Title of the talk

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.

F.M.D.Attar
Department of Physics,
Fergusson College, Pune.

Outline of the talk

- Introduction
- Experimental
  - 14 MeV Neutron Generator
  - Sample Preparation
  - Neutron Irradiation
  - Gamma-ray Activity Measurement
- Nuclear Model Calculations
- Results and Discussion
- Conclusion

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.**

- **In the present work the activation cross-sections for the $^{78}Se(n, p)^{78}As$ and $^{80}Se(n, p)^{80}As$ reactions having negative Q-values 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 and also with the cross-sections estimated using computer codes based on statistical model calculations.**

- **The statistical models mainly EMPIRE-II code and TALYS code were used for calculating the cross-sections.**

EXPERIMENTAL

14 MeV Neutron Generator

- **A 14 MeV Neutron Generator was Designed and Fabricated in the Department of Physics, University of Pune, Pune around 1980.**

- **Neutrons are produced through the D-T reaction.**

- **Deuterium ions of 175 keV energy are bombarded on a Tritium target of 8 Curie activity.**

- $_1H^2 + {}_1H^3 \longrightarrow {}_0n^1 + {}_2He^4 + Q\ (17.6\,MeV)$

- *** Neutron Flux ~ 5 x 10^7 to 10^8 n/cm^2 – Sec ***

Old **New**

A VIEW OF THE 14 MeV NEUTRON GENERATOR

Old

CONTROL PANEL OF 14 MeV NEUTRON GENERATOR

New

Sample Preparations

- **The selenium samples were made using high purity SeO_2(99.%) in powder form to 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.**

- **In the case of $^{80}Se(n, p)^{80}As$ reaction, $^{19}F(n, p)^{19}O$ reaction was used as monitor reaction.**

- **For the study of this reaction samples were made by mixing pure powder of CaF_2 (99.99%) with powder of SeO_2 (99.99%).**

- **In all these fifteen samples, the weight of each sample was 1 gm.**

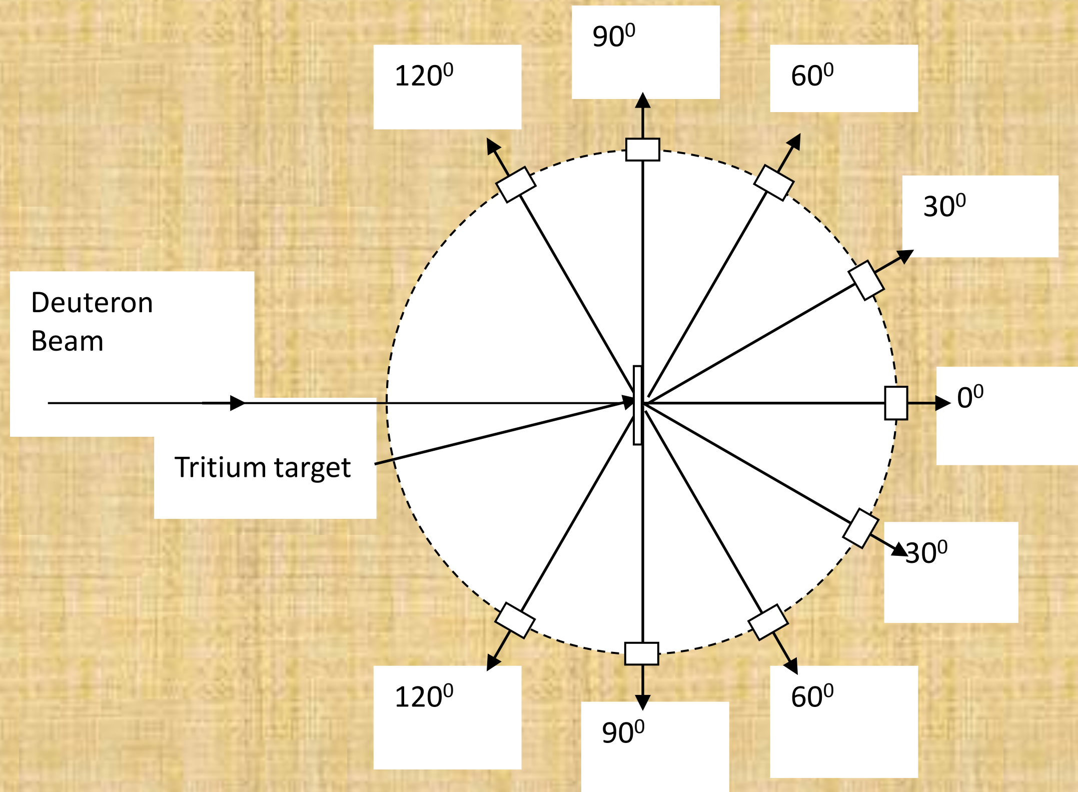
Neutron Irradiations

$^{78}Se(n, p)^{78}As$ Reaction

- **Five samples were taken and each was mounted on the horizontal plate at 0°, 30°, 60°, 90° and 120° 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.**



A schematic diagram of the sample irradiation set-up. The angular positions of the samples with reference to the incident deuteron beam on the tritium target are shown by small rectangles.

^{80}Se(n, p)^{80}As Reaction

- **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 was taken and five cycles of neutron irradiation and activity measurements were repeated.**

Table 1: The decay data of radioisotopes produced.

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

Measurement of Gamma-rays

- Gamma-ray detectors are used for the measurement of energies and intensities of the gamma-rays emitted by the radioisotopes.

- In the present work a HPGe (38.2%) was used.

- Canberra make Multi Gamma Standard MGS-3 source was used for the measurement of detection efficiency in close geometry and also for the energy calibration of the HPGe detector.

- This radioactive standard source was made of Cd-109, Co-60, Cs-137, Mn-54 and Sn-113 radioisotopes with precisely known weight of each radioisotope (88 keV to 1332keV).

- The quoted uncertainties of the sources were less than 4%.

Photograph of the HPGe detector.

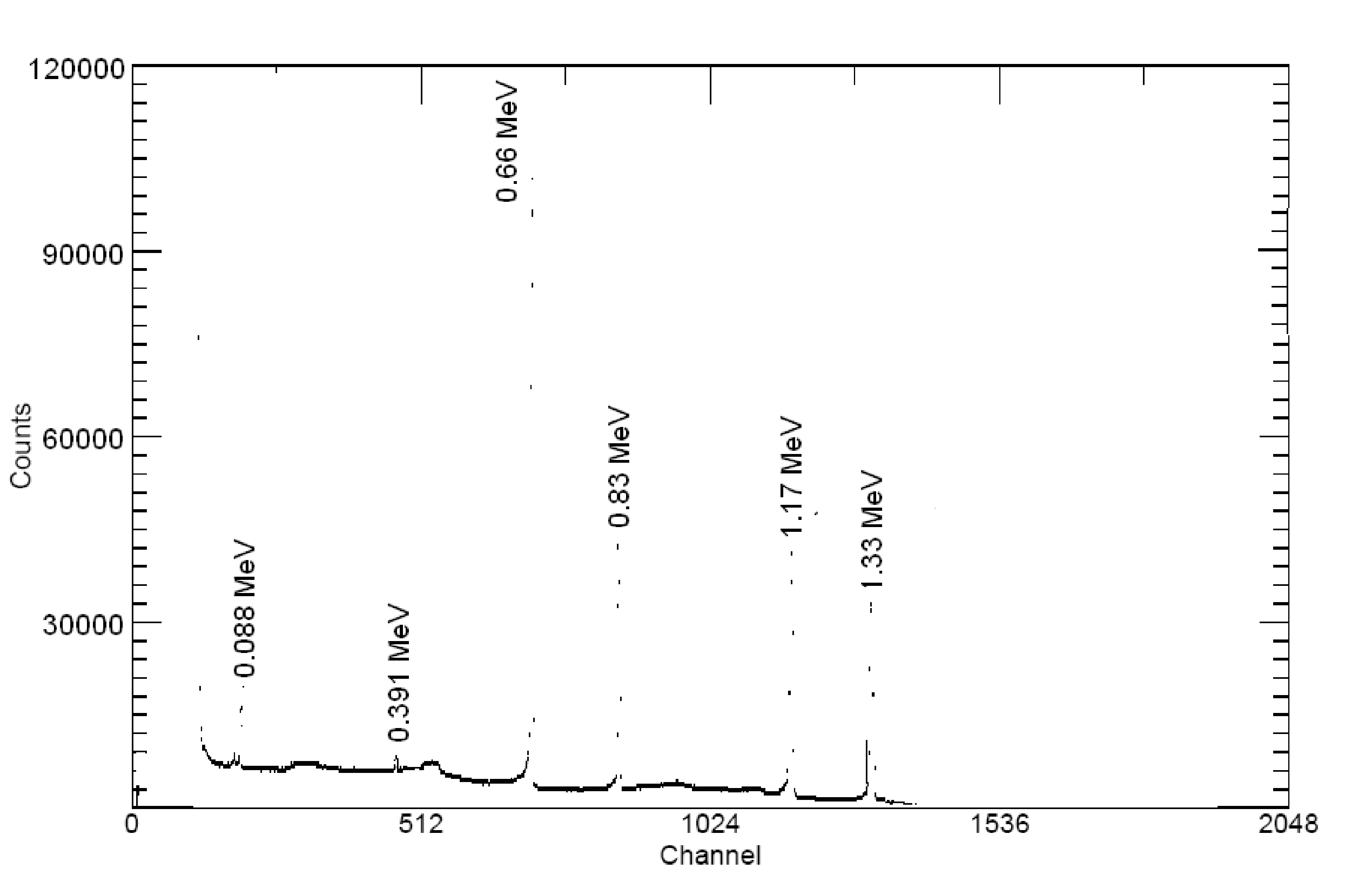


Figure -1: A typical gamma-ray spectrum of the MGS-3 source measured by the HPGe detector.

- **$^{78}Se(n, p)^{78}As$ Reaction**

- **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 samples irradiated at various angular positions using the HPGe detector immediately after the end of irradiation for the period of 900 seconds.**

- **$^{80}Se(n, p)^{80}As$ Reaction**

- **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.**

Measurement of Cross-sections

- The following expression is used for the determination of cross-sections of a nuclear reaction.

$$\sigma = \sigma_M \frac{A\varepsilon_M f_{dM}\lambda}{A_M\varepsilon f_d\lambda_M} \frac{N_M}{N} \frac{(1-e^{-\lambda_M t_1})}{(1-e^{-\lambda t_1})} \frac{e^{-\lambda_M t_2}}{e^{-\lambda t_2}} \frac{(1-e^{-\lambda_M t_3})}{(1-e^{-\lambda t_3})}$$

The subscript 'M' stands for the monitor reaction.

Error Analysis

- **For the estimation of cross-section for each reaction the error analysis was carried out using the quadrature method.**

- **In the activation formula, the uncertainty associated with the measurement of any parameter is independent of the uncertainty associated with the other parameters.**

- **The error, $\delta\sigma$, in the measured cross-section was estimated using the following expression.**

$$\delta\sigma/\sigma = \sqrt{(\delta e/e)^2 + (\delta n/n)^2}$$

- **where $\delta e/e$ is the total experimental error which includes the error due to all experimental quantities used in activation formula and $\delta n/n$ is the total error in the parameters of the nuclear data used.**

- **Also all the standard corrections were made.**

- **The estimated errors are as follows; (i) detector efficiency (~1.5%) (ii) self absorption of gamma-rays (<14%) (iii) neutron energy distribution (<1%) (iv) absolute gamma-ray intensity (<2.2%) and (v) reference cross-section of the reaction $^{56}Fe(n, p)^{56}Mn$ (2-3.7%) and for $^{19}F(n, p)^{19}O$ reaction (<5.28%).**

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 namely EMPIRE-II and TALYS codes 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.**

- **The cross-sections were therefore estimated using a few specific options over the neutron energy range 13.73 MeV to 14.77 MeV.**

EMPIRE-II Code

- **The pre-equilibrium emission effects involving both multi step compound and multi step direct theory were adopted for ^{78}Se(n, p)^{78}As reaction. However, the cross-sections for ^{80}Se(n, p)^{80}As reaction were calculated using DEGAS model.**

- **The cross-sections were calculated using four different level density options, namely (i) Empire-specific (ii) Fermi gas (iii) Gilbert Cameron and (iv) Hartree-Fock-BCS (HF-BCS) approach, over the neutron energy range 13.73 MeV to 14.77 MeV.**

- **For these reactions, the optical model parameters for neutrons and protons given by (i) Koning and (ii) Bechetti were used.**

- **A comparison between these cross-sections with the cross-sections measured in the present work provides important information about the best choices of the parameters for the respective reactions.**

TALYS code

- **Calculations were performed using –**
- **optical model parameters for neutrons, protons of A.J.Koning**
- **pre-equilibrium model.**
- **Initially, the calculations were carried out over 13.73 MeV to 14.77 MeV neutron energies using all the three level densities.**
- **(i) ldmodel 1- Fermi gas level density: Effective level density for ground state and collective effects on the barrier determined relative to the ground state.**
- **(ii) ldmodel 2 - Fermi gas level density: Explicit rotational and vibrational enhancement on ground state and fission barrier and**
- **(iii) ldmodel 3 - Microscopic level densities obtained from Goriely's Table.**

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 Figure 2 and Figure 3 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.**

Figure-2: Gamma-ray spectra of ^{78}As and ^{56}Mn radioisotopes.

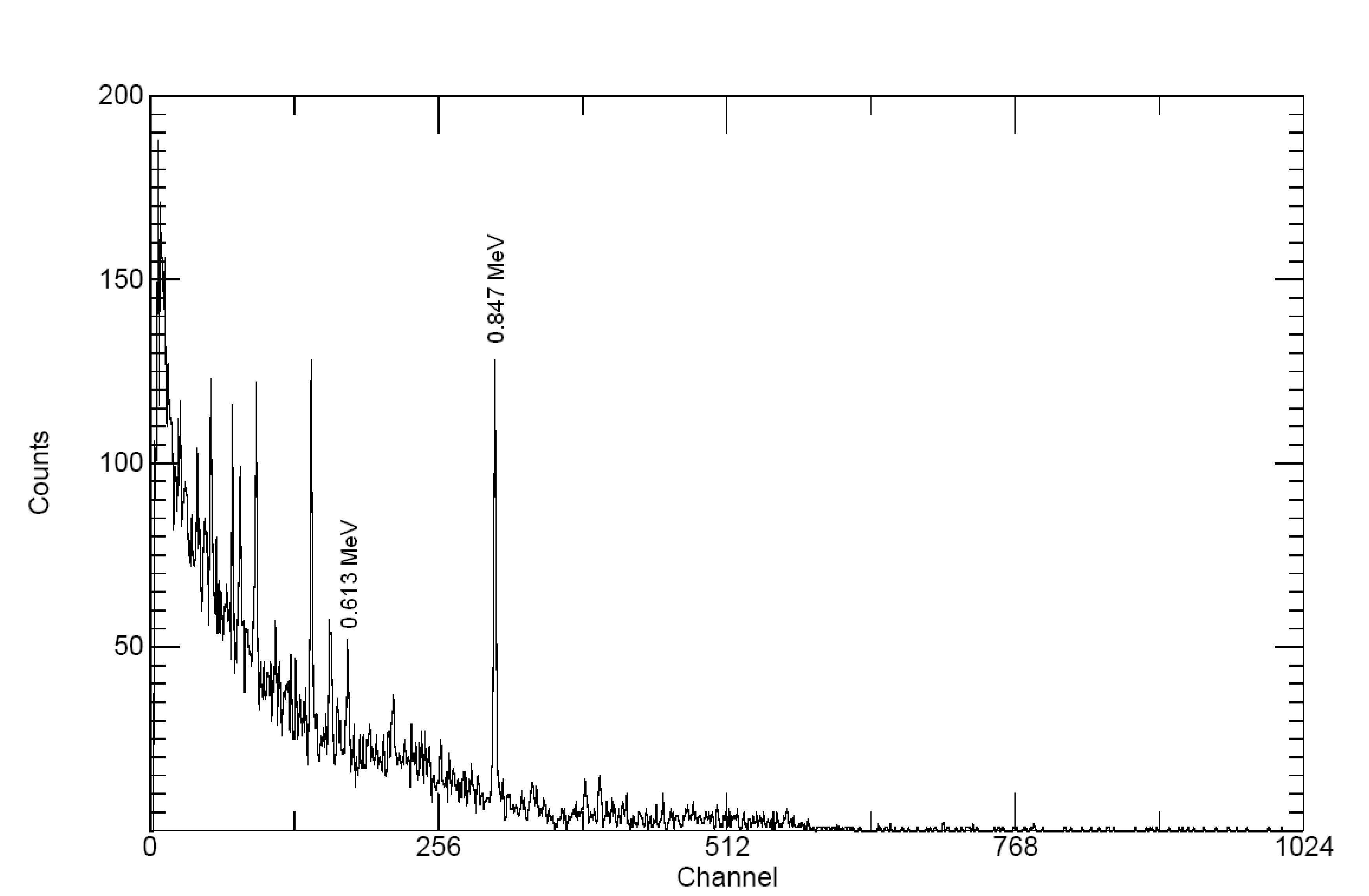
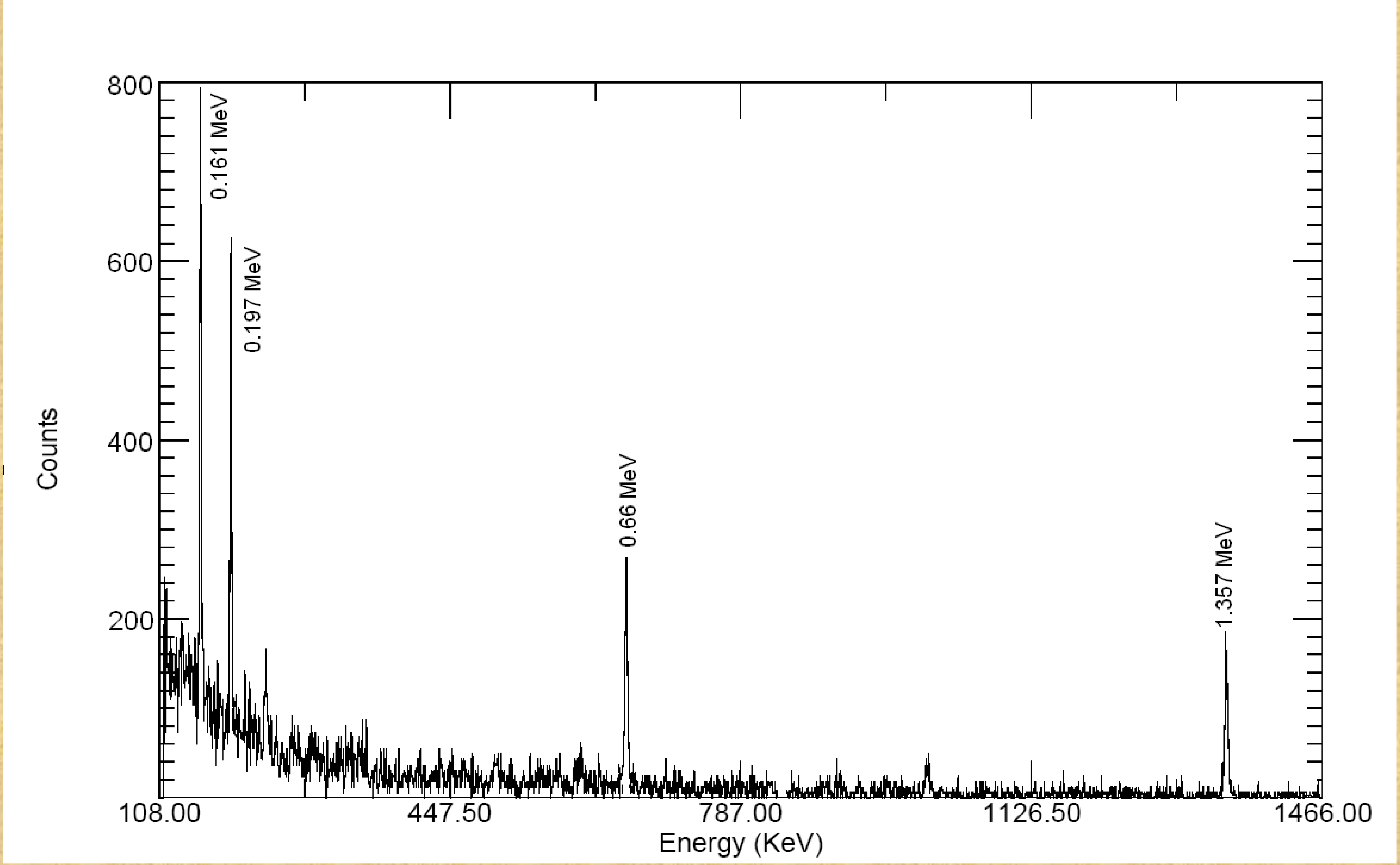


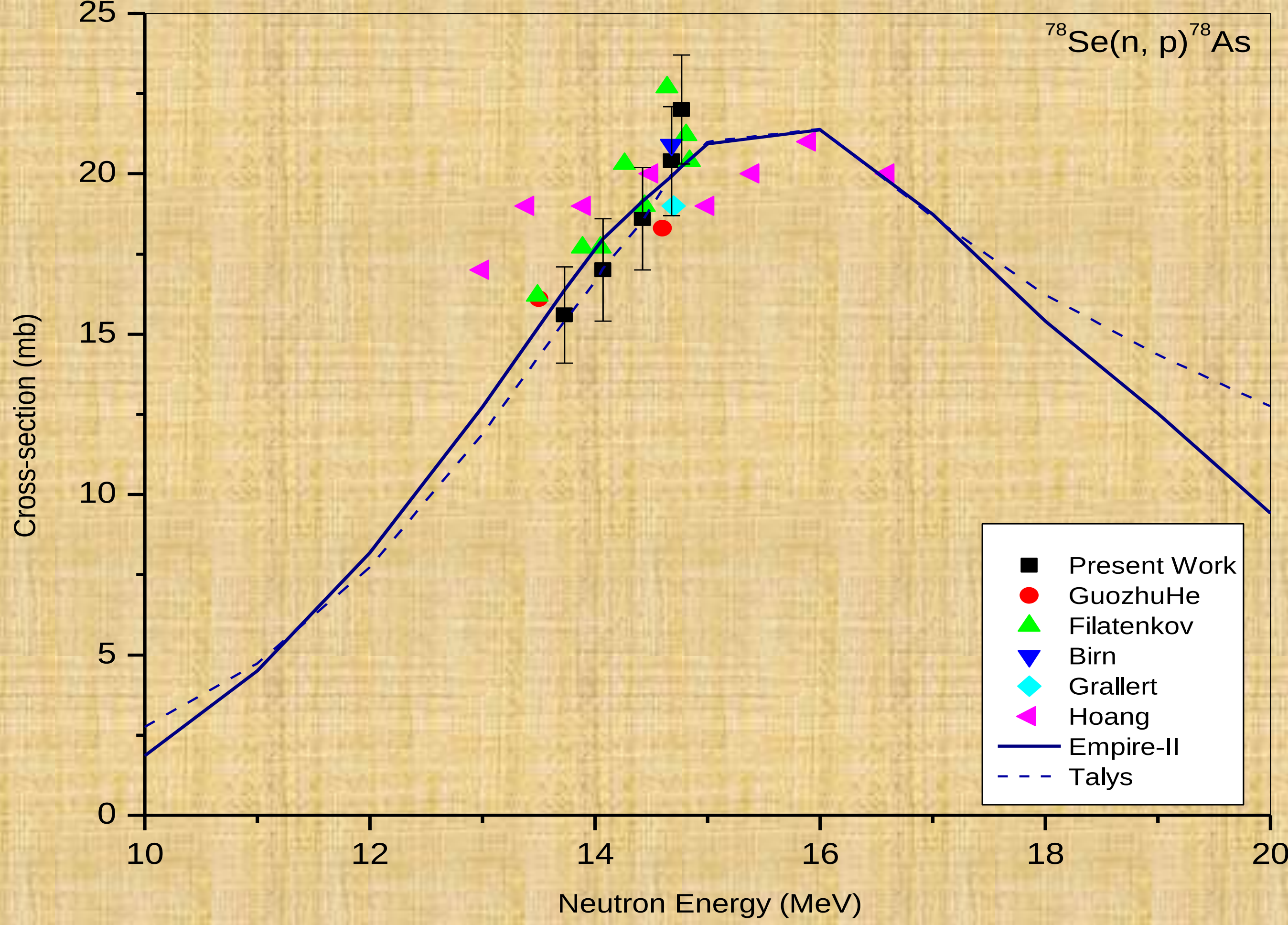
Figure-3: Gamma-ray spectra of ^{80}As and ^{19}O radioisotopes.



- **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 Figure 4 and Figure 5 respectively.**

Figure-4: Cross-sections for $^{78}Se(n, p)^{78}As$ reaction at different neutron energies.



- **It is observed in Figure 4 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.**

- **The decrease in the cross-section Above 16 MeV is mainly due to the initiation of $^{78}Se(n, pn)^{77}As$ reaction channel having threshold energy ~10.5 MeV, and therefore the probability of the $^{78}Se(n, p)^{78}As$ reaction decreases with increase in neutron energy.**

Table-2: Cross-sections for $^{78}Se(n, p)^{78}As$ reaction (i) measured in the present work and (ii) theoretically estimated using EMPIRE-II and TALYS codes over 13.73 MeV to 14.77 MeV neutron energies using best close options.

Neutron Energy (MeV)	Theoretical Cross-section (mb)		Measured cross-section (mb)
	EMPIRE-II	TALYS	
13.73	16.38	15.41	15.6±1.5
14.07	17.97	17.04	17±1.6
14.42	19.14	18.53	18.6±1.6
14.68	19.93	19.98	20.4±1.7
14.77	20.22	20.18	22±1.7

- **^{80}Se(n, p)^{80}As Reaction**

- **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 Figure 5.**

- **The measured cross-sections vary from 4.8 mb to 11 mb over 13.73 MeV to 14.77 MeV neutron energies.**

Figure - 5: Cross-sections for $^{80}Se(n, p)^{80}As$ reaction at different neutron energies.

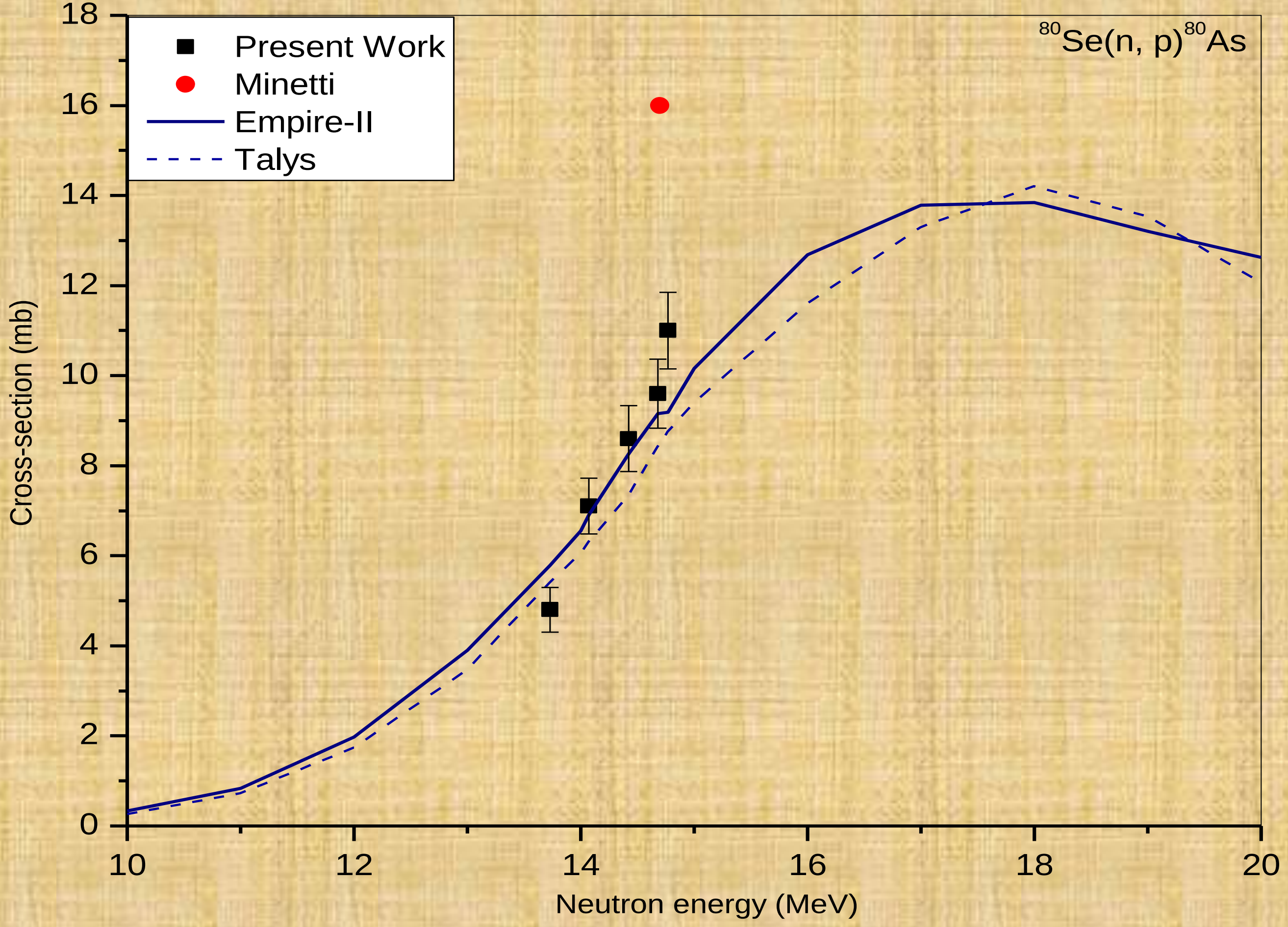


Table-3: Cross-sections for $^{80}Se(n, p)^{80}As$ reaction (i) measured in the present work and (ii) theoretically estimated using EMPIRE-II and TALYS codes over 13.73 MeV to 14.77 MeV neutron energies using best close options.

Neutron Energy (MeV)	Theoretical Cross-section (mb)		Measured cross-section (mb)
	EMPIRE-II	TALYS	
13.73	5.79	5.41	4.8±0.5
14.07	6.91	6.32	7.1±0.62
14.42	8.26	7.36	8.6±0.73
14.68	9.16	8.43	9.6±0.77
14.77	9.19	8.76	11±0.85

Conclusion

- The Activation cross-sections of (n, p) reactions for the selenium isotopes ^{78}Se and ^{80}Se were been measured over neutron energy range 13.73 MeV to 14.77 MeV using neutron activation technique.

- The cross-sections for these reactions were also been calculated theoretically over the neutron energy range 10 MeV to 20 MeV using Empire-II and Talys Codes.

- The measured values of the cross-sections are close to the corresponding theoretical values as well as those reported in literature.

Acknowledgements

- Dr.V.N.Bhoraskar, Emeretus Scientist CSIR, Department of Physics, University of Pune-4.
- Dr.S.D.Dhole, Professor, Department of Physics, University of Pune-4.
- BCUD, University of Pune, Pune-4.
- Dr.R.G.Pardeshi, Principal, Fergusson College, Pune.
- Head, Department of Physics, Fergusson College, Pune.

Thank You

Table-4: The cross-sections theoretically estimated using EMPIRE-II code for $^{78}Se(n, p)^{78}As$ reaction over 13.73 MeV to 14.77 MeV neutron energies using different level density options.

Neutron Energy (MeV)	LD-0		LD-1		LD-2		LD-3	
	KG	FDB	KG	FDB	KG	FDB	KG	FDB
13.73	7.86	9.62	4.88	5.98	7.53	8.89	16.38	19.59
14.07	8.79	10.64	5.35	6.5	7.95	9.29	17.97	21.42
14.42	9.48	11.68	5.69	7.04	8.03	9.69	19.14	22.72
14.68	9.98	12.04	5.93	7.28	8.09	9.64	19.93	23.59
14.77	10.18	12.2	6.03	7.36	8.14	9.62	20.22	23.9

Table-5: Theoretical cross-sections obtained using TALYS code for $^{78}Se(n, p)^{78}As$ reaction over 13.73 MeV to 14.77 MeV neutron energies using different level density options.

Neutron Energy (MeV)	Ldmodel 1	Ldmodel 2	Ldmodel 3
13.73	15.41	18.82	22.29
14.07	17.04	20.57	24.65
14.42	18.53	22.2	26.85
14.68	19.98	23.79	28.77
14.77	20.19	23.95	29.1

Table-6: Theoretical cross-sections estimated using EMPIRE-II code for $^{80}Se(n, p)^{80}As$ reaction over 13.73 MeV to 14.77 MeV neutron energies using different level density and nucleon potential options.

Neutron Energy (MeV)	LD-0		LD-1		LD-2		LD-3	
	KG	FDB	KG	FDB	KG	FDB	KG	FDB
13.73	3.2	4.33	1.9	2.58	1.57	2.11	1.5	2.09
14.07	3.76	5.05	2.2	2.98	1.72	2.31	1.75	2.41
14.42	4.22	5.67	2.51	3.39	1.86	2.5	2	2.74
14.68	4.68	6.24	2.75	3.69	1.96	2.63	2.19	2.97
14.77	4.86	6.46	2.84	3.8	2	2.68	2.26	3.06

Table-2.11: Cross-sections theoretically estimated for $^{80}Se(n, p)^{80}As$ reaction using TALYS code over 13.73 MeV to 14.77 MeV neutron energies using different level density options.

Neutron Energy (MeV)	Ldmodel 1	Ldmodel 2	Ldmodel 3
13.73	5.41	32.4	5.38
14.07	6.32	34.5	6.24
14.42	7.36	33.6	7.23
14.68	8.43	33.7	8.35
14.77	8.76	34.3	8.7

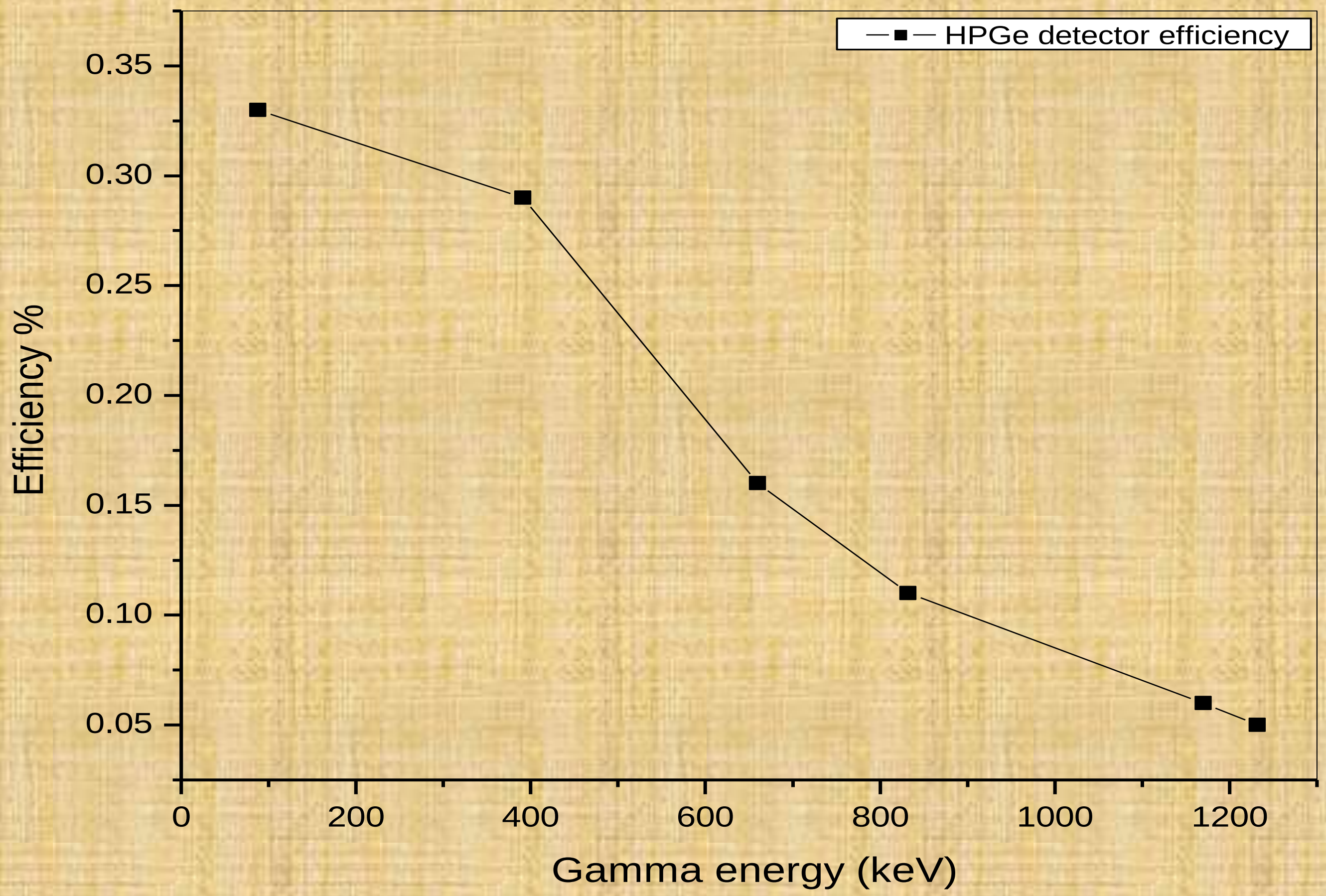


Figure -6: For the HPGe detector, variations in the efficiency with the gamma-ray energy.