

Measurement of cross sections in the region of sub-mbarn  
by 14 MeV neutron with well-type HPGe detector

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Seven neutron activation cross sections were newly measured at energy range between 13.4 and 14.9 MeV by a high efficiency well-type HPGe detector. The cross sections of the  $^{95}\text{Mo}(n,n'p)^{94m}\text{Nb}$ ,  $^{100}\text{Mo}(n,n'p)^{99m}\text{Nb}$ ,  $^{116}\text{Cd}(n,np)^{115g}\text{Ag}$ ,  $^{123}\text{Te}(n,n'p)^{122m}\text{Sb}$  and  $^{176}\text{Yb}(n,np)^{175}\text{Tm}$  reactions were obtained for the first time. The cross section of  $^{176}\text{Yb}(n,\alpha)^{173}\text{Er}$  and  $^{190}\text{Os}(n,p)^{190g}\text{Re}$  reactions were obtained at the six energy points between 13.4 and 14.9 MeV, although the previous results had been obtained at one energy point.

## 1 Introduction

Neutron activation cross section data around 14 MeV are important from the view point of the fusion reactor technology in terms of estimations of radiation damage, nuclear transmutations, induced activity and so on. In the view point of gas production, we need to know the (n,p), (n, $\alpha$ ) and (n,np) reaction cross sections, although producing short-lived nuclei are not important for the problem of induced activity. Our systematics proposed on the basis of 58 cross section data of (n,p) and 33 data of (n, $\alpha$ ) reaction. The systematics predicts well the excitation functions around 14 MeV within  $\pm 30\%$ . To construct the systematics for (n,np) reaction, we need to obtain the cross section data for (n,np) reaction. By the use of a high efficiency well-type HPGe detector, generally weak (n,np) cross section were mainly measured. Measured reactions and decay parameters are listed in Table 1.

## 2 Experiment

Experiments were carried out at the FNS (Fusion Neutronics Source) facility. A pneumatic sample transport system was used for the irradiation of samples. The angles of the irradiation position to the  $d^+$  beam were 0, 45, 70, 95, 120 and 155 degree, which covered the neutron energies from 14.9 to 13.4 MeV. The distance between the D-T neutron target and the irradiation position was 10 cm. The average neutron flux at the irradiation position was about  $1 \times 10^8$  n/cm<sup>2</sup>/s. The effective incident neutron energy at the irradiation position was determined by the ratio of the  $^{90}\text{Zr}(n,2n)^{89}\text{Zr}$  and  $^{93}\text{Nb}(n,2n)^{92\text{m}}\text{Nb}$  reaction rates. The induced activities were measured by a well-type HPGe detector. The efficiency in the bottom of the detector is 6-7 times larger than those at the surface position of the detector as shown Fig. 1. Corrections were made for time fluctuation of neutron flux, contribution of low energy neutron below 10 MeV, thickness of samples, self-absorption of the gamma ray and sum-peak effect of the gamma ray. The details of each correction are described elsewhere [1]. The total errors (  $\sigma_t$  ) were described by combining the experimental errors (  $\sigma_e$  ) and the errors of nuclear data (  $\sigma_r$  ) in quadratic:  $\sigma_t^2 = \sigma_e^2 + \sigma_r^2$ .

## 3 Experimental Results

Experimental results for the cross sections are shown in Table 2 and Figs. 2 - 8. The  $\sigma_{14}$  and the relative slope calculated by the systematics for  $^{176}\text{Yb}(n,\alpha)^{173}\text{Er}$  reaction is good agreement with experimental value.

## 4 Conclusion

By the use of a high efficiency well-type detector, the cross sections of the  $^{95}\text{Mo}(n,n'p)^{94\text{m}}\text{Nb}$ ,  $^{100}\text{Mo}(n,n'p)^{99\text{m}}\text{Nb}$ ,  $^{116}\text{Cd}(n,np)^{115\text{g}}\text{Ag}$ ,  $^{123}\text{Te}(n,n'p)^{122\text{m}}\text{Sb}$  and  $^{176}\text{Yb}(n,np)^{175}\text{Tm}$  reactions were obtained for the first time. The cross section of  $^{176}\text{Yb}(n,\alpha)^{173}\text{Er}$  and  $^{190}\text{Os}(n,p)^{190\text{g}}\text{Re}$  reactions were obtained at the six energy points between 13.4 and 14.9 MeV, although the previous results had been obtained at one energy point. The study of the systematics for (n,np) reaction are now in progress.

## References

- [1] K.Kawade et al.: JAERI-M 92-020 (1992)
- [2] E. Browne et al.: "Table of Radioactive Isotope", John Wiley & Sons, New York (1986).

[3] R.B. Firestone et al.: "Table of isotopes 8<sup>th</sup> Edition", John Wiley & Sons, New York (1996).

[4] Y. Kasugai et al.: Ann. Nucl. Energy Vol. 23, 1429 (1996)

Table 1 Measured reactions and decay parameters

Reaction	Half-life	Gamma-ray Energy (keV)	Intensity per decay (%)	Q-value(MeV)
$^{95}\text{Mo}(n,n'p)^{94m}\text{Mo}$	6.26m	871.097	$0.50 \pm 0.06$	-8.63
$^{100}\text{Mo}(n,n'p)^{99m}\text{Mo}$	2.6m	365.1	$2.53 \pm 0.17$	-11.1
$^{116}\text{Cd}(n,np)^{115g}\text{Ag}$	20.0m	229.1	$18 \pm 8$	-11.1
$^{123}\text{Te}(n,n'p)^{122m}\text{Sb}$	4.21m	61.413	$53.7 \pm 6.1$	-8.14
$^{176}\text{Yb}(n,np)^{175}\text{Tm}$	15.2m	514.867	$65 \pm 7$	-8.49
$^{176}\text{Yb}(n,\alpha)^{173}\text{Er}$	1.4m	895.2	$53.8 \pm 2.7$	5.92
$^{190}\text{Os}(n,p)^{190g}\text{Re}$	3.1m	186.68	$48.4 \pm 2.2$	-2.39

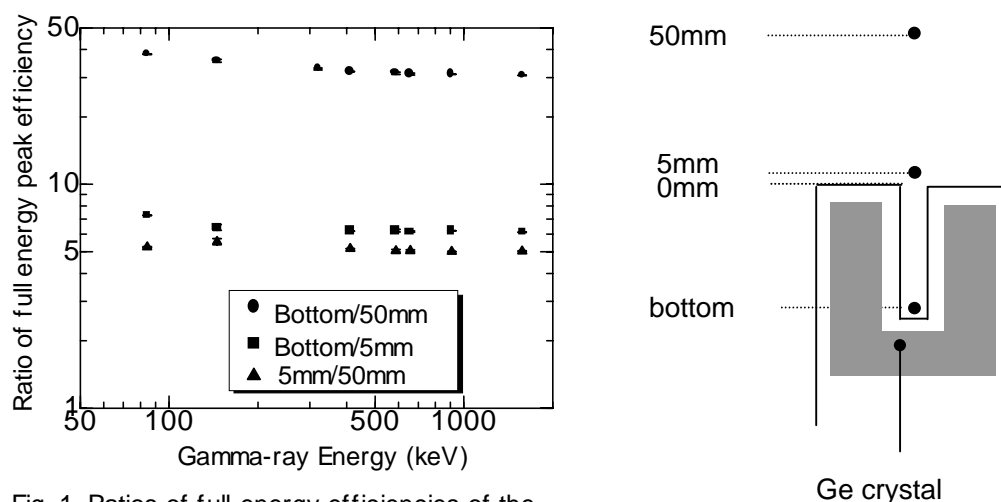


Fig. 1 Ratios of full-energy efficiencies of the well-type HPGe at 50mm, 5mm and bottom position. Lines are given for eye guide.

Table 2 Activation cross sections of short-lived nuclei

Neutron Energy(MeV)	$^{95}\text{Mo}(n,np)^{94m}\text{Nd}$				$^{100}\text{Mo}(n,np)^{99m}\text{Nd}$			
	Sigma(mb)	$t$ (%)	$e$ (%)	$r$ (%)	Sigma(mb)	$t$ (%)	$e$ (%)	$r$ (%)
14.87	28	30	16	12	3.2	23	21	11
14.64	21	36	25	12	2.9	23	20	11
14.35	17	36	25	12	2.6	24	22	11
14.02	11	43	35	12	2.3	25	23	11
13.70					1.3	34	33	11
13.40					1.2	43	41	11

Neutron Energy(MeV)	$^{116}\text{Cd}(n,np)^{115g}\text{Ag}$				$^{123}\text{Te}(n,np)^{122m}\text{Sb}$			
	Sigma(mb)	$t$ (%)	$e$ (%)	$r$ (%)	Sigma(mb)	$t$ (%)	$e$ (%)	$r$ (%)
14.87	0.57	59	32	45	0.56	31	20	5.0
14.64	0.45	61	35	45	0.47	30	20	5.0
14.02					0.19	39	32	5.0
13.70	0.40	84	68	45	0.13	71	68	5.0
13.40	0.27	87	71	45				

Neutron Energy(MeV)	$^{176}\text{Yb}(n,np)^{175}\text{Tm}$				$^{176}\text{Yb}(n,\alpha)^{173}\text{Er}$			
	Sigma(mb)	$t$ (%)	$e$ (%)	$r$ (%)	Sigma(mb)	$t$ (%)	$e$ (%)	$r$ (%)
14.87	0.87	26	8	12	0.76	43	35	10
14.64	0.73	27	9	12	0.52	46	38	10
14.35	0.55	27	10	12	0.41	47	40	10
14.02	0.30	30	16	12	0.48	47	40	10

Neutron Energy(MeV)	$^{190}\text{Os}(n,p)^{190g}\text{Re}$			
	Sigma(mb)	$t$ (%)	$e$ (%)	$r$ (%)
14.87	2.9	37	26	14
14.64	2.6	36	25	14
14.35	2.5	43	34	14
14.02	1.6	37	26	14
13.70	1.2	45	37	14
13.40	0.8	63	57	14

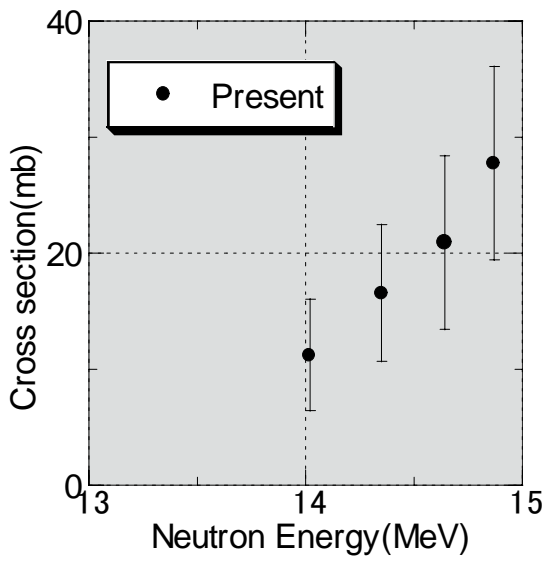


Fig. 2 Measured cross section data of  $^{95}\text{Mo}(n,n')^{94m}\text{Nb}$  reaction.

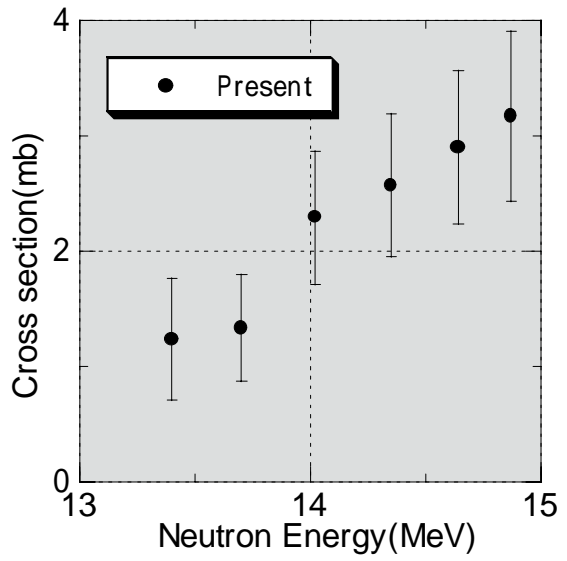


Fig. 3 Measured cross section data of  $^{100}\text{Mo}(n,n')^{99m}\text{Nb}$  reaction.

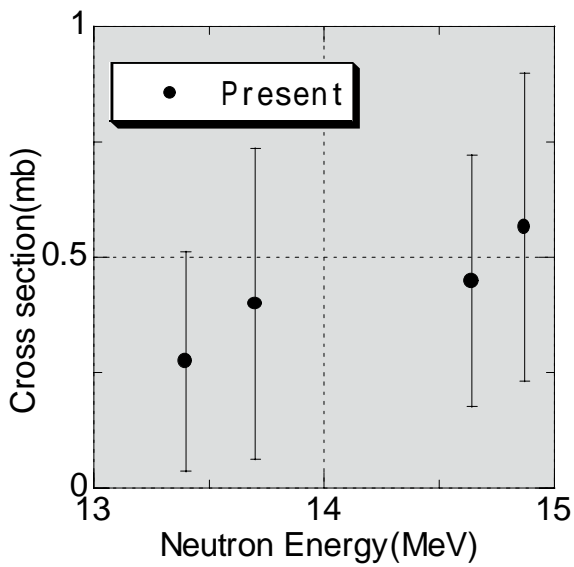


Fig. 4 Measured cross section data of  $^{116}\text{Cd}(n,np)^{115g}\text{Ag}$  reaction.

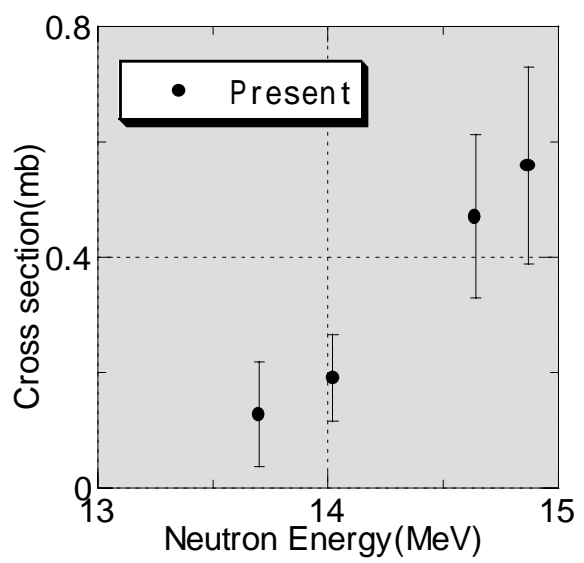


Fig. 5 Measured cross section data of  $^{123}\text{Te}(n,n')^{122m}\text{Sb}$  reactions.

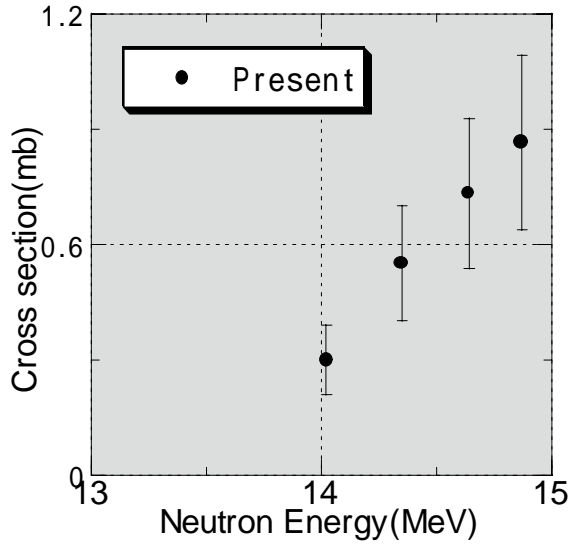


Fig. 5 Measured cross section data of  $^{176}\text{Yb}(n,np)^{175}\text{Tm}$  reaction.

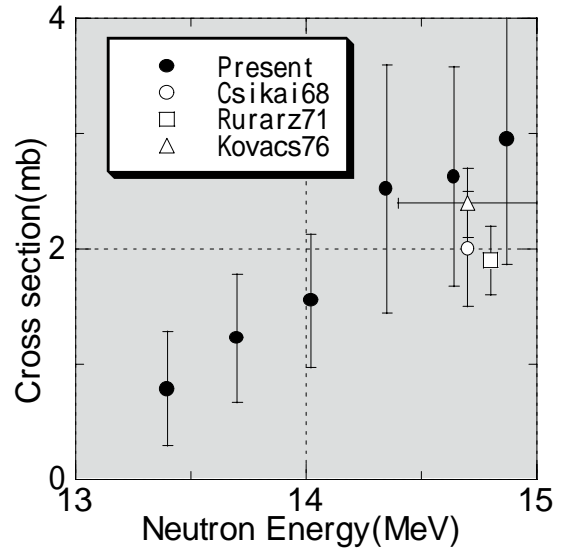


Fig. 7 Measured cross section data of  $^{190}\text{Os}(n,p)^{190g}\text{Re}$  reaction.

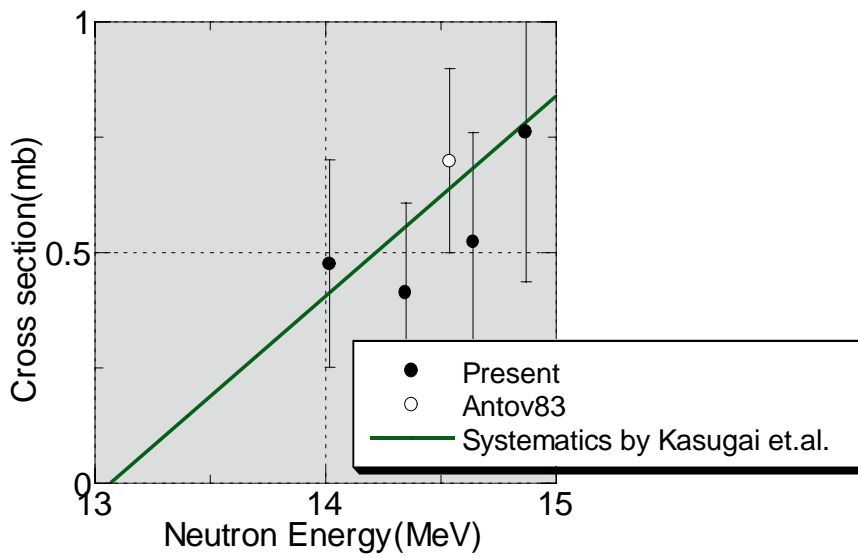


Fig. 6 Measured cross section data of  $^{176}\text{Yb}(n,\alpha)^{173}\text{Er}$  reaction.