Systematics of (n,n'p) reaction cross sections by 14 MeV Neutron

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Systematics of (n,n'p) reaction cross section in the energy range between 13.4 and 14.9 MeV were studied on the basis of experimental data measured by the Nagoya and Fusion Neutronics Source groups. Our group have been measured 31 (n,n'p) reaction cross section. In present work, 8 (n,n'p) cross sections were newly measured in the neutron energy range between 13.4 and 14.9 MeV by using a high efficiency well-type HPGe detector. The measured isotopes were ^{113}Cd, ^{123}Te, ^{148}Nd, ^{160}Gd, ^{170}Er, ^{174}Yb, ^{184}W and ^{186}W. Preliminary empirical formulae of a cross section at 14.7 MeV based on 37 data were deduced as a function (N-Z+2)/A, where N, Z and A are neutron, proton and mass numbers of the target nuclei. Comparing the experimental data with the calculated value, we estimated that the accuracy of the proposed empirical formulae was ±50 %.

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 obtain the (n,p), (n,α) and (n,n'p) reaction cross section data. Systematic cross section measurement programs have been performed by using the d-T neutron generator (the Fusion Neutronics Source: FNS) at Japan Atomic Energy Research Institute (JAERI). The FNS group measured 199 cross section data. A group of Nagoya University has also measured 74 activation cross section data, mostly for short-lived products ($T_{1/2}$ <20min) by using rotating T-target (OKTAVIAN) at Osaka University. In addition of data taking, we are about to propose empirical formulae which can reproduced partial excitation function of cross section around 14 MeV. Recently the systematics was proposed on the basis of 65 cross section data of (n,p) and 33 data of (n,α) reaction[1),2)]. The systematics for (n,p) and (n,α) reaction predicts well the excitation functions around 14 MeV within ±20 % and 30 %, respectively. To construct the systematics for (n,n'p) reaction, we needs to obtain more cross section data for (n,n'p) reaction. By using a high efficiency well-type HPGe detector, (n,n'p) cross section in the region of μbarn could be measured. As shown in Fig. 1, the cross section at 14 MeV as a function of (N-Z)/A was plotted[3)], where N, Z, A, Sn and Sp are neutron, proton, mass numbers, neutron separation energy and proton separation energy of the target nuclei. However the data fall on two curves, one for nuclei with Sn<Sp and the other for nuclei with Sn>Sp. We tried to propose the single empirical formulae as a function of a simple parameter.

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 as shown in Fig. 2. 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 1×10^8 n/cm^2-s. The effective incident neutron energy at the irradiation position was determined by the ratio of the ^{90}Zr(n,2n)^{89}Zr and ^{93}Nb(n,2n)^{92m}Nb reaction rates. The induced activities were measured with a well-type HPGe detector[4)]. The efficiency in the bottom of the detector is 6-7 times larger than those at the surface position of the detector as shown in Fig. 3. 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 (δ_t) were described by combining the experimental errors (δ_e) and the errors of nuclear data (δ_r) in quadratic: $\delta_t^2 = \delta_e^2 + \delta_r^2$.

Measured reactions and decay parameters are listed in Table 1.

3 Experimental Results

Numerical data of the present cross section were given in Table 2. Present cross section data were shown in Fig. 4 together with the previous data and the evaluation data of JENDL 3.2 and ENDF/B-VI. The cross section data of 6 reactions were obtained around 14 MeV for the first time. The cross section data of ^{186}W(n,np)^{185}Ta reported by Kasugai et. al., which was measured by using the rotating target (OKTAVIAN) at Osaka University, were good agreement with present result.

4 Preliminary systematics of (n,n'p) reaction cross section

To study the systematics of the cross sections of (n,n'p) reaction at 14.7 MeV, our cross section data in present work and the data in ref. (7) were used. In Fig. 5, the cross section data at 14.7 MeV were plotted as a function of (N-Z+2)/A. It is evident that the cross sections depend on the (N-Z)/A. The systematics is expressed by the formulae given by

$$\sigma_{14.7}(mb) = 10500(N - Z + 2)) \times \exp\left(-68.2 \times \frac{(N - Z + 2)}{A}\right)$$

To find the overall quality of proposed empirical formulae, the distribution of the deviation which given by $R=(\sigma_{exp}-\sigma_{sys})/\sigma_{exp}$ is shown in Fig. 6. Sixty-five percent of the data are in between –0.50 and 0.50. This means that one standard deviation of the R-distribution is about 0.50. The accuracy of proposed formulae are within ±50% as a whole.

5 Conclusion

Eight cross sections of (n,n'p) reaction were measured in the energy range between 13.4 and 14.9 MeV. The measured isotopes were ^{113}Cd, ^{128}Te, ^{148}Nd, ^{160}Gd, ^{170}Er, ^{174}Yb, ^{184}W and ^{186}W. The cross section data except for ^{128}Te and ^{186}W were obtained for the first time.

Preliminary empirical formulae of cross section ($\sigma_{14.7}$) was deduced as a function of (N-Z+2)/A. The accuracy of empirical formulae was ±50%. The proposed on a relative slope formula of excitation function around 14 MeV are now in progress

Reference

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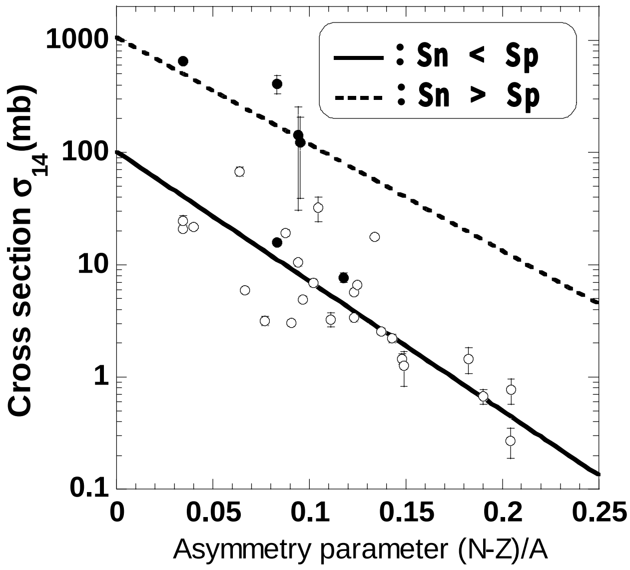

Fig.1 The cross sections σ_{14} for (n,np) reactions at 14.0 MeV as a function of asymmetry parameter (N-Z)/A. N, Z and A are neutron, proton and mass number of target nuclei.

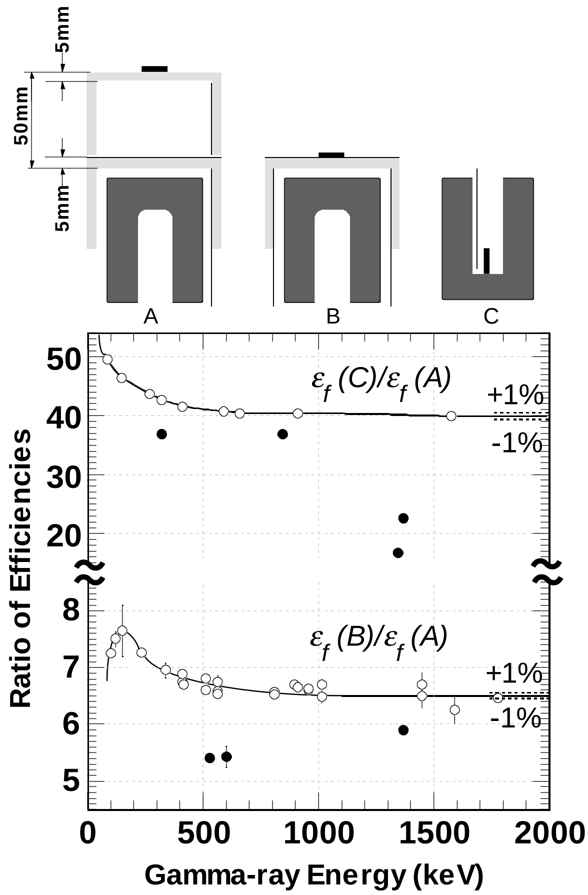

Fig. 3 Efficiency calibration method. A standard position is 5 cm for detector A. Practical positions are on the surface and in the bottom for a well type detector C. Ratio of detection efficiencies at the surface and in the bottom to that at 5 cm. Open circle show single gamma-ray emitters and closed ones show cascade gamma-ray emitters.

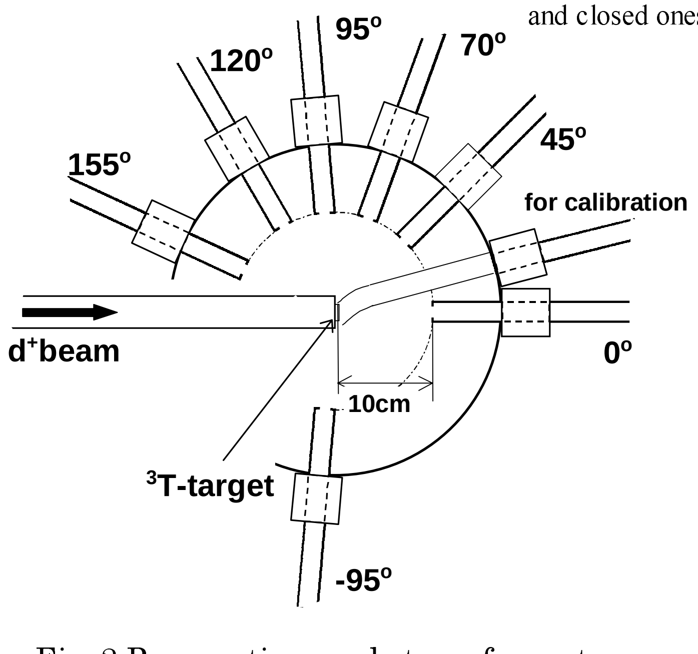

Fig. 2 Pneumatic sample transfer system.

Table 1 Measured reactions and decay parameters [5),6)]

Reaction	Half-life	Gamma-ray Energy (keV)	Intensity per decay (%)	Q-value(MeV)
^{113}Cd(n,np)^{112}Ag	3.13h	617.27	43(4)	-8.92
^{128}Te(n,np)^{127}Sb	3.85d	685.7	36.6(8)	-9.58
^{148}Nd(n,np)^{147}Pr	13.4m	314.68	13.2(17)	-9.23
^{160}Gd(n,np)^{159}Eu	18.1m	67.8	19(4)	-9.18
^{170}Er(n,np)^{169}Ho	4.7m	788.4	22.0(22)	-8.60
^{174}Yb(n,np)^{173}Tm	8.24h	398.9	87.9(20)	-7.98
^{184}W(n,np)^{183}Ta	5.1d	246.06	28.0(10)	-7.70
^{186}W(n,np)^{185}Ta	49.4m	177.59	25.6(5)	-8.40

Table 2 Activation cross sections

Neutron Energy (MeV)	^{113}Cd(n,n'p)^{112}Ag				^{128}Te(n,n'p)^{127}Sb			
	σ(mb)	δ_t(%)	δ_e(%)	δ_r(%)	σ (mb)	δ_t(%)	δ_e(%)	δ_r(%)
14.87	1.0$_{2}$	16	12	11	0.7$_{2}$	30	30	3.6
14.64	0.5$_{1}$	25	22	11				
14.35	0.2$_{1}$	51	50	11	0.3$_{2}$	64	64	3.6

Neutron Energy (MeV)	^{148}Nd(n,np)^{147}Pr				^{160}Gd(n,np)^{159}Eu			
	σ (mb)	δ_t(%)	δ_e(%)	δ_r(%)	σ (mb)	δ_t(%)	δ_e(%)	δ_r(%)
14.87	0.20$_{4}$	21	17	13	0.3$_{2}$	60	56	21
14.64	0.16$_{4}$	26	22	13				
14.35	0.10$_{4}$	37	35	13				
14.02	0.06$_{3}$	54	52	13				

Neutron Energy (MeV)	^{170}Er(n,np)^{169}Ho				^{174}Yb(n,np)^{173}Tm			
	σ (mb)	δ_t(%)	δ_e(%)	δ_r(%)	σ (mb)	δ_t(%)	δ_e(%)	δ_r(%)
14.87	0.05$_{2}$	61	45	10	0.82$_{15}$	18	18	3.2
14.64					0.82$_{15}$	19	19	3.2
14.35					0.41$_{8}$	20	19	3.2
14.02					0.28$_{6}$	20	20	3.2
13.70					0.30$_{7}$	23	23	3.2
13.40					0.12$_{5}$	38	38	3.2

Neutron Energy (MeV)	^{184}W(n,np)^{183}Ta				^{186}W(n,np)^{185}Ta			
	σ (mb)	δ_t(%)	δ_e(%)	δ_r(%)	σ (mb)	δ_t(%)	δ_e(%)	δ_r(%)
14.87	1.3$_{3}$	21	20	4.7	0.40$_{6}$	15	15	3.6
14.64	0.8$_{2}$	30	30	4.7	0.25$_{4}$	16	16	3.6
14.35	0.4$_{2}$	45	45	4.7	0.18$_{4}$	20	20	3.6
14.02					0.05$_{3}$	50	50	3.6

* δ_e: experimental error, δ_r: nuclear data error, δ_t: total error, $\delta_t^2=\delta_e^2+\delta_r^2$

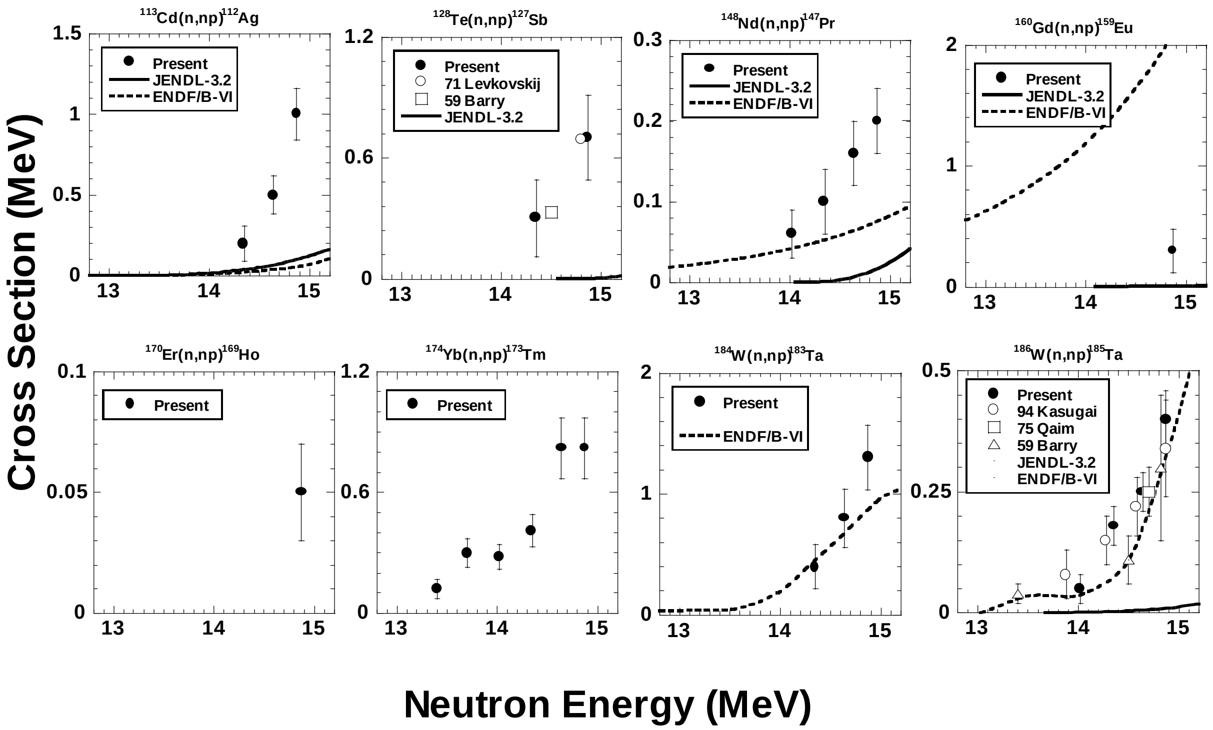

Fig. 4 Measured (n,n'p) reaction cross section data for isotopes of ^{113}Cd, ^{128}Te, ^{148}Nd, ^{160}Gd, ^{170}Er, ^{174}Yb, ^{184}W and ^{186}W.

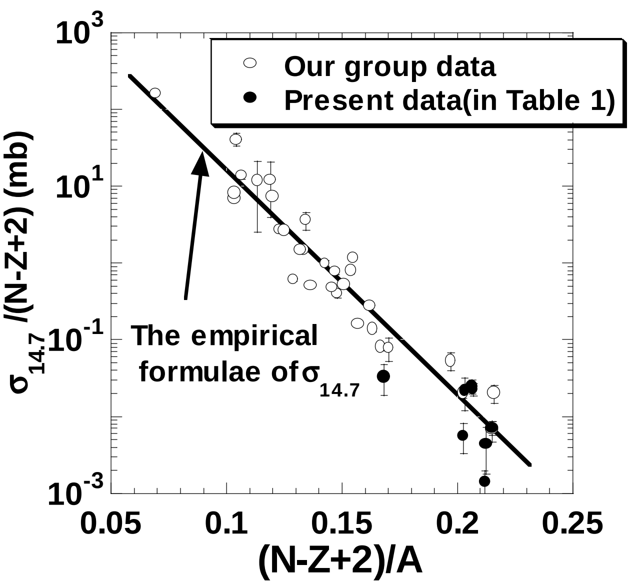

Fig. 5 The Value of $\sigma_{14.7}$/(N-Z+2) as a function of (N-Z+2)/A. The solid line shows the fitting function which leads to the empirical formula of $\sigma_{14.7}$.

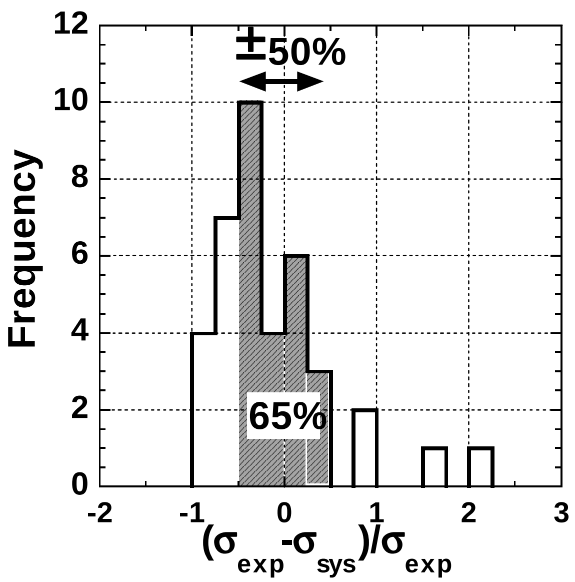

Fig. 6 The distribution of R=(σ_{exp}-σ_{sys})/σ_{exp}, where σ_{exp} is the experimental cross sections and σ_{sys} is the calculated cross section dedused by the empirical formulae in Fig. 5.