EPJ Web of Conferences **128**, 01001 (2016) DOI: 10.1051/epjconf/201612801001
TESNAT 2016

Calculations of (n,2n) reaction cross sections for ^{74,76,78,80,82}Se up to 20 MeV

Halide Şahan[1,a], *Muhittin* Şahan[1], *Eyyup* Tel[1]

[1]*Osmaniye Korkut Ata University, Faculty of Arts and Science, Department of Physics, Osmaniye, Turkey*

Abstract. In the present work, the excitation functions of (n,2n) reactions for five isotopes of selenium (74,76,78,80,82Se) are calculated using ALICE/ASH, EMPIRE-3.2.2, PCROSS, and TALYS 1.6 computer codes based on statistical model up to 20 MeV. The theoretical calculations provide information of the (n,2n) excitation functions with the increasing target neutron number of selenium element. The calculated cross-sections were compared with experimental data from EXFOR and also with the cross-sections estimated with semi empirical formula developed by Tet et al. (2008) [18]. Results show a reasonably good agreement between the calculations and the experimental data from literature.

1 Introduction

The theoretical calculation models are necessary to provide the estimation of the particle–induced reaction cross sections due to the experimental difficulty [1,2]. In past years the cross section of selenium isotopes (^{74,76,78,80,82,84}Se) around 14-15 MeV have been measured by many researches such as Hille and Münzer [3]; Minetti and Pasquarelli [4]; Casanova and Sanchez [5]; Hoang et al. [6] and Guozhu He [7].

Selenium, discovered by Berzelius in 1817, is a non-metallic chemical element with symbol Se. Selenium with 34 protons and having from 40 to 48 neutrons is rarely occurs in its elemental state in nature as pure or compounds. There are six naturally isotopes of Selenium (^{74,76,78,80,82,84}Se), five of which are stable (^{74,76,77,78,80}Se). Selenium occurs in minerals such as eucairite (CuAgSe), crooksite (CuThSe) and clausthalite (PbSe). Selenium element is used extensively in electronics and metal alloys such as the lead plates and also glass industry to give a red color to glasses and enamels. Selenium is an essential trace element for some species, including humans. Our bodies contain about 14 milligrams, and every cell in a human body contains more than a million selenium atoms. It can cause health problems in human body.

In the present work, neutron interactions with five selenium isotopes as ^{74}Se($n,2n$)^{73}Se, ^{76}Se($n,2n$)^{75}Se, ^{78}Se($n,2n$)^{77}Se, ^{80}Se($n,2n$)^{79}Se, and ^{82}Se($n,2n$)^{81}Se by four nuclear reaction codes such as ALICE/ASH [8], EMPIRE [9], TALYS [10], and PCROSS [11] have been investigated and then compared with experimental data from EXFOR [12] in the literature and with evaluated data ENDF/B-VII.1 (2014) library.

The empirical formula for ($n,2n$) reaction cross sections at neutron energy of 14.5 MeV was developed by Tel et al. [13]. These formulas have been given as follows;

$$\ln\sigma_{n,2n} = \begin{Bmatrix} 7.15\left[1-2.45e^{-31.620(N-Z)/A}\right] & \text{for even } A \\ 7.65\left[1-1.59e^{-23.06(N-Z)/A}\right] & \text{for odd } A \end{Bmatrix} \quad (1)$$

For (n,2n) reaction cross sections of ^{74}Se($n,2n$)^{73}Se, ^{76}Se($n,2n$)^{75}Se, ^{78}Se($n,2n$)^{77}Se, ^{80}Se($n,2n$)^{79}Se and ^{82}Se($n,2n$)^{81}Se at 14-15 MeV, the calculated cross sections for isotopes of $^{74,76,78,80,82}Se$ were compared with a semi empirical formula developed by Tel et al. [13].

2 Results and Discussions

In this work, as target element, cross sections for ^{74}Se($n,2n$)^{73}Se, ^{76}Se($n,2n$)^{75}Se, ^{78}Se($n,2n$)^{77}Se, ^{80}Se($n,2n$)^{81} and ^{82}Se($n,2n$)^{81} reactions have been theoretically calculated at neutron energy centred around 14-15 MeV using four computer codes based on statistical model. These computer codes are ALICE/ASH [8], EMPIRE-3.2.2 [9], PCROSS [11], and TALYS 1.6 [10]. These model calculations were compared with the semi empirical formula developed by Tel et al. [13] and experimental data form EXFOR.

Figs. 1-5 show theoretical calculations of ALICE/ASH, EMPIRE, PCROSS, and TALYS 1.6, experimental data form EXFOR, semi-empirical data from Tet et al. (2008), and evaluated ENDF/B-VII.1 data for the $^{74,76,78,80,82}Se$ reactions. More *detailed* information about our calculations and comparisons for the $^{74,76,78,80,82}Se$ reactions are given below.

Calculated cross sections of $^{74}Se(n,2n)\ ^{73}Se$ reaction between 10 and 20 MeV is shown in Fig. 1. The experimental data obtained from six different researches using EXFOR at 10 to 20 MeV and the empirical cross section data evaluated by Tel et al. [13] were compared

---

[a] Corresponding author: muhittinsahan@osmaniye.edu.tr

with PCROSS, EMPIRE and TALYS and ALICE/ASH data. While the cross section data from TALYS 1.6 code has higher value to be 441.0 mb, which is approximately the same value of ENDF/B-VII.1 data, the cross section data from PCROSS has lower value to be 223.14 mb as seen from Fig. 1. All calculation data in Fig. 1 almost agree well with the measured data from EXFOR at 13 MeV up to 17 MeV. Semi-empirical cross section data evaluated by Tel et al. [13] estimated to be ~330.60 mb at 14.5 MeV is closer agreement with the data calculated using PCROSS, EMPIRE, and ALICE/ASH data.

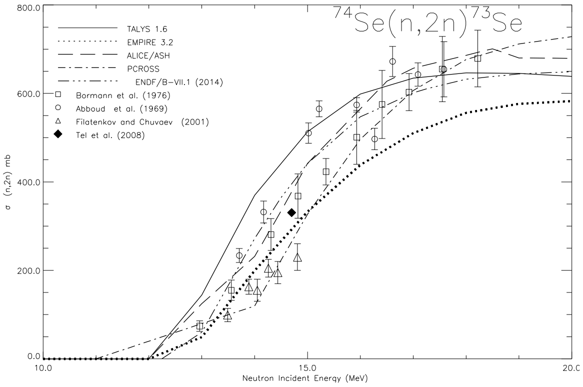

Fig. 1. Excitation function of ^{74}Se(n,$2n$)^{73}Se reaction cross sections calculated by TALYS, EMPIRE, ALICE/ASH, and PCROSS and ENDF/B-VII.1 (2014) along with experimental data and semi-empirical calculation.

The cross-section data of *^{76}Se(n,2n)^{75}Se* reaction are given in Fig. 2. The theoretical calculations produced by EMPIRE, TALYS, PCROSS and ALICE/ASH are compared with the earlier six experimental data from EXFOR and are also compared with the empirical data (Tel, et al.) [13] at 14.5 MeV energy. In general, Fig. 2 illustrates a marked increase in energy value with increasing cross section of ^{76}Se(n,$2n$)^{75}Se for the empirical cross-section calculations and experimental data. Fig. 2 shows the degree of agreement between the theoretical and experimental cross sections.

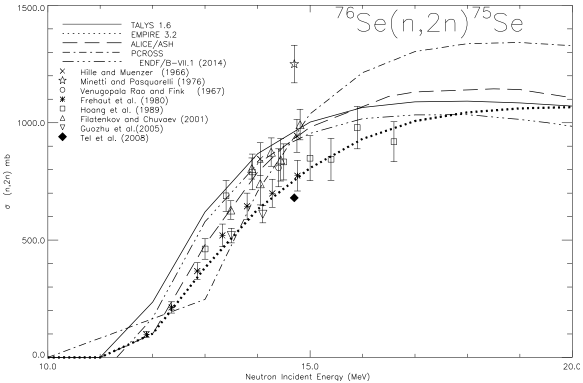

Fig. 2. Excitation function of ^{76}Se(n,$2n$)^{75}Se reaction cross sections calculated by TALYS, EMPIRE, ALICE/ASH, and PCROSS and ENDF/B-VII.1 (2014) along with experimental data and semi-empirical calculation.

Fig. 3 shows the excitation function of the nuclear reaction of ^{78}Se(n,$2n$)^{77}Se up to 20 MeV. Examining the nuclear reaction ^{78}Se(n,$2n$)^{77}Se in Fig. 3, the EMPIRE code calculation has provided a full harmony with experimental data of Frehaut et al. (1980) from EXFOR [12] 10 MeV and 15 MeV. Semi-empirical cross-section data developed by Tel et al. [13] has same cross section of 940 mb at 14-15 MeV.

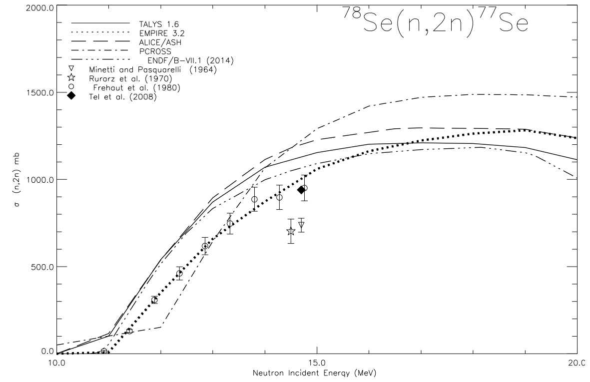

Fig. 3. Excitation function of ^{78}Se(n,$2n$)^{77}Se reaction cross sections calculated by TALYS, EMPIRE, ALICE/ASH, and PCROSS and ENDF/B-VII.1 (2014) along with experimental data and semi-empirical calculation.

The excitation function of the ^{80}Se(n,$2n$)^{79}Se nuclear reaction between 10 MeV and 20 MeV is shown in Fig. 4. Only one suitable experimental data with high error bars given by Bormann et al. (1967) from EXFOR [8] is available for ^{80}Se(n,$2n$)^{79}Se reaction in literature. There is a good correlation between theoretical calculations from four computer codes and all semi-empirical data at 14-15 MeV and experimental data. Semi-empirical cross-section data developed by Tel et al. [13] has same cross section of 940 mb at 14-15 MeV. EMPIRE from four models at 14-15 MeV is the same cross section value (mean 1100 mb) with semi-empirical cross-section data developed by Tel et al. [13]. Experimental data from EXFOR at 14-15 MeV have the same value with ALICE/ASH, TALYS and PCROSS codes. For ^{80}Se(n,$2n$)^{79}Se reactions, the experimental data are between 13.0- 16.75 MeV as seen from Fig. 4.

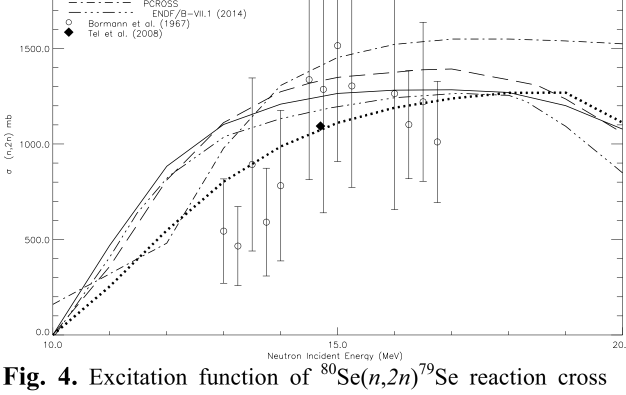

Fig. 4. Excitation function of ^{80}Se(n,$2n$)^{79}Se reaction cross sections calculated by TALYS, EMPIRE, ALICE/ASH, and

PCROSS and ENDF/B-VII.1 (2014) along with experimental data and semi-empirical calculation.

The computed cross sections based on ALICE/ASH, EMPIRE, PCROSS, and TALYS together with experimental data (EXFOR) [12] and evaluated ENDF/B-VII.1 data file for (n,2n) reaction on ^{82}Se isotope from 10 MeV to 20 MeV are shown in Fig. 5. Our theoretical values do agree with the available experimental data in the energy range of 10-15 MeV. Four experimental data are available for ^{82}Se(n,$2n$)^{81}Se reaction. The evaluated values of cross-sections are in reasonable agreement with the experimental values reported by Minetti and Pasquarelli (1967), Hasan et al. (1972), Kao and Alford (1975), and Filatenkov (2001) (All from EXFOR) [12].

3 Conclusion

In this work, cross sections for ^{74,76,78,80,82}Se reactions have been calculated in the energy range from 10 to 20 MeV using nuclear model calculations such as ALICE/ASH [8], TALYS 1.6 [10], EMPIRE-3.2.2 [9], and PCROSS [11]. In order to compare with the model calculations, we obtained ENDF/B-VII.1 results. As seen all figures, cross section values increase generally from 10 MeV to 15 MeV and then decrease to 20 MeV. The calculated cross sections are a reasonably good agreement between the calculated and experimental data, which is available in EXFOR database library.

References

1. R.A. Forrest, J. Kopecky, Fusion Engineering and Design, **82**, 73 (2007)
2. L. Goyal, P. Gur, Pramana-J. Phys.**72**, (2), 355 (2009)
3. P. Hille, H. Münzer, Acta Phys. Austr. **23**, 44 (1966)
4. B. Minetti, A. Pasquarelli, Nucl. Phys. **A100**, 186 (1967)
5. J.L. Casanova, M.L.Sanchez, Ann. Fis. (Spain) **72**, 186 (1976)
6. H.M. Hoang, U. Garuska, A. Marcinkowski, B. Zwieglinski, Z. Phys. A Atomic Nuclei **334**, 285-291 (1989)
7. He Guozhu, Liu Zhongjie, LuoJunhua, Kong Xiangzhong, Indian Journal of Pure & Applied Physics ,**43**, 729, (2005)
8. C.H.M. Broeders, A.Yu. Konobeyev, Yu.A. Korovin, V.P. Lunev, M. Blann, ALICE/ASH manual, FZK 7183, http://bibliothek.fzk.de/zb/berichte/FZKA7183.pdf (2006)
9. M. Herman, et al., EMPIRE-3.2 Malta modular system for nuclear reaction calculations and nuclear data evaluation, User's Manual (2013)
10. A. Koning, S. Hilaire, S. Goriely, TALYS 1.6- A Nuclear Reaction Program, User Manual, 1st edition (NRG, The Netherlands, 2013).
11. R. Capote, et al., Final Report on Research contract 5472/RB, INDC (CUB)-004, (Higher Institute of Nuclear Science and Technology, Cuba). Translated by the IAEA, (PCROSS program code) (1991)
12. EXFOR/CSISRS, Brookhaven National Laboratory, National Nuclear Data Center, (http://www.nndc.bnl.gov/exfor/) (2009)
13. E. Tel, Ş. Okuducu, M. H. Bölükdemir, G. Tanir, Int. J. Mod. Phys. E, **17** (3), 567 (2008)