J Fusion Energ
DOI 10.1007/s10894-015-9896-5

ORIGINAL RESEARCH

# Cross Section Calculations of Neutron Induced Reactions on $^{124,126,128,134,136}Xe$

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**Abstract** In the nuclear energy applications Xenon is a desirable material because of its high molecular weight and inert nature. The cross section calculations of $^{124}Xe(n,2n)^{123}Xe$, $^{126}Xe(n,2n)^{125}Xe$, $^{128}Xe(n,2n)^{127}Xe$, $^{134}Xe(n,2n)^{133}Xe$ and $^{136}Xe(n,2n)^{135}Xe$ reactions were performed by ALICE/ASH (with Weisskopf-Ewing equilibrium model), TALYS 1.6 (with two component exciton model suggested by Kalbach) and EMPIRE 3.2 Malta (with exciton model recommended by Clinev and Ribansky) nuclear reaction codes. In addition, semi-empirical cross section formula of Tel et al. was used to obtain cross sections at 14–15 MeV energy. Obtained results were compared to available experimental data by EXFOR database and TENDL-2013 data.

**Keywords** Equilibrium · Preequilibrium · Xe isotopes · ALICE/ASH · TALYS · EMPIRE

## Introduction

Data on interactions of nuclei with the neutron particles up to energies of 20 MeV have been extensively utilised in the research and development (R&D) related to future fusion technology and fast reactors [1]. Nuclear data are required to explain reaction mechanisms and to develop more nuclear model. And also, the nuclear models are frequently needed because of the experimental difficulties [2]. The nuclear fusion power is one of the alternative energy sources of the future, because it can be a clean, safe and economically attractive option in a competitive energy marketplace. So fusion is to play an important role in the world's energy. The design, performance and material choices of the nuclear components are dominant factors in arriving at an attractive power device [3]. Various plasmas such as Xenon and Argon have been extensively investigated because of its application in nuclear reactor and medicine. And also, Xenon is widely used in bubble chambers in industry. The Xenon plasma parameters and, the X-ray emission properties of Xenon plasma were investigated by Akel [4]. In this paper, the cross sections at interactions with neutron particles of Xenon materials were investigated using nuclear models. The nuclear model predictions (equilibrium and pre-equilibrium) can play an important role determining the maximum cross section of the (n,x) reactions. Thereby, considerable efforts have been devoted to development of nuclear reaction codes [1]. The ALICE/ASH code has been used to simulate the interactions of intermediate energy nucleons and nuclei with target nuclei. It can calculate the energy and angular distributions of particles emitted after nuclear reactions, total inelastic cross sections and residual nuclear yields with energies up to 300 MeV [5]. For the analysis and estimation of nuclear reactions, TALYS computer code system [6] has been widely used. Interactions between seven different particle types (photon, neutron, proton, deuteron, triton, $^{3}He$ and alpha particle) and target nuclides of mass 12 and heavier can be simulated by TALYS code

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Published online: 04 March 2015

in the 1 keV–200 MeV energy range. On the other hand, the code EMPIRE [7] is a nuclear reaction code system including various nuclear models, and designed for calculations over a broad range of energies (from keV up to few hundred MeV) and incident particles as photons, nucleons, deuterons, tritons, hellions. Looking at the literature neutron induced reactions about Xe isotopes was studied for different energy regions. Several measurements and calculations were made [8–11]. In this paper, neutron interactions with five Xe isotopes as $^{124}$Xe(n,2n)$^{123}$Xe, $^{126}$Xe(n,2n)$^{125}$Xe, $^{128}$Xe(n,2n)$^{127}$Xe, $^{134}$Xe(n,2n)$^{133}$Xe, $^{136}$Xe(n,2n)$^{135}$Xe by three nuclear reaction code system such as ALICE/ASH [5], TALYS 1.6 [6] and EMPIRE 3.2 Malta [7] were investigated.

## Calculations and Methods

This study has been conducted to theoretically calculate the cross sections of $^{124,126,128,134,136}$Xe isotopes. Various equilibrium and preequilibrium reaction models can be used for calculating the nuclear excitation functions [13–16]. For calculating the cross sections, we used three different nuclear program codes. "Exciton" and "two component exciton" models were used in TALYS 1.6, EMPIRE 3.2 Malta nuclear program code for preequilibrium reaction systematics, respectively [17, 18]. Weisskopf–Ewing model has been preferred to investigate the equilibrium reaction systematic [19]. The ALICE-ASH nuclear program code has been used for the equilibrium model calculations. The reason to prefer of Weisskopf–Ewing model is to make comparisons between equilibrium and preequilibrium reaction mechanisms. Obtained results and TENDL-2013 [20] library data were compared with the experimental data from EXFOR database [12].

The TALYS 1.6 computer program code is very efficient to study the interactions between the particles and nuclei. And also, the program allows making some calculations such as gamma-strength functions, nuclear model parameters and nuclear level densities. There are many methods to study the preequilibrium reaction mechanisms with different reaction mechanisms. In this study, two component exciton model developed by Kalbach was used for calculation of preequilibrium cross sections [17]. The method uses specific notations for particle or hole numbers of protons and neutrons, $p_\pi$ ($p_\nu$) and $h_\pi$ ($h_\nu$) respectively. In addition, neutron and proton exciton numbers are given $n_\pi = p_\pi + h_\pi$ and $n_\nu = p_\nu + h_\nu$. Detailed information and discussion about the TALYS 1.6 nuclear code program can be found in Ref. [6]. On the other hand, the EMPIRE 3.2 Malta nuclear computer code program uses exciton model [18] for preequilibrium reaction mechanisms recommended by Cline [21] and Ribansky [22],

$$-q_{t=0}(n) = \lambda_+(E, n+2)\tau(n+2) + \lambda_-(E, n-2)\tau(n-2) - [\lambda_+(E,n) + \lambda_-(E,n) + L(E,n)]\tau(n) \tag{1}$$

where $q_t(n)$ is initial occupation probability of composite nucleus in the state with the "$n$" exciton number. $\lambda_+(E,n)$ and $\lambda_-(E,n)$ are the transition rates of decay to neighboring states, and $L(E,n)$ is the total emission rate integrated over emission energy for $\gamma$-rays and particles. Detailed information and discussions about the EMPIRE 3.2 computer code can be found in Ref. [7]. The equilibrium emission for nuclear reactions in this study is calculated according to Weisskopf–Ewing model [19] neglecting angular momentum. In this model, the basic parameters are inverse reaction cross sections, binding energies, the pairing and the level density parameters. Here, the reaction cross section as incident channel "$a$" and exit channel "$b$" can be written following,

$$\sigma_{ab}^{WE} = \sigma_{ab}(E_{inc})\Gamma_b \Big/ \sum_{b\prime} \Gamma_{b\prime} \tag{2}$$

where, the symbol $E_{inc}$ is incident energy [5, 19].

## Results and Discussion

In this study, cross sections of neutron induced reactions such as $^{124}$Xe(n,2n)$^{123}$Xe, $^{126}$Xe(n,2n)$^{125}$Xe, $^{128}$Xe(n,2n)$^{127}$Xe, $^{134}$Xe(n,2n)$^{133}$Xe and $^{136}$Xe(n,2n)$^{135}$Xe have been calculated up to 50 MeV energy. The obtained calculation results for the neutron cross sections of these reactions have been compared with cross sections taken from the EXFOR database and TENDL library as shown in Figs. 1, 2, 3, 4 and 5.

### $^{124}$Xe(n,2n)$^{123}$Xe Nuclear Reaction

When the nuclear reaction $^{124}$Xe(n,2n)$^{123}$Xe is examined in Fig. 1, the ALICE/ASH code calculation (with equilibrium model) has provided a full harmony with experimental data of Bazan [8] at the 14, 14.4 and 14.7 neutron energies. The cross section results of the preequilibrium models via the codes EMPIRE 3.2 Malta and the TALYS 1.6, and TENDL-2013 library data are in the good agreement with Sigg and Kuroda [9] and Kondaiah et al. [10]. In addition, the cross section data of Sigg and Kuroda [9] at 14.6 MeV is in good agreement with result of cross section formula of Tel et al. [23]. All cross sections for the considered reaction have maximum position in the neutron energy range of 13–20 MeV.

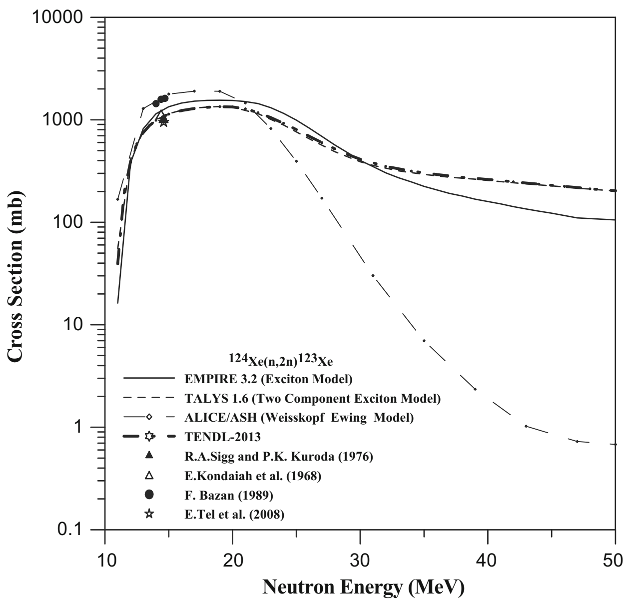


**Fig. 1** Excitation functions of $^{124}$Xe(n,2n)$^{123}$Xe reaction calculated by EMPIRE-3.2 Malta, TALYS-1.6 and ALICE/ASH along with the experimental data, the formula result of Tel et al. [23], and TENDL-2013

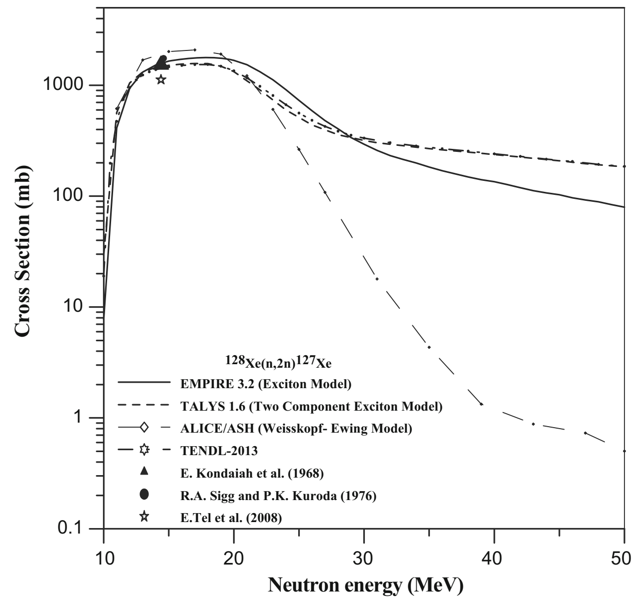


**Fig. 3** Excitation functions of $^{128}$Xe(n,2n)$^{127}$Xe reaction calculated by EMPIRE-3.2-Malta, TALYS-1.6 and ALICE/ASH along with the experimental data, the formula result of Tel et al. [23], and TENDL-2013

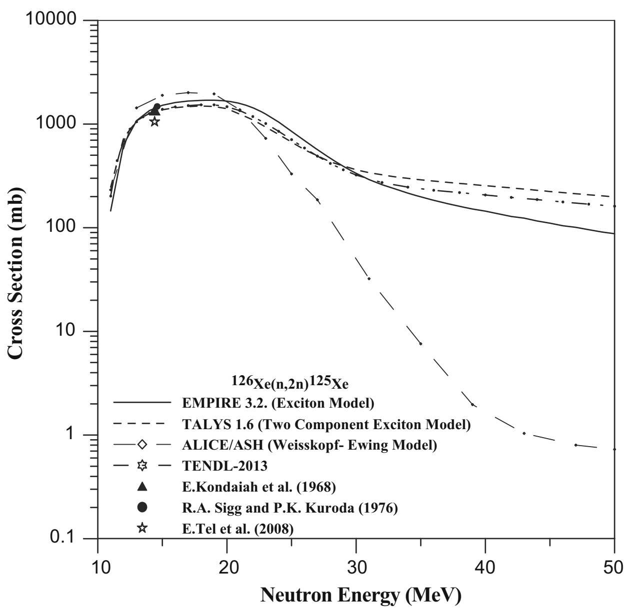


**Fig. 2** Excitation functions of $^{126}$Xe(n,2n)$^{125}$Xe reaction calculated by EMPIRE-3.2-Malta, TALYS-1.6 and ALICE/ASH along with the experimental data, the formula result of Tel et al. [23], and TENDL-2013

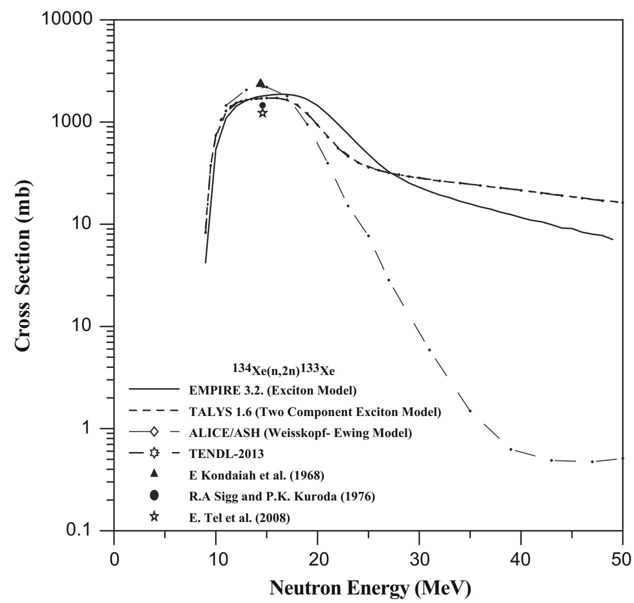


**Fig. 4** Excitation functions of $^{134}$Xe(n,2n)$^{133}$Xe reaction calculated by EMPIRE-3.2-Malta, TALYS-1.6 and ALICE/ASH along with the experimental data, the formula result of Tel et al. [23], and TENDL-2013

## $^{126}$Xe(n,2n)$^{125}$Xe Nuclear Reaction

The cross sections for nuclear reaction $^{126}$Xe(n,2n)$^{125}$Xe are shown in Fig. 2. When figure is examined, two experimental data have been used for the comparison with theoretical calculations. The experimental data of the Sigg and Kuroda [9] and the Kondaiah et al. [10] give similar and closer results with model calculations including the exciton model, two component exciton model and the Weisskopf–Ewing model by nuclear codes. On the other

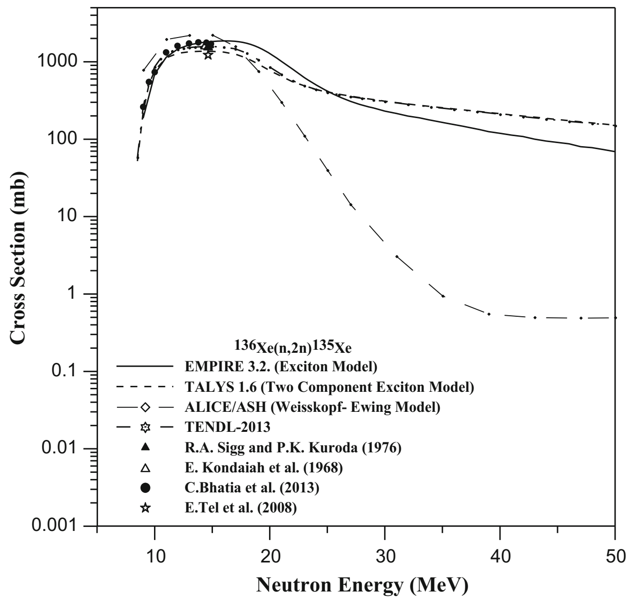


**Fig. 5** Excitation functions of $^{136}$Xe(n,2n)$^{135}$Xe reaction calculated by EMPIRE-3.2-Malta, TALYS-1.6 and ALICE/ASH along with the experimental data, the formula result of Tel et al. [23], and TENDL-2013

hand, the experimental cross section data for this reaction are consistent with result of cross section formula of Tel et al. [23]. All excitation functions for $^{126}$Xe(n,2n)$^{125}$Xe nuclear reaction give maximum cross sections in the energy range of 13–20 MeV.

### $^{128}$Xe(n,2n)$^{127}$Xe Nuclear Reaction

The excitation functions for $^{128}$Xe(n,2n)$^{127}$Xe reaction have been given in Fig. 3. When all the results are analyzed, it can be said that all the models are in harmony with the experimental results of the Sigg and Kuroda [9] and the Kondaiah et al. [10]. And also the harmony continuous approximately up to energy of 25 MeV. Above 25 MeV incident energy, the Weisskopf–Ewing model calculations by ALICE/ASH code give lowest results. The agreement between the experimental data of the Kondaiah et al. [10] and the result of cross section formula of Tel et al. [23] at 14.4 MeV is acceptable. All model calculation results appear to give maximum value about incident energy 13–20 MeV for the investigated reaction.

### $^{134}$Xe(n,2n)$^{133}$Xe Nuclear Reaction

In Fig. 4, $^{134}$Xe(n,2n)$^{133}$Xe nuclear reaction cross sections have been theoretically calculated and compared with the experimental cross section values reported by Sigg and Kuroda [9] and Kondaiah et al. [10]. As seen in the figure, the obtained cross section values from the ALICE/ASH code give a full harmony with experimental data of Kondaiah et al. [10] at the 14.4 MeV energy. On the other hand, the experimental data of 1460 mb reported by Sigg and Kuroda [9] at the 14.6 MeV energy is in good agreement with cross section formula result of Tel et al. [23]. TENDL-2013 library data and TALYS code calculations for this reaction give almost the same excitation function results.

### $^{136}$Xe(n,2n)$^{135}$Xe Nuclear Reaction

The nuclear reaction $^{136}$Xe(n,2n)$^{135}$Xe is examined in Fig. 5. The experimental cross section values of Bhatia et al. [11] have shown a perfect fit with preequilibrium model results by EMPIRE 3.2 Malta code for incident neutron energy region of 8.96–14.85 MeV. In addition, the experimental cross section data of the Sigg and Kuroda [9] and the Kondaiah et al. [10] are generally consistent with predictions of the exciton model and two component exciton model for this nuclear reactions. Above the maxima of excitation functions, the Weisskopf–Ewing model calculations by ALICE/ASH code give lowest results. Thereby, the trend of the nuclear cross section data can be characterized by different nuclear models at the different energy ranges.

## Conclusions

Cross sections for the $^{124}$Xe(n,2n)$^{123}$Xe, $^{126}$Xe(n,2n)$^{125}$Xe, $^{128}$Xe(n,2n)$^{127}$Xe, $^{134}$Xe(n,2n)$^{133}$Xe and $^{136}$Xe(n,2n)$^{135}$Xe reactions induced by neutrons of the Xe target materials have been calculated in certain energy values. The calculated cross sections have been compared with the existing experimental values and the obtained conclusions can be summarized as follows;

- The energy range at maximum cross section value of the excitation functions appears the region of 13–20 MeV for (n,2n) nuclear reactions in this work.
- At the maxima position of excitation functions, the calculated cross sections using different nuclear models by the codes ALICE/ASH, TALYS 1.6 and EMPIRE 3.2 Malta give generally consistent results with experimental data.
- It is seen that equilibrium and pre-equilibrium processes for (n,2n) nuclear reactions exhibit the different excitation function shapes above maximum region of cross sections (above 20 MeV).
- The Weisskopf–Ewing model calculations by ALICE/ASH code give lowest results neutron energies above the maxima of excitation functions.

- Semi-empirical cross section formulae have good predictions for obtaining the cross section values at the particular energies.
- As a result, more theoretical and experimental works are needed, because the measurements of investigated (n,2n) reaction cross sections in the literature are not very large.

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