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ACTIVATION CROSS SECTION MEASUREMENTS BY 15–35 MeV QUASI-MONOENERGETIC p-Be NEUTRONS

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Abstract : A quasi-monoenergetic neutron field of energies from 15 MeV to 35 MeV has been developed by using the Be (p, n) reaction, for obtaining the data on activation cross sections at energies above 20 MeV which are presently very poor. This quasi-monoenergetic neutron field was utilized to measure the activation cross sections for materials of C, Na, Mg, Al, Si, Ca, Ti, V, Cr, Mn, Co, Cu, Zn, Zr, Nb, Mo and Au. The average cross sections were obtained from the measured activities and the excitation functions were estimated by unfolding technique.

(neutron activation, average cross section, Be (p, n) reaction, excitation function, quasi-monoenergetic neutron, unfolding)

Introduction

The experimental data on neutron activation cross sections at neutron energies above 20 MeV are very poor, except for several reactions. This may be because of the lack of the intense monoenergetic neutron beam of energy higher than 20 MeV. The activation cross sections for high energy neutrons are increasingly required for a safety design of an accelerator facility and for a material damage study.

We developed a quasi-monoenergetic high-energy neutron field for activation experiments up to 40 MeV by a proton bombardment on a Be target. By using this neutron beam having different proton energies of 20 MeV to 40 MeV, average activation cross sections were obtained and the excitation functions were also determined by the unfolding technique.

Development of Quasi-Monoenergetic Neutron Field

A proton beam of 20, 25, 30, 35 and 40 MeV extracted from the cyclotron of the Institute for Nuclear Study, University of Tokyo, bombards the 1-mm-thick (Ep = 20 to 35 MeV) and 2-mm-thick (Ep = 40 MeV) Be targets which are backed by the water coolant, as shown in Fig. 1. The proton beam partially loses its energy as shown in Table 1 and fully shops in the water. The proton beam was focused on the target, and the beam size of about 4-mm diameter was small enough for protons not to hit the 18-mm-diam graphite collimator.

The neutron spectra at 0 degree were measured with a 51-mm-diam by 51-mm-long NE213 scintillation counter by utilizing an n-γ discrimination technique. The pulse height distribution by neutrons was unfolded to energy spectrum with the revised FERDO code[1] and the response function matrix[2]. The room-scattered neutrons were also measured by placing a concrete shadow bar of 10 cm by 50 cm which shielded the direct neutrons from the target to the detector. Figure 2 shows the neutron spectra obtained by subtracting the room-scattered neutrons. The vertical bars indicate the error obtained by the FERDO

Table 1 Characteristics of p-Be Neutron Field

Proton energy (MeV)	40	35	30	25	20
Target thickness (mm)	2.0	1.0	1.0	1.0	1.0
Proton energy loss in target (MeV)	4.7	2.5	2.9	3.4	4.4
Total neutron yield above 3 MeV (n sr^{-1} C^{-1})	1.60×10^{16}	5.76×10^{15}	5.60×10^{15}	4.44×10^{15}	3.66×10^{15}
Peak region (MeV)	31−39	28−34	22−39	17−24	11−19
Peak neutron yield (n sr^{-1} C^{-1})	7.46×10^{15}	2.33×10^{15}	2.96×10^{15}	2.30×10^{15}	1.89×10^{15}
Percentage of peak area	48	40	53	52	52

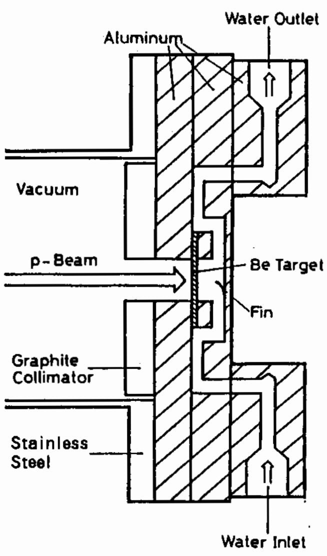

Fig. 1 Sectional plan of the Be target system

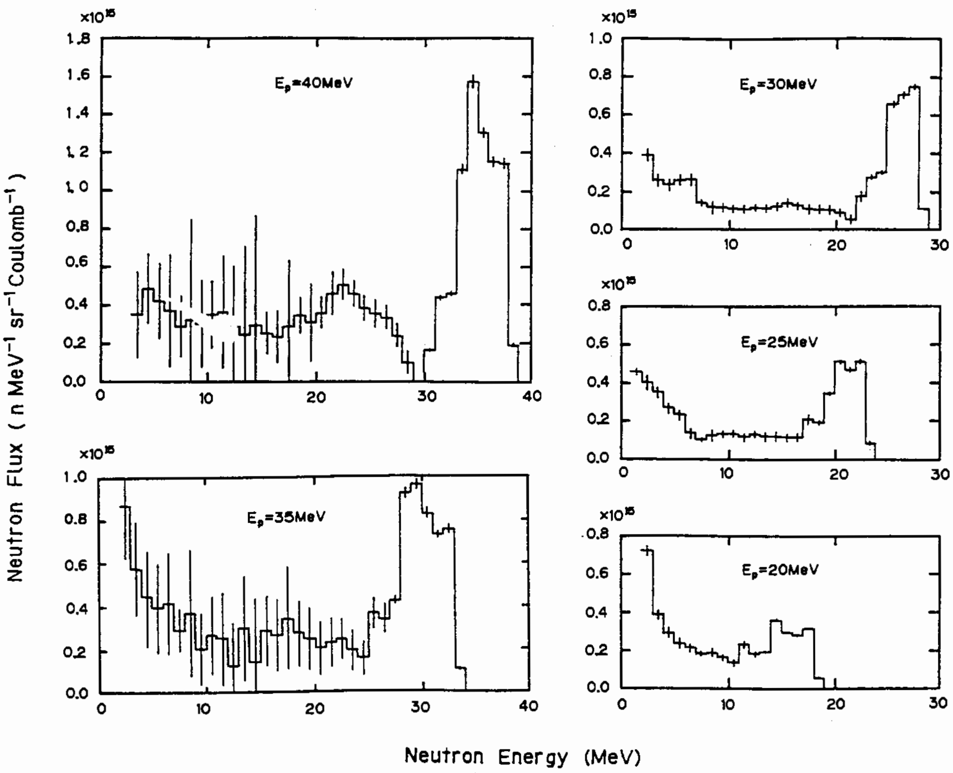

Fig. 2 Quasi-monoenergetic neutron spectra for proton energies of 40, 35, 30, 25 and 20 MeV

code. The neutrons below the peak region would be mainly due to the ^{9}Be (p, n) reaction to highly excited state of residual boron nuclei and the ^{16}O (p, n) reaction in the water, and partly due to the high-energy neutron scattering by the target backing. The characteristics of the neutron spectra are shown in Table 1 .

Activation Cross Section Measurement

The activation cross sections of C, Na, Mg, Al, Si, Ca, Ti, V, Cr, Mn, Co, Cu, Zn, Zr, Nb, Mo, and Au were measured by irradiating the samples of these materials at a position of 20 cm from the Be target. The proton beam intensity (about 5 μA) were monitored by integrating the current on the Be target assembly and the neutron fluxes on a sample were measured during irradiation with the aluminum and gold foils directly attached on the sample. The neutron fluxes were estimated from the ^{27}Al (n, α) and ^{197}Au (n, 2 n) reactions whose cross-sections were evaluated by Greenwood[3]. The reaction rates were obtained from the gamma-ray activities of the irradiated samples measured by a high purity Ge detector.

Determination of Average Cross Section

Since this quasi-monoenergetic neutron field has a lower energy tail as seen in Fig. 1 , the unfolding technique is required to obtain the excitation function of neutron activation reaction. As a first step, the average cross section at neutron energies above 14 MeV were estimated from five reaction rates measured by five types of quasi-monoenergetic neutron irradiation. By neglecting neutrons below 14 MeV, five neutron spectra in Fig. 1 were summed up in each 5 MeV interval from 14 MeV to 39 MeV. The reaction rates can be written in the following matrix form,

$$A_j = \sum_{i \leq j} \phi_{ij} \, \overline{\sigma_i} \qquad (j = 1 \text{ to } 5) \qquad (1),$$

where Aj = reaction rate for j-th quasi-monoenergetic neutrons,

ϕij = i-th component of j-th quasi-monoenergetic neutrons,

σi = average cross section at i-th energy interval.

By solving Eq. (1), the average cross section $\overline{\sigma}$ can be obtained and the error of $\overline{\sigma}$ is also estimated from the propagation law of the errors of A and ϕ. Because of the neglection of neutrons below 14 MeV, this method gives the average cross sections of reactions having threshold energy above about 14 MeV, that is, mainly (n, Xn) reactions.

Some examples of average cross sections thus obtained are shown in Figs. 3 to 6, together with their threshold energies and the maximun values. The average cross sections of ^{12}C (n, 2n) and ^{197}Au (n, 2n) reactions are compared with the O5S data[4] and the Greenwood data[3], respectively, and the present data show pretty good agreement with the O5S and Greenwood data. On the contrary, the present average cross section of ^{23}Na (n, 2n) is much higher than the ENDF/B-V data below 20 MeV[5]. For ^{50}Cr (n, 2n) and ^{50}Cr (n, 3n) reactions, no other data presently exist.

Excitation Function of Activation Reaction

The excitation function of activation reaction can be obtained by applying the unfolding technique to different quasi-monoenergetic neutrons. The unfolding of the following equation

$$A = \int \sigma(E)\phi(E)\,dE \qquad (2),$$

has been performed with the SAND-II code[6] by using the initial guess of σ (E) given in Ref. (3) or calculated with the ALICE code[7].

Some examples of the unfolded results of the excitation functions are shown in Figs. 3 and 6. The present data of the excitation function of ^{12}C (n, 2n) reaction give almost the same values as the O5S data[4]. The excitation function of ^{197}Au (n, 2n) reaction shows good agreement with Greenwood's data[3], but the present peak value between 13 to 17 MeV is 10% larger than Greenwood's value and small difference can be seen between these two values above 18 MeV. It was revealed from these comparisons that the unfolded excitation functions give reasonable results, then we are now performing to obtain excitation functions of activation reactions of the irradiated samples.

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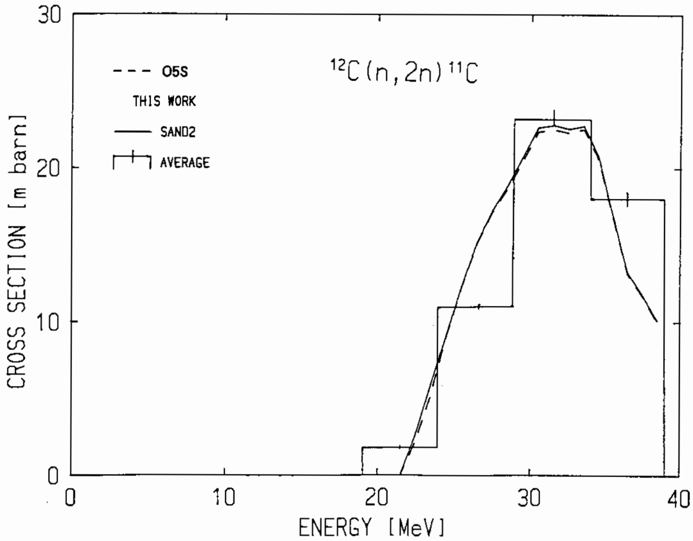

Fig. 3 Average cross sections and excitation functions of ^{12}C (n, 2n) reaction

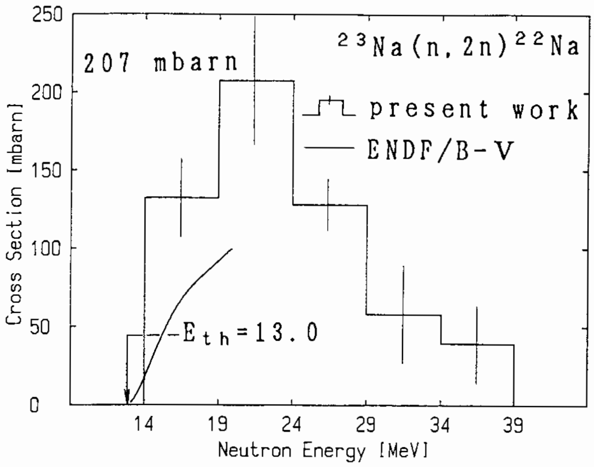

Fig. 4 Average cross sections of ^{23}Na (n, 2n) reaction

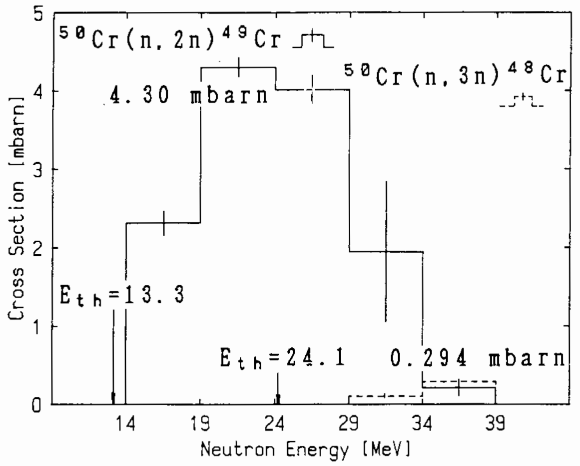

Fig. 5 Average cross sections of ^{50}Cr (n, 2n) and ^{50}Cr (n, 3n) reactions

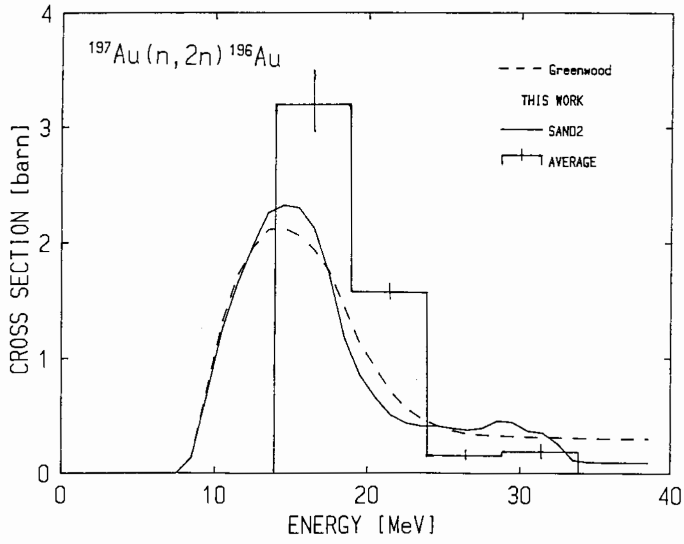

Fig. 6 Average cross sections and excitation functions of ^{197}Au (n, 2n) reaction