ACTIVATION CROSS-SECTIONS OF (n, p) REACTIONS FOR THE SELENIUM ISOTOPES ^{78}Se AND ^{80}Se MEASURED OVER NEUTRON ENERGY RANGE 13.73 MeV TO 14.77 MeV

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The cross-sections of ^{78}Se(n, p)^{78}As and ^{80}Se(n, p)^{80}As reactions were measured using ^{56}Fe and ^{19}F respectively as monitor elements at five neutron energies over the range 13.73 MeV to 14.77 MeV. The cross-sections were also theoretically estimated using statistical nuclear models EMPIRE-II and TALYS codes using different model parameters over 10 MeV to 20 MeV neutron energies covering the range of the neutron energies used for experimental measurements. The results indicate that the cross-sections estimated using Empire-II and Talys code could match with the experimental cross-sections by making proper choice of model parameters.

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I. INTRODUCTION

The neutron-induced reactions which are important for some specific nuclear applications can be investigated by measuring the activities of the reaction products. Some reactions exhibit characteristics thresholds, cross-sections, emission of radiations and decay half-lives which qualify them for use as monitors in fast neutron dosimeters as well as for elemental analysis [1]. In the present work the activation cross-sections for ^{78}Se(n, p)^{78}As and ^{80}Se(n, p)^{80}As reactions having negative Q-values [2] were measured at 13.73 MeV, 14.07 MeV, 14.42 MeV, 14.68 MeV and 14.77 MeV neutron energies using neutrons produced from D-T reaction in the laboratory. The measured cross-sections were compared with the literature data [1] and also with the cross-sections estimated using computer codes based on statistical model calculations. These theoretical models were developed to explain the experimental data. The statistical models mainly EMPIRE-II code [3] and TALYS code [4] were used for calculating the cross-sections.

II. EXPERIMENTAL

A. Neutron Irradiations

The neutron irradiation work was carried out at the 14 MeV neutron generator laboratory [5], Department of Physics, University of Pune, Pune. Deuterium ions of energy 175 keV and current ~100 μA were bombarded on a 8 Curie tritium target. The selenium samples were made using high purity SeO_2(99.%) in powder for study the ^{78}Se(n, p)^{78}As and ^{80}Se(n, p)^{80}As reactions. In the case of ^{78}Se(n, p)^{78}As reaction, the Fe-56 isotope in the form of natural iron powder was used as monitor. Each sample was made by mixing a known weight of SeO_2 powder with a known weight of iron powder and packing in a polyethylene bag. The total weight of the selenium powder and the iron powder was ~1 gm. The polyethylene bag was folded in such a way that the size of each sample was close to 10 mm x 10 mm. Such fifteen samples were made for studying ^{78}Se(n, p)^{78}As reaction with ^{56}Fe(n, p)^{56}Mn as monitor reaction. Later on five samples were taken and each was mounted on the horizontal plate at 0^o, 30^o, 60^o, 90^o and 120^o with reference to the deuterium ion beam incident on the tritium target.

In this manner, each sample could be placed at a distance of 50 mm from the centre of tritium target. All the five samples were irradiated with neutrons simultaneously for a period of 40 minutes. As per the energy distribution of the emitted neutrons the samples mounted at 0^o, 30^o, 60^o, 90^o and 120^o angular positions were irradiated. The decay data of the reaction products produced through ^{78}Se(n, p)^{78}As and ^{56}Fe(n, p)^{56}Mn reactions after neutron irradiation are given in Table I [6-8]. The cross-section for each reaction was obtained by taking average of three measurements made at each angular position. In the case of ^{80}Se(n, p)^{80}As reaction, ^{19}F(n, p)^{19}O reaction was used as monitor reaction. The half-life of ^{80}As is 15.2 seconds whereas half-life of ^{19}O is 26.9 seconds. For the study of this reactions samples were made by mixing pure powder of CaF_2 (99.99%) powder with SeO_2 (99.99%). In all these fifteen samples, the weight of each sample was 1 gm. Initially one sample was placed at 0^o and irradiated with neutrons for a period of 60 seconds and then brought to the Gamma-ray detector. A pneumatic transfer system was employed to take the sample from the neutron irradiation position to the HPGe detector room for the measurement of gamma-ray activity within a period of 0.5 second. In this manner five cycles of neutron irradiation and gamma-ray activity measurements were repeated. After that another sample was kept at 30^o position and five cycles of neutron irradiation and activity measurements were repeated. Following the same experimental procedure, the activation experiments were repeated by irradiating samples at 60^o, 90^o and 120^o.

Table I: The decay data of radioisotopes produced [6-8]

Nuclear Reaction	Abundance (%)	Half-life	E_γ (MeV)	f_d (%)
^{78}Se(n, p)^{78}As	23.77±0.28	90.7±0.2 m	0.613	54±0.6
^{80}Se(n, p)^{80}As	49.61±0.41	15 .2±0.2 s	0.66	42±0.5
^{56}Fe(n, p)^{56}Mn	91.75±0.36	2.57±0.0001 hr	0.847	99±0.3
^{19}F(n, p)^{19}O	100	26.91±0.08 s	0.197 1.357	95.9±2.1 50.4±1.1

B. Measurement of Gamma-ray Activities

The induced gamma-ray activities of the irradiated samples were measured with the HPGe detector. The gamma-ray detection efficiency of this detector was measured with a Canberra make Multi Gamma Standard MGS-3 source in separate experiment. The energy calibration of the detector was also carried out using the MGS-3 gamma source. After the end of the irradiation period, the sample was transferred to the counting room with the help of the pneumatic transfer system designed and developed in the laboratory. The induced gamma-ray activities from ^{78}As and ^{56}Mn radioisotopes produced in the sample were measured for a period of 900 seconds. Initially the gamma-ray activity of sample irradiated at 0^{o} position was measured. Later on the gamma-ray activities of the samples irradiated at 30^{o}, 60^{o}, 90^{o} and 120^{o} angular positions were measured in sequence.

The induced gamma-activities of (i) 0.613 MeV due to ^{78}As and (ii) 0.847 MeV due to ^{56}Mn were measured for the sample irradiated at 0^{o} position using the HPGe detector immediately after the end of irradiation. Following the same experimental procedure, the induced gamma-ray activities of remaining four samples irradiated at 30^{o}, 60^{o}, 90^{o} and 120^{o} angular positions measured sequentially. The total period of 20 seconds was required between the end of counting the activity of the first sample and the starting of counting the activity of the next sample. Accordingly, the total cooling time for each sample was accounted while estimating the induced gamma-ray activities.

In the case of ^{80}Se(n, p)^{80}As reaction, the pneumatic transfer system was also been used to bring the neutron irradiated sample to the detector room. The induced gamma-ray activities of (i) 0.66 MeV due to ^{80}As and (ii) 0.197 MeV due to ^{19}O were measured for a period of 60 seconds. A cooling period of 120 seconds was kept after the measurement of the gamma-ray activity. Such twenty activation cycles, each consists of 60 seconds of neutron irradiation and 60 seconds for the measurement of induced gamma-ray activities were repeated. The MCA was switch off during the neutron irradiation period through a remote electronic system.

The radioisotope ^{16}N produced in ^{16}O(n, p)^{16}N reaction has half-life 7.13 seconds and emits gamma-rays of energies 210.75 MeV (1%), 6.13 MeV (69%) and 7.11 MeV (5%). These gamma-rays were discriminated by adjusting the upper level of single channel analyzer. The radioisotope ^{77}Se^{m} produced in ^{78}Se(n, 2n)^{77}Se^{m} reaction has half-life 17.36 seconds and emits gamma-ray of energy 0.161MeV (53.2%), Therefore the photopeak of 0.161 MeV gamma-ray energy has appeared in the gamma-ray spectra of ^{80}As(n, p)^{80}As and ^{19}F(n, p)^{19}O reactions. Moreover, the radioisotopes are not produced by irradiating calcium with 14 MeV neutrons even in a one hour irradiation period.

III. DATA ANALYSIS

Fig. 1 shows gamma-ray spectra of ^{78}As and ^{56}Mn radioisotopes and similarly Fig. 2 show gamma-ray spectra of ^{80}As and ^{19}O radioisotopes produce through nuclear reactions induced by neutron. The activation cross-sections for the ^{78}Se(n, p)^{78}As and ^{80}Se(n, p)^{80}As reactions were determined at 13.73 MeV, 14.07 MeV, 14.42 MeV, 14.68 MeV and 14.77 MeV neutron energies using standard activation formula.

IV. NUCLEAR MODEL CALCULATIONS

The cross-sections for ^{78}Se(n, p)^{78}As and ^{80}Se(n, p)^{80}As reactions were estimated using statistical nuclear models EMPIRE-II code [3] and TALYS code [4] over neutron energy range 10 MeV to 20 MeV. In these models, a number of options are available for nuclear level density, nucleon potential etc.

V. RESULTS AND DISCUSSION

The recorded gamma-ray activities from (i) ^{78}As and ^{56}Mn produced in ^{78}Se(n, p)^{78}As and ^{56}Fe(n, p)^{56}Mn reactions, (ii) ^{80}As and ^{19}O produced in ^{80}Se(n, p)^{80}As, ^{19}F(n, p)^{19}O reactions are shown in Fig.1 and Fig.2 respectively. The activation cross-sections for ^{78}Se(n, p)^{78}As and ^{80}Se(n, p)^{80}As reactions were obtained at 13.73 MeV, 14.07 MeV, 14.42 MeV, 14.68 MeV and 14.77 MeV neutron energies using standard activation formula. Similarly, the theoretical values of the cross-sections were estimated theoretically over 10 MeV to 20 MeV neutron energies using EMPIRE-II and TALYS codes. The variations in the cross-sections of ^{78}Se(n, p)^{78}As and ^{80}Se(n, p)^{80}As reactions with neutron energy are shown in Fig. 3 and Fig. 4 respectively. It is observed in Fig.3 that the measured activation cross-sections for formation of ^{78}As through ^{78}Se(n, p)^{78}As reaction vary from 15.6 mb to 22 mb over the neutron energy range 13.73 MeV to 14.77 MeV. This decrease in the cross-section ABOVE 16 MeV is mainly due to the initiation of ^{78}Se(n, pn)^{77}As reaction channel [9] having threshold energy ~10.5 MeV [7], and therefore the probability of the ^{78}Se(n, p)^{78}As reaction decreases with increase in neutron energy. The measured and the calculated cross-sections for the ^{80}Se(n, p)^{80}As reaction along with a few literature cross-sections are shown in Fig.4. The measured cross-sections vary from 4.8 mb to 11 mb over 13.73 MeV to 14.77 MeV neutron energies.

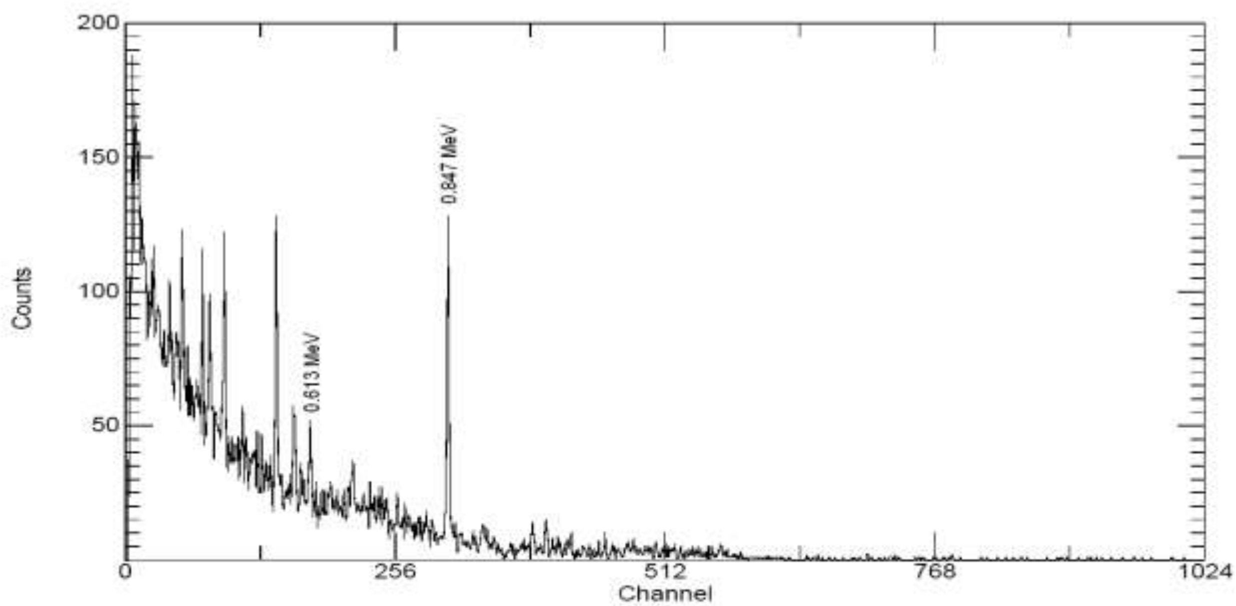

Fig.1. Gamma- ray spectra of ^{78}As and ^{56}Mn radio nuclei.

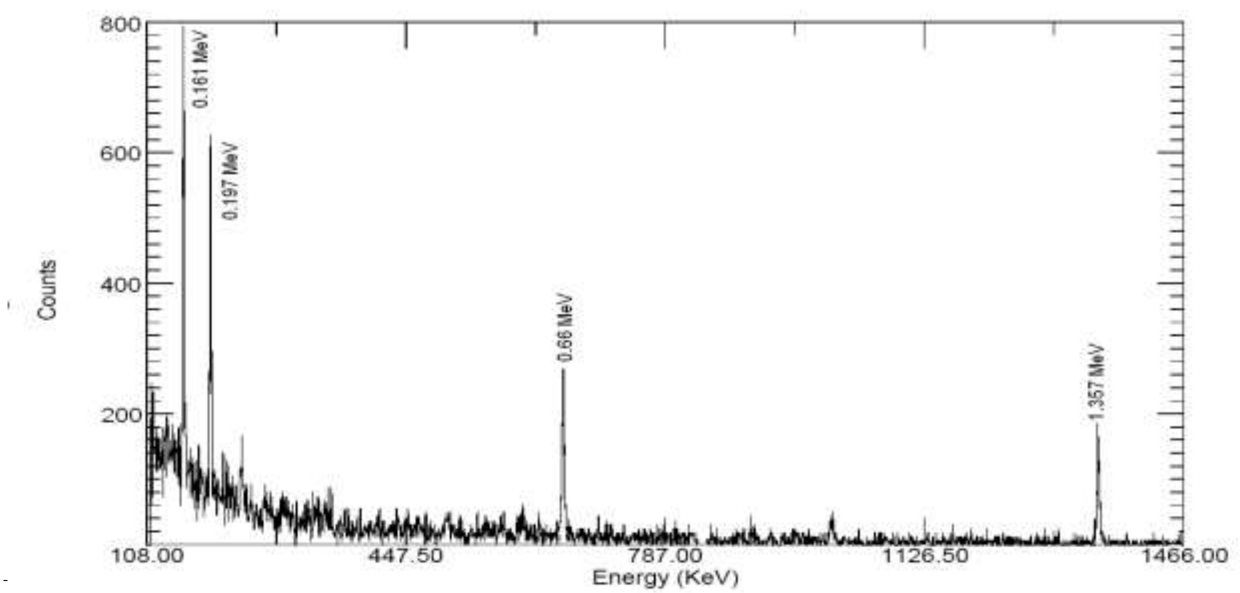

Fig.2. Gamma- ray spectra of ^{80}As and ^{19}O radio nuclei.

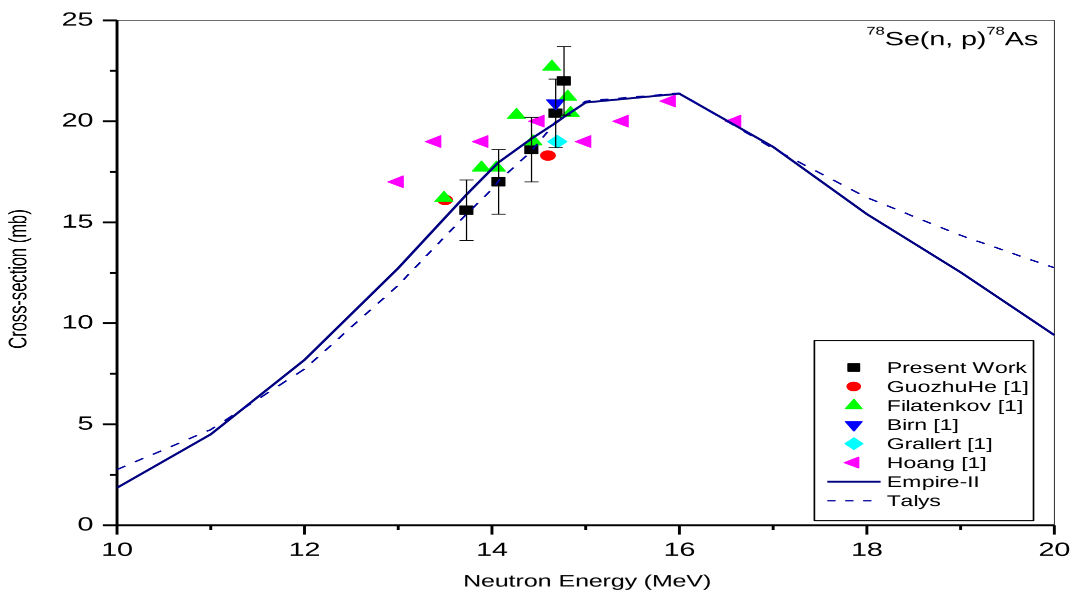

Fig.3. Cross-sections for $^{78}Se(n, p)^{78}As$ reaction at different neutron energies.

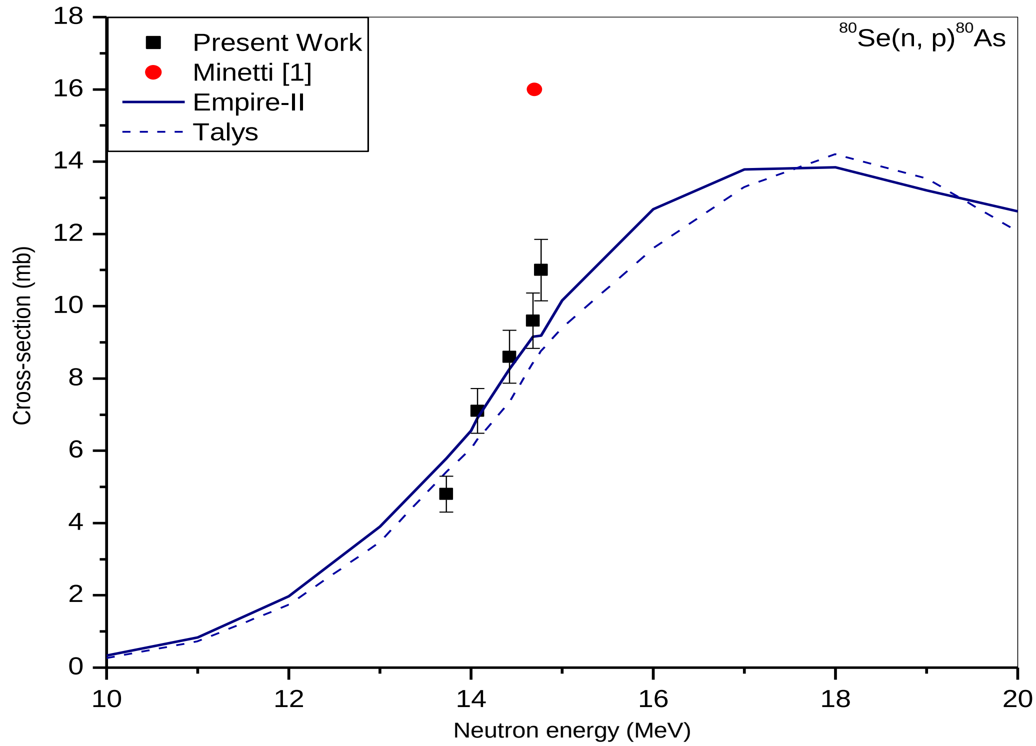

Fig.4. Cross-sections for $^{80}Se(n, p)^{80}As$ reaction at different neutron energies.

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