calculations. Then, best strength function is used together with nuclear level density models and calculations are reperformed using TALYS code for each reaction. To analyze the effect of nuclear level density models, Constant Temperature Model (CTM), Back-Shifted Fermi Gas Model (BSFGM, and Generalized Superfluid Model (GSM) are used. The predictions are presented and discussed with the experimental data taken from EXFOR [20] library. The best combinations of models are decided by evaluating the statistical analysis.

The rest of this paper is organized as follows: In section "Materials and Methods", calculation method is presented. In section "Results and Discussion", I represent my results and their discussions. Finally, in section "Conclusion", I give some concluding remarks.

MATERIALS AND METHODS

For the gamma induced nuclear reactions, γ-ray strength functions are the key input. This function is used to calculate the reaction cross section with the statistical theory and defines the transmission coefficients.

The phenomenological model, Brink Axel is used to determine the γ-ray strength functions for $E1$, $E2$ and $M1$ modes [21,22]. According to this model, gamma ray strength function is given as a standard Lorentzian form below as

$$f_{Xl}(E_\gamma) = \frac{1}{(2l+1)\pi^2\hbar^2c^2}\frac{\sigma_{Xl}E_\gamma\Gamma_{Xl}^2}{(E_\gamma^2-E_{Xl}^3)+E_\gamma^2\Gamma_{Xl}^2}, \quad (1)$$

where σ_{Xl} is the strength, E_{Xl} is the energy, and Γ_{Xl} is the width of resonance. They are the giant dipole parameters.

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For $E1$ radiation, this standard Lorentzian form is generalized and written as

$$f_{E1}\left(E_\gamma,T\right)=\frac{\sigma_{E1}\Gamma_{E1}}{(2l+1)\pi^2\hbar^2c^2}\left[\frac{E_\gamma\tilde{\Gamma}_{E1}\left(E_\gamma\right)}{\left(\left(E_\gamma^2-E_{E1}^2\right)+E_\gamma^2\tilde{\Gamma}_{E1}\left(E_\gamma\right)\right)^2}+\frac{0.7\Gamma_{E1}4\pi^2T^2}{E_{E1}^3}\right], \tag{2}$$

where $\tilde{\Gamma}_{E1}(E_\gamma)$ is temperature and energy dependent width [23] and given as

$$\tilde{\Gamma}_{E1}\left(E_\gamma\right)=\Gamma_{E1}\frac{E_\gamma^2+4\pi^2T^2}{E_{E1}^2}, \tag{3}$$

where T is a nuclear temperature and written below

$$T=\sqrt{\frac{E_n+S_n-\delta-E_\gamma}{a(S_n)}}, \tag{4}$$

where δ is the pairing correction, E_n is the neutron energy, S_n is the neutron separation energy, and a is the nuclear level density parameter.

Bardeen Cooper Schrieffer (BCS) [24] model is a microscopic option for $E1$ radiation. It can be found a detail information for this model and the other microscopic gamma ray strength function models (Hartree-Fock Bogolyubov and Goriely's hybrid) from Reference input Parameter library (RIPL-3) database [25].

Nuclear level density is the number of excited levels around an excitation energy. The first model of nuclear level density has been proposed by Bethe [26] called as Fermi gas model. According to this model, nucleons do not interact with each other, have equispaced single particle states, and collective levels are absent. The total nuclear level density formulation is given as

$$\rho^{tot}(U)=\frac{1}{12\sqrt{2}\sigma}\frac{\exp\left[2\sqrt{aU}\right]}{a^{1/4}U^{5/4}}, \tag{5}$$

where a is the main variable of the nuclear level density and called nuclear level density parameter, U is the excitation energy, and σ is the spin-cutoff parameter.

The default option of TALYS computer code is Constant Temperature Model (CTM) [27]. This model considers the energy region in two parts as low and high. For Back-Shifted Fermi Gas Model (BSFGM) [28] Fermi gas expression is used for all energy range. The other nuclear level density model, Generalized Superfluid Model (GSM) [29] based on BCS theory has a pairing correlation, and is characterized by a phase transition.

γ -ray strength functions and nuclear level density models are inputs to calculate the reaction cross sections. Therefore, if these two inputs are used together in the calculations, successful results can be obtained.

TALYS computer code is used for all calculations. It is a computer program which simulates nuclear reactions, which are caused by light particles such as gamma, proton, neutron, triton etc. from 1 keV to 1 GeV. γ -ray strength functions and nuclear level density models can be used as an optional input in TALYS.

RESULTS AND DISCUSSION

In this work, cross sections of ^{76}Se(g,n)^{75}Se, ^{77}Se(g,n)^{76}Se, and ^{78}Se(g,n)^{77}Se reactions are calculated with different γ -ray strength functions and nuclear level density models by using TALYS computer code. The predictions are shown in Figs. 1-6, and statistical results are presented in Tables 1 and 2.

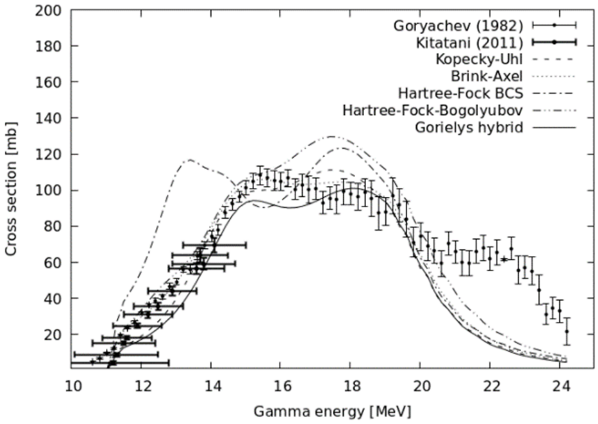

Figure 1. Comparison of gamma ray strength function calculations with the experimental data for ^{76}Se(g,n)^{75}Se

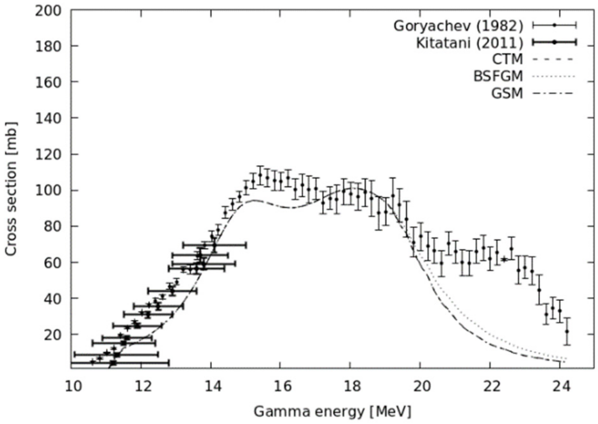

Figure 2. Comparison of nuclear level density calculations with the experimental data for ^{76}Se(g,n)^{75}Se

^{76}Se(g,n)^{75}Se reaction cross section calculations with γ -ray strength functions are given in Fig. 1. The results of Hartree-Fock BCS tables show two humps at the giant dipole resonance region. Hartree-Fock BCS and Hartree-Fock

Bogolyubov display the predictions far from the experimental data. According to the statistical analysis given in Table 1, Goriely's hybrid model are chosen the best γ -ray strength function, which reproduces the experimental data.

Table 1. Statistical analysis of (g,n) reaction cross section calculations using gamma ray strength functions.

Target	Kopecky-Uhl	Brink Axel	Hartree-Fock BCS	Hartree-Fock Bog.	Goriely's hybrid
^{76}Se	0.7179	0.7858	0.4743	0.8006	0.8127
^{77}Se	0.2166	0.7157	0.7780	0.8126	0.6675
^{78}Se	0.5019	0.4028	0.2210	0.6114	0.5925

The calculations for ^{76}Se(g,n)^{75}Se reaction are redone by using Goriely's hybrid model with nuclear level density models. The calculation results with nuclear level density models are given in Fig. 2. All models have close predictions. However, statistical analysis for nuclear level density models given in Table 2 is presented that for this reaction, best combination is Goriely's hybrid model and BSFGM.

Table 2. Statistical analysis of (g,n) reaction cross section calculations using nuclear level density models

Target	CTM	BSFGM	GSM
^{76}Se	0.8127	0.8467	0.8142
^{77}Se	0.8126	0.8433	0.8750
^{78}Se	0.6114	0.6526	0.5826

In Fig. 3, comparisons of ^{77}Se(g,n)^{76}Se reaction cross section calculations with γ -ray strength functions are shown. All predictions have higher peaks at 15 MeV-20 MeV energies. According to the statistical analysis table for γ -ray strength functions, Kopecky Uhl generalized Lorentzian form is the worst model, and Hartree-Fock Bogolyubov model has the best result compared the others. The cross sections are recalculated using Hartree-Fock Bogolyubov model with nuclear level density models. Predictions are compared with the experimental data and shown in Fig. 4. According to the statistical analysis for nuclear level density models, GSM has the best prediction to reproduce the experimental data.

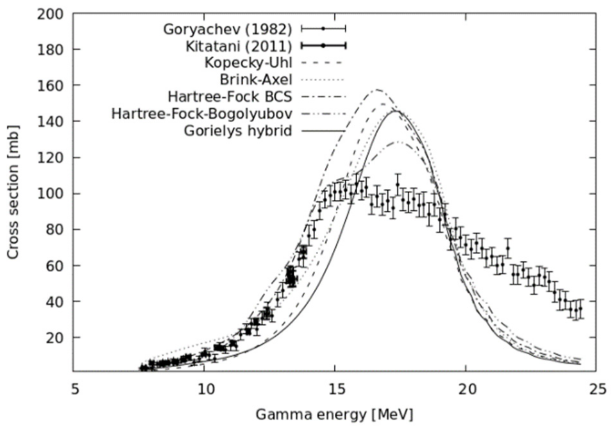

Figure 3. Comparison of gamma ray strength function calculations with the experimental data for ^{77}Se(g,n)^{76}Se

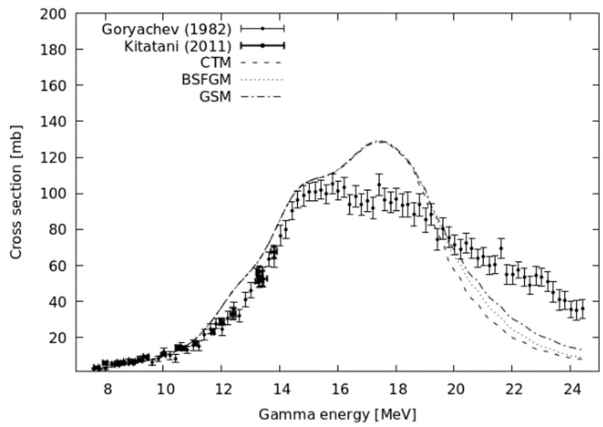

Figure 4. Comparison of nuclear level density calculations with the experimental data for ^{77}Se(g,n)^{76}Se

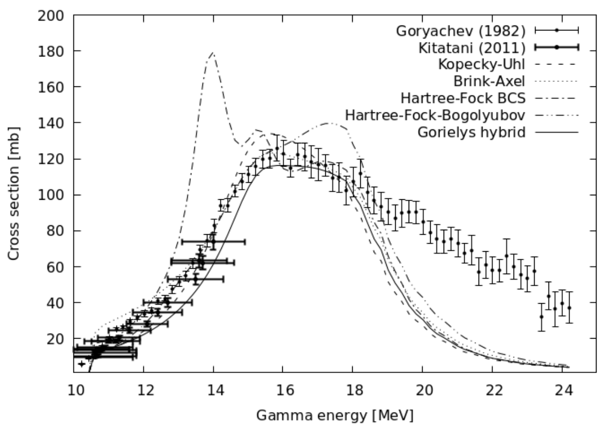

Figure 5. Comparison of gamma ray strength function calculations with the experimental data for ^{78}Se(g,n)^{77}Se

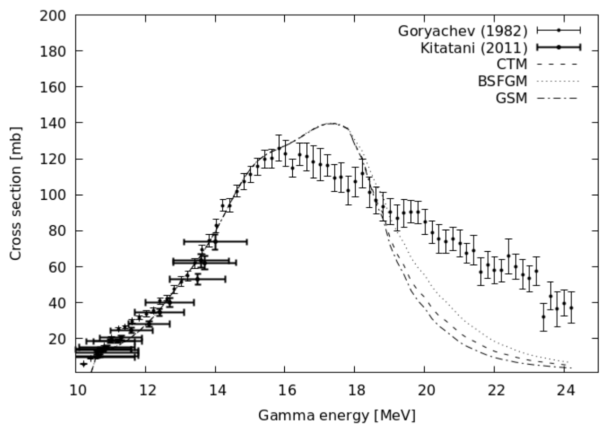

Figure 6. Comparison of nuclear level density model calculations with the experimental data for ^{78}Se(g,n)^{77}Se

For $^{78}Se(g,n)^{77}Se$ reaction, calculations are performed with γ -ray strength functions and compared with the experimental data in Fig. 5. All models have similar geometries after 18 MeV gamma energy. Hartree-Fock BCS and Hartree- Fock Bogolyubov models are far away from the experimental data at between 13 MeV-18 MeV energies. According to the statistical analysis table, Hartree-Fock Bogolyubov is the closest model to the experimental data. After γ -ray strength function model is determined, calculations are redone for nuclear level density models and represented in Fig. 6. According to Table 2, BSFGM can be chosen as a suitable nuclear level density model for this reaction.

CONCLUSION

The photoneutron cross sections of $^{76,77,78}Se$ isotopes are analyzed using available γ-ray strength functions and nuclear level density models in TALYS computer code. The following concluding remarks can be written as:

- The results of nuclear level density model calculations performed with γ -ray strength function models agree with the experimental data for all reactions in this study.
- For all investigated reactions, microscopic γ-ray strength functions are more successful to reproduce the experimental data than the others.
- Hartree-Fock BCS is the worst model to explain the experimental data for all calculations.
- All nuclear level density models have close predictions with each other.

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Conflict of interest statement. The authors declare that they have no conflict interest.

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ДОСЛІДЖЕННЯ ФОТОНЕЙТРОННИХ РЕАКЦІЙ ЗА ДОПОМОГОЮ СТАТИСТИЧНОГО АНАЛІЗУ

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Добре відомими вхідними даними для визначення перетину реакції є щільність ядерного рівня (NLD) і силові функції γ-променів. У цій роботі за допомогою останньої версії комп'ютерного коду TALYS проаналізовано вплив силових функцій γ-випромінювання та моделей NLD на фотонейтронні реакції ізотопів ^{76,77,78}Se. Для силових функцій γ-променів у розрахунках використовуються макроскопічні та мікроскопічні параметри, доступні в TALYS. Моделі функції сили Копекі-Ула та Брінка Акселя як макроскопічні варіанти, таблиці Хартрі-Фока BCS, таблиці Хартрі-Фока Боголюбова та гібридна модель Горілі як мікроскопічні варіанти. Проведено статистичний аналіз для визначення силової функції γ-променів, яка досить добре відтворює експериментальні дані. Потім розрахунки поперечного перерізу фотонейтронів переробляються за допомогою визначеної функції сили γ-випромінювання за допомогою моделей NLD. В NLD розрахунках краще використовувати модель постійної температури (CTM), модель газу Фермі зі зсувом назад (BSFGM) і узагальнену надтекучу модель (GSM). Прогнози порівнюються між собою та наявними експериментальними даними. Для отримання всіх експериментальних даних використовується бібліотека EXFOR.

Ключові слова: моделі густини ядерних рівнів; поперечний переріз; силові функції γ-променів; фотонейтронні реакції; TALYS