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Calculations of (n,2n) reaction cross sections for Barium isotopes from 5 to 20 MeV

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Abstract. In this study, the excitation functions of (n,2n) reactions for ^{30,32,34,35,37,38}Ba isotopes are calculated using TALYS 1.6, EMPIRE-3.2.2, and ALICE-GDH codes based on statistical model up to 20 MeV. Moreover, the cross section for each isotope have also been estimated at 14.2 MeV using semi empirical formula developed by four different authors. The calculated and estimated cross-sections are compared with experimental cross-sections from EXFOR and compared with the evaluation data in ENDF/B-VII.1 library. Results are close agreement with the experimental data from literature.

1 Introduction

The nuclear reaction models have been developed estimate the reaction cross-sections due to lack of experimental data [1-4]. Most of existing information concerning the mechanism of (n, 2n) have been acquired from the data taken at neutron energies near 14 MeV. Importance of theoretical cross-section calculations for fast fission and fusion reactors increase in recent years. Fission products accumulate in an operating reactor as the fuel undergoes fission [5]. Cross sections for (n,2n) reactions induced by neutrons of 14-15 MeV energies have been calculated by many researches covering all the elements of the periodic table.

In this study, the (n,2n) cross sections for $^{30,32,34,35,37,38}Ba$ isotopes were calculated from 10 MeV to 20 MeV neutron energies using TALYS 1.6, EMPIRE-3.2.2, and ALICE. Ba, first isolated in 1808 by English chemist Sir Humphry Davy, is a chemical element with atomic number 56 and is a soft silvery metallic alkaline earth metal. There are seven naturally occurring isotopes of barium ($^{30,32,34,35,37,38}Ba$) [6]. The most common naturally occurring minerals of barium are $BaSO_4$ and $BaCO_3$, called as barite. Since radioactive isotopes of barium are among the comparatively abundant fission products, they have a biological importance [7]. The barium isotopes which is already found to be product of irradiated uranium are associated with one of the two nuclei formed by uranium fission [8].

Calculations were performed by using EMPIRE [9], TALYS [10], and ALICE [11] codes. These model codes are used for evaluating of many nuclear data in literature. The GDH model for pre-equilibrium emissions [12,13] and the W-E model for equilibrium calculations [14] are used in the ALICE.

In this study, semi empirical formulae developed by four different authors were also used for Ba isotopes at 14.5 MeV. These formulae have been in Table 1.

Table 1: Four different semi empirical formulae of the (n,2n) reaction at 14.5 MeV.

Author	Formula, $\sigma(n,2n)$ (mb)	Mass region
Tel et al. [15]	$=\exp\{7.15[1-2.45\exp(-31.62s)]\}$ $=\exp\{7.65[1-1.59\exp(-23.06s)]\}$	14≤*A*≤241 *for even A* *for odd A*
Goyal &Gur [16]	$= -69558.98(Z/A)^3 + 13430.42(Z/A) + 1116.7$ $= 25340(Z/A)^3 - 40114(Z/A) + 16543$	*for even A* *for odd A*
Ikeda *et al.* [17]	$=\exp\left[7.7590(1-0.80645\exp(-17.038(N-Z)/A))\right]$	For all A
Bychkov et al. [19]	$=(100+A)\{1-\exp[-10.0(N-Z)/A][-5.7301+135.94(N-Z)/A]\}$ $=(100+A)\{3.3082+19.963(N-Z)/A\}$	0.03 ≤ (N-Z)/A≤0.11 (N-Z)/A≥0.11

It is important to emphasize that a correction was made on the formula given by Tel et al. (2008) [15]. When the formula was multiplied by a factor of 1.4, the results were seen a good agreement with model calculations and experimental data at 14.5 MeV.

2 Results and Discussions

In this present work, (*n,2n*) reaction cross sections were theoretically calculated for the reactions ^{130}Ba(n,2n)^{129}Ba, ^{132}Ba(n,2n)^{131}Ba, ^{134}Ba(n,2n)^{133}Ba, ^{135}Ba(n,2n)^{134}Ba, ^{136}Ba(n,2n)^{135}Ba, ^{137}Ba(n,2n)^{136}Ba, and ^{138}Ba(n,2n)^{137}Ba at an incident neutron energy of 14.2 MeV using their different models up to 20 MeV. These models are given as EMPIRE [8], TALYS [10], and

ALICE/ASH [11]. The evaluation data in ENDF/BVII.1 library and the experimental cross-section data from EXFOR [16] were also used for comparison.

The calculated cross-sections were shown in Figs. 1-7. Figs. 1-7 show theoretical EMPIRE 3.2 Malta, TALYS 1.6, ALICE/GDH calculations, and also show the evaluated ENDF/B-VII.1 data. The semi-empirical data and the ENDF/B-VII.1 data were used to compare with three calculated cross section code data. Moreover, the experimental data were also plotted in all figures around 14.5 MeV.

Theoretical calculations for the ^{130}Ba(n,2n)^{129}Ba reaction obtained from there computer codes using EMPIRE-3.2.2, TALYS-1.6, and ALICE/GDH in the energy range up to 20 MeV have been given in Fig. 1. Theoretical results have been compared with the evaluated nuclear data of ENDF/B-VII.1, the available experimental values from EXFOR [16], and semi-empirical calculation developed by Tel et al. [15], Goyal and Gur [16], Ikeda et al. [17], and Bychkov et al. [18]. From the Fig.1, all theoretical calculations and ENDF data near 14 MeV are in agreement with available measured data of Lu et al., Pepelnik et al. [16] and the data (1431.75mb) from Tel et al [15] while the experimental data from Konno et al. [16] were higher.

The theoretical cross section calculations of ^{132}Ba(n,2n)^{131}Ba reaction of EMPIRE-3.2.2, TALYS-1.6, and ALICE/GDH in the energy range from 10 MeV to 20 MeV were given in Fig. 2. The semi empirical formulae data by Tel et al. [15]. Sakane et al. [16] are also in approximately agreement with the results of ALICE/ASH and ENDF lines at energy range between 13 MeV and 15 MeV. However, Luo et al. and Kondo et al. have higher cross section values at the same energy range. The calculated cross section data from TALYS and EMPIRE are lower values.

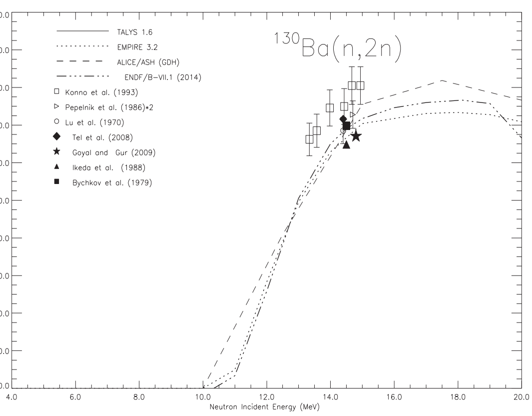

Fig.1. ^{130}Ba(n,2n)^{129}Ba reaction cross section.

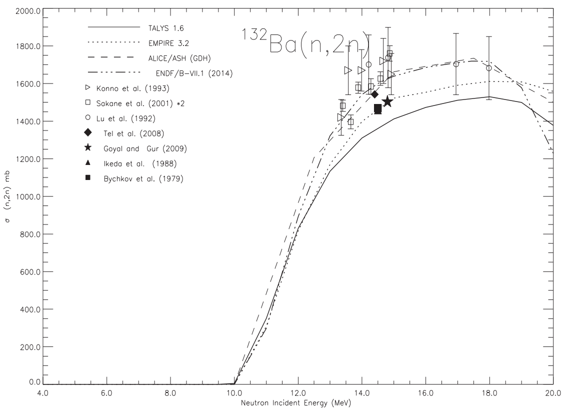

Fig.2. ^{132}Ba(n,2n)^{131}Ba reaction cross section.

The cross section results of ^{134}Ba (n,2n)^{133}Ba up to 20 MeV is shown in Fig. 3. As seen from Fig. 3, ALICE/GDH and EMPIRE lines show a close harmony with experimental data by Konno et al. and Xiangzhong et al. from EXFOR [16]. The agreement between calculated values from ENDF and TALYS-1.6 and results of the experimental data of Ikeda et al. from EXFOR [16] have similar values at 14-15 MeV. Moreover, the semi empirical calculated data using Table 1 are approximately same values with Ikeda et al. data and with ENDF data.

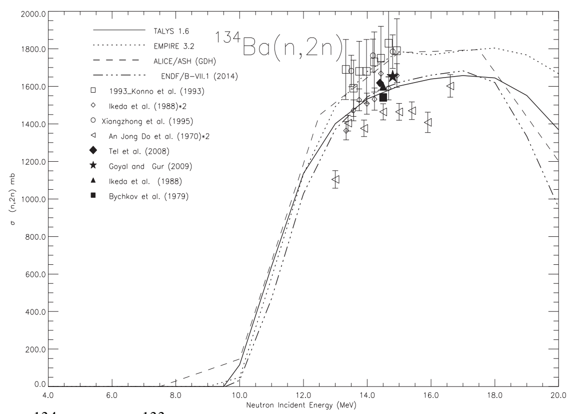

Fig.3. ^{134}Ba(n,2n)^{133}Ba reaction cross section.

The excitation function of the ^{135}Ba(n,2n)^{134}Ba up to 20 MeV was given in Fig. 4. From Fig. 4, the line from of ALICE/GDH seems to be higher than the other lines, especially between 6 and 18 MeV. The only one experimental data (Strohmaier et al.) [16] was found in literature. EMPIRE-3.2.2, TALYS-1.6, and ENDF/B-VII.1 data points are in agreement with each other and experimental data at all energy ranges. Strohmaier et al.'s measurements agree with the calculation between 7 to 20 MeV. All semi empirical calculations at 14.2 MeV agree with all calculated results except for ALICE-GDH data.

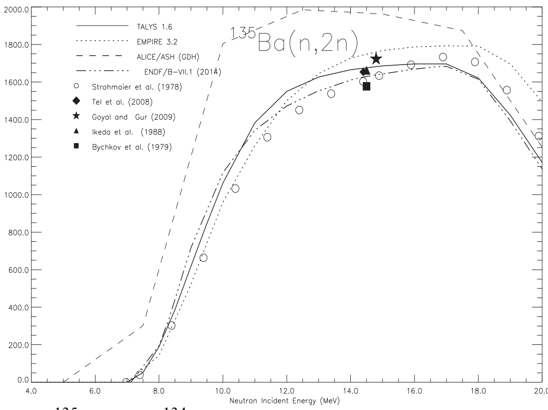

Fig.4. ^{135}Ba(n,2n)^{134}Ba reaction cross section.

Calculations of ^{136}Ba(n,2n)^{135}Ba up to 20 MeV was presented in Fig. 5. For ^{136}Ba(n,2n) reaction, three experimental data were found from literature. All experimental data were multiplied by a factor of 2. Ikeda et al.'s measurements agree with the calculation between 13.3 and 14.9 MeV. Strohmaier et al.'s measurements agree with the calculation below 11.5 MeV. Above 5 MeV, however, their data are much higher than the calculation. There is good agreement between the cross-section between 10 and 15 MeV calculated with three computer codes and ENDF/B-VII.1 files and the experimental data from EXFOR. Semi empirical data using formulae given in Table 1 at 14.2 MeV were also close agreement with both calculated data from EMPIRE, TALYS, and ENDF/B-VII.1 files and also experimental data.

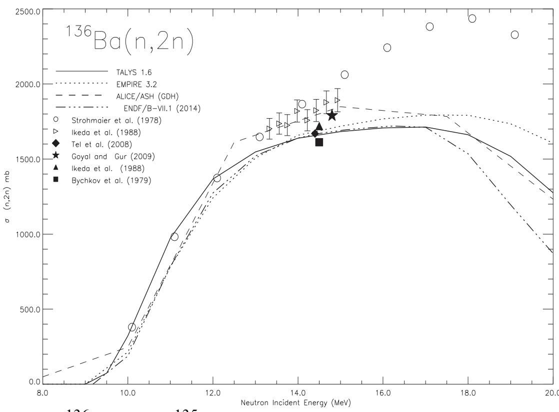

Fig.5. ^{136}Ba(n,2n)^{135}Ba reaction cross section.

The cross sections of ^{137}Ba(n,2n)^{135}Ba were given in Fig. 5. The theoretical calculations of EMPIRE-3.2.2, ALICE-GDH, and TALYS-1.6 codes, and ENDF/B-VII.1 give approximately good agreement with experimental and semi-empirical data except from Strohmaier et al. [16], the obtained semi empirical data from Tel et al. [15] was seen same value with theoretical data from EMPIRE at 14.5 MeV.

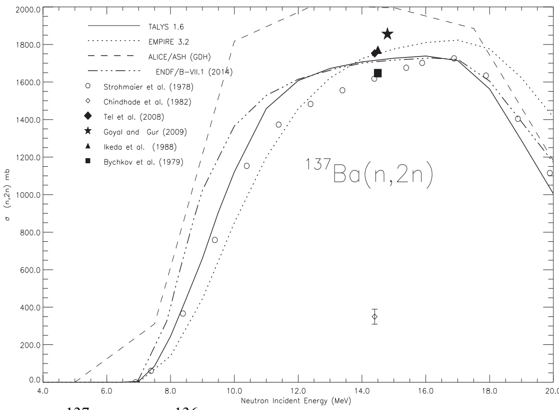

Fig.6. ^{137}Ba(n,2n)^{136}Ba reaction cross section.

The calculated ^{138}Ba(n,2n)^{137}Ba reaction cross sections and comparison with EXFOR database are shown in Fig. 7. As seen from Fig. 7, all theoretical lines from codes seem to be slightly same with experimental data and with ENDF/B-VII.1. The semi empirical data by Tel et al. [15] and Bychkov et al. are also close to data calculated with TALYS, while Ikeda et al. and Goyal and Gur are close to data calculated with ALICE-GDH.

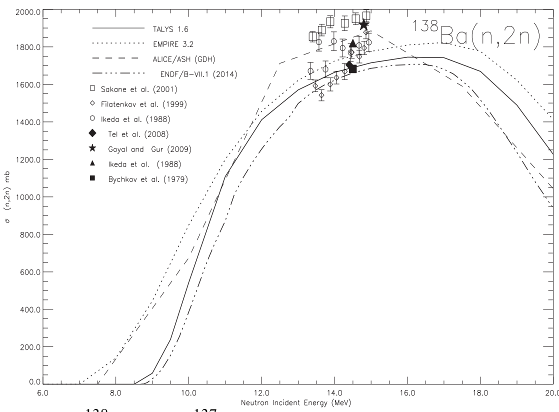

Fig.7. ^{138}Ba(n,2n)^{137}Ba reaction cross section.

3 Conclusion

In this work, we deduce excitation functions for the following reactions: ^{130}Ba(n,2n)^{129}Ba, ^{132}Ba(n,2n)^{131}Ba, ^{134}Ba(n,2n)^{133}Ba, ^{135}Ba(n,2n)^{134}Ba, ^{136}Ba(n,2n)^{135}Ba, ^{137}Ba(n,2n)^{136}Ba, and ^{138}Ba(n,2n)^{137}Ba. Theoretical calculated results within TALYS, EMPIRE, and ALICE nuclear model codes were compared with evaluated nuclear data from EXFOR, ENDF data libraries and also compared with some published semi empirical formula based on the statistical model obtained from literature. The model calculations are seen in general in agreement with the experimental cross-sections from EXFOR and semi-empirical cross section data from literature.

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