# Measurement of (n, $\gamma$), (n, p), (n, 2n) and (n, $\alpha$) cross sections on various nuclei in the energy range of 8.2 to 14.6 MeV

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## Introduction

We have studied several reactions induced by fast neutrons on $^{232}$Th, $^{100}$, $^{98}$, $^{96}$, $^{95}$Mo, $^{70}$,$^{67}$Zn targets. The samples studied here have usage in various systems that have applications in the nuclear technology development. The present information of cross section is expected to provide useful input for design and safe operation of various nuclear systems as well as provide a data base for testing and validating of nuclear model calculations.

## Experiment and data reduction

The experiments were performed using various facilities in the country. For the measurement at 14.6 MeV, we have used the neutron generator[1] at Purnima laboratory, BARC, Mumbai. Neutrons were generated using the reaction d + t $\longrightarrow$ n + $^{4}$He (Q - value = + 17.6 MeV) by bombarding 53 keV deuterons on thick tritium target of 6 curie activity. The samples ($^{nat}$Mo and $^{nat}$Zn) were mounted, for irradiation, at $\sim$ 0 degree and close to the tritium target for flux optimization. Iron and aluminum foils of same cross sectional area as that of the samples were used as standard for cross section normalization. All the samples were irradiated under atmospheric conditions for 3.5 hours and the neutron flux calculated to be (1.02 $\pm$ 0.04) x $10^6$ n/cm$^2$/sec. The measurements on $^{232}$Th(n, $\gamma$)$^{233}$Th and $^{232}$Th(n, 2n)$^{231}$Th reactions were done at the Mumbai pelletron facility for which the reaction p+$^{7}$Li $\longrightarrow$ n+$^{7}$Be (Q = -1.64 MeV) was used as neutron source. The neutron energies were 8.2, 9.9 and 11.9 MeV corresponding to proton energies of 10.0, 11.8 and 13.8 MeV. For these energies there can be contribution of other group of neutrons coming from reactions leading to $^{7}$Be excitation. The relative contribution of these reactions is being estimated in a coupled reaction channel calculations. This information together with EMPIRE calculations can be used to correct the measured cross sections[2–4]. The off-line counting of the samples was carried out at the Radiochemistry Division, BARC using a 40% HPGe coupled to a 8k MCA and the resolution of the detector was 2.0 keV for 1332 keV gamma ray of $^{60}$Co. The gamma activities were measured for more than three half lives. The spectrum was recorded for suitable time period in order to get good counting statistics. The major gamma lines of 778.2keV(96.5%),140.5keV(89.0%), 184.6 keV (48.7%),438.6keV(94.8%), 765.8keV(99.9%), 756.7keV(54.4%), 311.9keV(38.6%), 84.2keV (6.6%) for the reactions $^{96}$Mo(n,p)$^{96}$Nb,$^{100}$Mo(n,2n)$^{99}$Mo, $^{67}$Zn(n,p)$^{67}$Cu, $^{70}$Zn(n,2n)$^{69m}$Zn, $^{95}$Mo(n,p)$^{95}$Nb, $^{98}$Mo(n,$\alpha$)$^{95}$Zr, $^{232}$Th(n,$\gamma$)$^{233}$Th and $^{232}$Th(n,2n)$^{231}$Th respectively, were identified. The measured cross sections for some of the reactions studied at the Purnima Laboratory are listed in Table 1. The error represents uncertainties in the measurement of peak area, monitor cross section, detector efficiency and target foil thickness. The analysis for other reaction

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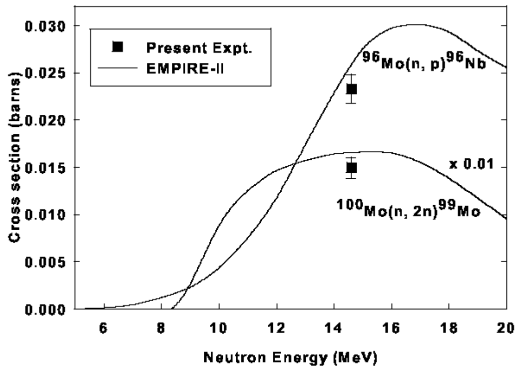


FIG. 1: Preliminary results of measured and calculated(EMPIRE-II) cross sections for $^{96}$Mo(n, p)$^{96}$Nb and $^{100}$Mo(n, 2n)$^{99}$Mo reactions.

systems is in progress.

TABLE I: Measured cross section along with EMPIRE-II calculated values.

| Reaction | $T_{1/2}$ | $\sigma_{exp}$(mb) | $\sigma_{cal}$(mb) |
|---|---|---|---|
| $^{100}$Mo(n,2n)$^{99}$Mo | 65.94h | 1490.0± 111.3 | 1653.0 |
| $^{96}$Mo(n, p)$^{96}$Nb | 23.35h | 23.3 ±1.5 | 25.8 |
| $^{67}$Zn(n,p)$^{67}$Cu | 2.58 d | 38.1± 1.7 | 38.9 |
| $^{70}$Zn(n,2n)$^{69m}$Zn | 13.7 h | 854.3± 81.9 | 920.0 |

## Nuclear model calculations

Statistical model code EMPIRE-II(version 2.19)[5] was used to investigate the reactions studied here. The code is based on the standard Hauser- Feshbach formalism for compound nucleus decay and the preequilibrium contribution is calculated in the exciton model. Appropriate optical model potentials were used for calculation of particle transmission coefficients. The EMPIRE specific level density approach was used in calculations. In case of $^{100}$Mo(n, 2n)$^{99}$Mo and $^{96}$Mo(n, p)$^{96}$Nb reactions, default level density parameters were used. The level density parameter was scaled up by factor of 1.7 for $^{67}$Zn(n,p)$^{67}$Cu reaction whereas for $^{70}$Zn(n, 2n)$^{69m}$Zn reaction it was scaled down by a factor of 0.6. A consistency check was done to find whether the discrete level schemes for the involved nuclei are consistent with the level density parameterization and the EMPIRE calculations were repeated with reduced number of discrete levels until a good agreement with level densities was achieved. The results of the present EMPIRE calculations are plotted in Figs. 1 and 2 and show a reasonably good agreement with our data.

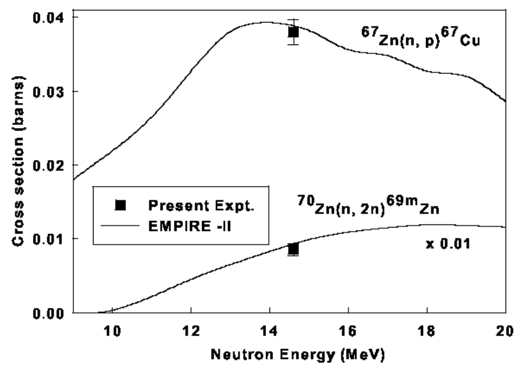


FIG. 2: Preliminary results of measured and calculated(EMPIRE-II) cross sections for $^{67}$Zn(n, p)$^{67}$Cu and $^{70}$Zn(n, 2n)$^{69m}$Zn reactions.

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