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Regular Article

# Cross sections for the $(n, p)$ reaction of selenium isotopes within 10.5 to 19.81 MeV neutron energies

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**Abstract** The cross sections of the selenium isotopes $^{76}$Se, $^{77}$Se, $^{78}$Se and $^{80}$Se within 10.5–19.81 MeV neutron energy range have been measured through neutron activation method along with off-line $\gamma$-ray spectrometry. The quasi-monoenergetic neutrons were produced from the $^{7}$Li$(p, n)$ reaction at 14UD BARC-TIFR Pelletron Accelerator Facility, Mumbai, India. The statistical codes TALYS-1.9 and EMPIRE-3.2.2 were applied for the theoretical calculation of reaction cross sections with different level density models from 2 to 22 MeV neutron energies. Besides this, the Se$(n, p)$ As reaction cross sections were also calculated from different systematic formulae within 14–15 MeV neutron energies. The measured data were compared with existing literature data available in the EXFOR database, evaluated data of ENDF/B-VIII.0, JENDL-4.0 and TENDL-2019 libraries and with theoretical outcomes through TALYS-1.9 and EMPIRE-3.2.2 codes. The uncertainties in existing cross sections were calculated through the method of covariance analysis by including partial uncertainties and correlation among the different attributes. The $(n, p)$ reaction cross sections of selenium isotopes at higher neutron energies first time measured in the present work can be added as new data in the nuclear data library.

## 1 Introduction

The experimentally measured cross sections for the neutron-induced reactions on various nuclei are useful for verifying the validity of the different theoretical models [1]. The D-T fusion will produce neutrons of ≈14.6 MeV energy and scattered neutron spectra from thermal to 14.6 MeV, and the interaction of neutrons with structural materials of the reactor open $(n, p)$, $(n, 2n)$, $(n, \gamma)$, $(n, \alpha)$, etc., reaction channels. In experimental EXFOR database [2], the measured data are available for several nuclei, but there is a large inconsistency

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THE EUROPEAN PHYSICAL JOURNAL A

Regular Article - Experimental Physics

# Neutron induced reaction cross section of $^{51}$V with covariance analysis

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**Abstract** The cross section of the $^{51}\mathrm{V}(n, p)^{51}\mathrm{Ti}$ reaction was measured at 7.87, 13.05 and 16.98 MeV neutron energies using the activation technique and offline $\gamma$-ray spectrometry. Vanadium targets were activated along with Al monitor foil to measure the cross section relative to the standard $^{27}\mathrm{Al}(n, \alpha)^{24}\mathrm{Na}$ reference reaction. The quasi-monoenergetic neutron beams were produced via the $^{7}\mathrm{Li}(p, n)$ reaction at the 14UD BARC-TIFR Pelletron Facility, Mumbai, India. Statistical nuclear reaction Talys (ver. 1.9) code was used for the theoretical estimations of the $^{51}\mathrm{V}(n, p)^{51}\mathrm{Ti}$ reaction cross section. Additionally, the effects of different input parameters were considered in present work to reproduction of the experimental data more accurately. The experimental data of the present measurements were discussed and compared with the previous measurements taken from the EXFOR compilation and latest evaluations of the ENDF/B-VIII.0, JENDL/AD-2017 and TENDL-2019 libraries. The covariance method was used to estimate the magnitudes of the uncertainties in the present cross section measurements. Furthermore, the different systematic formulae at 14–15 MeV energies were used to calculate the $(n, p)$, $(n, 2n)$ and $(n, \alpha)$ reactions cross section for structural material vanadium. The calculated cross sections from the formulae were discussed and compared with the available experimental data.

## 1 Introduction

Neutron-induced reaction cross sections on structural materials are essential for the construction of the International Thermonuclear Experimental Reactor (ITER) and Accelerator Driven Sub-critical system (ADSs) [1,2] as well as production of the medical isotopes for radiation therapy. Besides this, the neutron induced cross sections data are also helpful in the nuclear heating, induced radioactivity, nuclear transmutation rates, and radiation damage of the structural materials due to gas formation on the first wall of the materials [3]. The D-T reaction produces neutrons and $\alpha$-particles, 80% of the energy carried by neutrons ($\approx$ 14MeV neutrons) transferred to the fusion reactor first wall and the breeding blanket. The remaining energies are carried by $\alpha$-particles, charged particles and low energy neutrons, which induce sputtering, erosion and blistering in the plasma-facing materials [4]. In the neutron energy range of 15–21 MeV, the neutron induced reaction cross sections of structural materials are also important for developing Accelerator Driven Sub-critical system (ADSs) for future nuclear energy generation.

Vanadium based alloys have excellent properties that make them an essential structural material for reactor technology. In the fusion reactor, vanadium is considered the reactor structural material for the first wall/blanket applications due to the low activation properties of the vanadium alloys. The vanadium based alloys have high thermal conductivity and lower thermal expansion coefficient, which lower thermal stress for a given temperature than other alloys and enhancing reactor lifetime capability and wall load. The lower helium generation rate, lower bulk nuclear heating rate and better tritium breeding performance due to lower neutron absorption are shown by the vanadium based alloys [5,6]. Thus, it is essential to study the higher energy neutron induced reaction cross section of vanadium from an application point of view. Besides this, the higher energy neutron

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# Systematic study of the (*n*, 2*n*) reaction cross section for $^{121}$Sb and $^{123}$Sb isotopes

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**Abstract:** The cross sections of the $^{121}\mathrm{Sb}(n,2n)^{120}\mathrm{Sb}^{\mathrm{m}}$ and $^{123}\mathrm{Sb}(n,2n)^{122}\mathrm{Sb}$ reactions were measured at 12.50, 15.79 and 18.87 MeV neutron energies relative to the standard $^{27}\mathrm{Al}(n,\alpha)^{24}\mathrm{Na}$ monitor reaction using neutron activation and offline γ-ray spectrometry. Irradiation of the samples was performed at the BARC-TIFR Pelletron Linac Facility, Mumbai, India. The quasi-monoenergetic neutrons were generated via the $^{7}\mathrm{Li}(p,n)$ reaction. Statistical model calculations were performed by nuclear reaction codes TALYS (ver. 1.9) and EMPIRE (ver. 3.2.2) using various input parameters and nuclear level density models. The cross sections of the ground and the isomeric state as well as the isomeric cross section ratio were studied theoretically from reaction threshold to 26 MeV energies. The effect of pre-equilibrium emission is also discussed in detail using different theoretical models. The present measured cross sections were discussed and compared with the reported experimental data and evaluation data of the JEFF-3.3, ENDF/B-VIII.0, JENDL/AD-2017 and TENDL-2019 libraries. A detailed analysis of the uncertainties in the measured cross section data was performed using the covariance analysis method. Furthermore, a systematic study of the $(n,2n)$ reaction cross section for $^{121}$Sb and $^{123}$Sb isotopes was also performed within 14–15 MeV neutron energies using various systematic formulae. This work helps to overcome discrepancies in Sb data and illustrate a better understanding of pre-equilibrium emission in the $(n,2n)$ reaction channel.

**Keywords:** antimony, (*n*, 2*n*) reaction cross section, $^{7}$Li(*p*, *n*) reaction neutron source, neutron activation and offline γ-ray spectrometry, systematic formulae, covariance analysis, TALYS (ver. 1.9) and EMPIRE (ver. 3.2.2) codes

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## I. INTRODUCTION

Nuclear data such as cross section, half-life, decay modes, decay radiation properties, and γ-rays from radionuclides of the various radioisotopes are widely used in nuclear medicine, radiation shielding, fusion/fission reactor design, radioactive waste disposal and transmutation, radiation safety, etc. Neutron-induced reaction cross section data for different nuclei is often used to predict various theoretical nuclear models [1]. The $(n,2n)$ reaction cross sections of the $^{121}$Sb and $^{123}$Sb isotopes are essential for neutron multiplication calculations. In recent years, the $^{121}\mathrm{Sb}(n,2n)^{120}\mathrm{Sb}$ and $^{123}\mathrm{Sb}(n,2n)^{122}\mathrm{Sb}$ reaction cross sections within the energy range 13 to 20 MeV was measured by several authors, as mentioned in the EXFOR compilation [2]. The available experimental and evaluated data of the $^{121}\mathrm{Sb}(n,2n)^{120}\mathrm{Sb}$ and $^{123}\mathrm{Sb}(n,2n)$ $^{122}$Sb reactions from threshold to 20 MeV shows disagreement at the same incident energy. Since there are significant discrepancies in the measured cross section and evaluated data from different libraries for common incident neutron energy, it is difficult to refine and correct various statistical parameters.

The compound nucleus, direct and pre-equilibrium emission are the different models used to understand the reaction mechanism, and the optimum parameters needed to understand these processes. Therefore, it is essential to improve the accuracy of measured experimental data and understand these reaction models [3]. Some of the anti-

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# Experimental and theoretical study of the $^{65}$Cu$(n, p)^{65}$Ni reaction cross section from reaction threshold up to 25 MeV

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The cross section of the $^{65}$Cu$(n, p)^{65}$Ni reaction was studied experimentally at three different neutron energies using an activation technique. The quasimonoenergetic neutrons were produced via the $^{7}$Li$(p, n)$ reaction at the 14UD BARC-TIFR Pelletron facility in Mumbai, India. Al monitor foils along with Cu samples were activated to determine the incident neutron flux. The activities of the reaction products were measured using a high resolution high purity germanium spectrometry system. Statistical model calculations were performed using the reaction codes TALYS (ver. 1.9) and EMPIRE (ver. 3.2.3) from the reaction threshold to the neutron energy of 25 MeV. Additionally, the effects of various combinations of the theoretical nuclear level densities (NLDs), optical model potentials (OMPs), preequilibrium models (PEs), and $\gamma$-ray strength functions ($\gamma$ SFs) were considered for the reproduction of experimental data. The input parameters needed in theoretical calculations to reproduce the present and previous measurements were taken from the RIPL-3 database. The present results are compared with the previous measurements, with the latest evaluations of the ENDF/B-VIII.0, JEFF-3.3, JENDL-4.0/HE, CENDL-3.2, TENDL-2019, and FENDL-3.2 libraries, and with the theoretically calculated values based on TALYS and EMPIRE codes. Furthermore, the cross section of the $^{65}$Cu$(n, p)^{65}$Ni reaction was estimated within the neutron energies of 14–15 MeV using different systematic formulas. These estimated cross sections by various systematic formulas were compared with the available experimental data. The present data will help to understand the nuclear reaction theory (models) in higher energy regions and improve the evaluated nuclear data evaluation that is needed for fundamental nuclear applications.

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## I. INTRODUCTION

The use of copper as a first wall material has been considered in reactor designs that have high thermal loads on the first wall or require a shield of high electrically conductive material surrounding the plasma to help stabilize its location. Other designs also use copper as a heat sink with other materials for highly loaded diverter collector plates. Copper alloys are also considered for the electrically conducting central column of the close aspect ratio tokamaks for the new concept of compact fusion machines [1]. The ones that generate gaseous elements such as hydrogen and helium by the $(n, xp)$ and $(n, x\alpha)$ reactions are of prime concern for studying the structural stability of reactor materials from the multiple neutrons induced reactions that take place within a fusion reactor. These reactions cause damage to the first wall and structural and blanket material of the fusion reactor. In addition, other processes such as atomic displacements and transmutations may create microstructural defects and the processing of hydrogen and helium changes the physical properties of the products [2].

In addition, the study of the neutron induced reactions $(n, \gamma)$, $(n, p)$, $(n, \alpha)$, $(n, 2n)$, etc., on different nuclei provides an experimental archive to assess the relevance of the theoretical models of nuclear physics for practical applications. The experimental results help to evaluate the statistical model code and limit the parameter set used therein. Such studies can also provide valuable insight into the reaction mechanisms that dominate different regions of energy. It should be noted that updating the evaluated cross sections depends on the availability of accurate measurements obtainable from advanced neutron sources. For a given $(n, xp)$ reaction, the contributions of the direct, preequilibrium, and statistical compound nucleus processes to the emission of charged particles can be estimated [3,4]. For the analysis of the nuclear structure and the reaction mechanisms, the precise calculations of neutron induced reaction cross sections of different materials within a wide range of neutron energy are essential. Nuclear data are very important in nuclear technology research, such as the

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# Activation cross section for the $(n,2n)$ and $(n,p)$ reactions on $^{103}$Rh, $^{48}$Ti and $^{52}$Cr from reaction threshold up to 25 MeV energy region

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A R T I C L E I N F O

*Keywords:*
The $(n,2n)$ and $(n,p)$reactions cross sections
$^7$Li$(p,n)$neutron source
Activation and off-line γ-ray spectrometric techniques
TALYS (ver. 1.95) and EMPIRE (ver. 3.2.3) codes

A B S T R A C T

Activation and off-line γ-ray spectrometric methods were used to measure the ground and isomeric state $(n,2n)$ reaction cross section for $^{103}$Rh at two different neutron energies. The standard $^{27}$Al $(n,\alpha)^{24}$Na reference reaction was used to normalise neutron flux. The proton beam from the 14UD BARC-TIFR Pelletron facility in Mumbai, India, was utilised to create high-energy quasi-monoenergetic neutrons via the $^7$Li $(p,n)$ reaction. Statistical model calculations including the level density, pre-equilibrium and optical potential model were performed using the TALYS (ver. 1.95) and EMPIRE (ver. 3.2.3) reaction codes. In addition, because of considerable discrepancies in measured data, the literature $(n,p)$ reaction cross section of $^{52}$Cr and $^{48}$Ti targets were examined theoretically in the present work. The measured cross sections are discussed and compared with the latest evaluated data of the FENDL-3.2b, CENDL-3.2, TENDL-2019, JENDL-5.0, and ENDF/B-VIII.0 libraries, and experimental data based on the EXFOR compilation. The theoretical investigation of the $(n,2n)$ reaction cross section was performed for the ground and isomeric state for the first time from reaction threshold to 25 MeV energies. The experimental data corresponding to the ground, isomeric state and isomeric ratio were reproduced consistently by the theoretical calculations. The present experimental results are good with certain literature data and theoretical values.

## 1. Introduction

Studies of neutron induced reactions are of immense interest in reactor applications. In a reactor, when neutrons originated from fusion or fission reactions interact with its structural materials, control rods, fuel and shielding materials, and change the mechanical and physical properties of these materials. Therefore, it is necessary to have cross section data for these materials at all possible neutron energies. This nuclear data is required for calculating nuclear heating, induced radioactivity, nuclear transmutation rates, and radiation damage caused by gas production on prospective first wall material. The fusion reaction of deuterium and tritium (D-T) produces $\alpha$ particles and neutrons. The high-energy (14 MeV) neutrons produced from the fusion reaction, transfer their energy to the breeding blanket and the reactor's first wall. The measured experimental data of fusion reactor structural materials and evaluated data from different libraries show a large discrepancy in cross section data at the same incident neutron energy. Therefore, accurate activation cross section data at 14–15 MeV neutron energies are needed to design, construct, and evaluate the fusion reactor. The structural materials studies are now also considered for accelerator-driven subcritical systems (ADSs) and the fourth-generation nuclear reactor (Swedish Nuclear Fuel and Waste, 2008).

The systematic study of gas-producing reaction $(n,p)$ is needed because this reaction is harmful to the mechanical stability of the reactor. The existing data for this reaction was inconsistent and could not be used to resolve the discrepancy. The $(n,p)$ reactions on Cr and Ti

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