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《Original》 Measurement of Fast Neutron Spectrum and Flux in Central Thimble of TRIGA MARK-II Reactor

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Abstract

The measurements of the fast neutron flux and its spectrum have been carried out by the threshold detectors in the central thimble of TRIGA Mark-II reactor operating at 250 KW. The following reactions have been employed for these measurements, viz:
Ni^{58}(n,p) Co^{58}; Mg^{24}(n,p) Na^{24}; Al^{27}(n, α) Na^{24}. From the activation data the fast neutron spectrum were calculated by CDC-3600 computer making use of two semi-empirical methods. It has been verified that the validity of assumption of a fission spectrum in the central thimble exists only above 1 to 2 Mev energy level. With this spectrum, a fast neutron flux in the range of 1×10^{12} n/cm^2-sec above the energy of 2.6 Mev was observed in the central thimble of TRIGA MARK-II reactor.

요 약

250kw로 운전중에 있는 TRIGA MARK-II의 중심공에서 threshold deector를 사용하여 고속중성자속과 스펙토룸을 측정하였다. 이 측정에는 다음과 같은 반응을 이용하였다. 즉 Ni^{58}(n,p) Co^{58}; Mg^{24}(n,p) Na^{24}; Al^{27}(n,α) Na^{24}. 반응에서 측정된 실험결과로 부터 반실험적인 방법에 의하여 CDC-3600계산기를 이용하여 고속중성자의 스펙토룸과 중성자속을 계산하였다. 중심공에서는 분열 스펙토룸의 가정이 1 내지 2Mev 이상에서만 타당하다는 것이 밝혀졌다. 이 스펙토룸을 이용하여 2.6Mev 이상의 고속중성자속은 1×10^{12}n/cm^2-sec 정도가 됨을 관측하였다.

1. Introduction:

The quantitative approach toward fast neutron flux and its spectrum at any position of irradiation in a reactor is very important from the point of view of available experimental facilities. Taking this purpose into account, flux and spectrum measurements were undertaken in the central thimble of TRIGA MARK-II reactor.

For the monitoring of fast neutron flux with threshold detectors, the use of various (n,p), (n, α), (n, 2n) reactions for monitoring of fast flux with threshold detectors has become a standard practice.[1)2)] The procedure of achieving accuracies less than a few percent is relatively simple and is not difficult to attain. However, the interpretation of reaction rates of these detectors is difficult and is generally based on the assumption that it is of a pure fission spectrum. This assumption may not be true, on the ground that it depends on the irradiation position and the energy of interest. In order to remedy this problem, therefore, the experimental results were analysed for equivalent fission flux by using fission cross-section or real flux density by using energy dependent cross-section and the spectrum to calculate effective cross-section. This effective cross-section is then used to calculate flux density. However, since the calculation is difficult, one has to determine it experimentally either using multi-group or some empirical methods involving paramenters which describe the reactor spectrum.

2. Theory

The energy distribution of fission neutron for the U^{235}+n (thermal) fission reaction proposed by Cranberg et al.[3] is given by

$$\phi(E)\,dE = Ce^{-\beta E}\,\sinh\sqrt{\mu E}\;dE \qquad (1)$$

where μ and β are 2.29 and 1.036 respectively for a pure fission spectrum.

A material irradiated in a reactor is rarely exposed to an uncontaminated fission neutron spectrum. This arises from the fact that fission neutrons are moderated by collisions with reactor components, coolant and moderator. Under such circumstances it is convenient to introduce a term 'K' which is defined as the ratio of cross-section of a threshold reaction measured in a reactor spectrum to that measured in a fission spectrum. Therefore

$$K = \frac{\bar{\sigma}_{\text{reactor}}}{\bar{\sigma}_{\text{fission}}} \qquad (2)$$

The meaning of 'K' can be derived from following considerations. In Hughs's notation[4].

$$\sigma_{\text{fission}} = \frac{\sigma_0 \int_{E_{eff}}^{\infty} n(v)\,v\,dv}{\int_0^{\infty} n(v)\,v\,dv} \qquad (3)$$

where σ_0 is the cross-section at unit penetrability and

$\int_0^{\infty} n(v)\,vdv$ is the fission flux.

The approximated value of $\sigma_{0\,\text{reactor}}$ is obtained by dividing the reaction rate R of the threshold detector by reactor thermal flux. (nv_0), where n is the total neutron density and $v_0=2200$ meters/sec. i.e.

$$\bar{\sigma}_{\text{reactor}} \approx \frac{R}{nv_0} = \frac{\int_{E_{eff}}^{\infty} n(v)\,vdv}{nv_0} \qquad (4)$$

The validity of the approximate prediction will be held in the region of moderator midways between rods, where the integrated flux is about equal to the thermal flux due to the moderation. Some approximate results of our experiments with TRIGA MARK-II reactor indicate that the unmoderated fission flux drops by about a factor of 10 in the same region of the reactor.

If one assumes that the distribution of fission neutrons in a reactor has the same shape as the uncontaminated fission neutrons above the energy at which threshold reaction begins to occur, then the term $\int_{E_{eff}}^{\infty}$ n(v) vdv in equations (3) and (4) are identical. Combining equations (3) and (4) together, we get

$$K = \frac{\int_0^{\infty} n(v)\,vdv}{nv_0} \qquad (5)$$

The term 'K' is, therefore, the ratio of the total flux in a fission spectrum having the same magnitude above the energy at which threshold begins to occur as the reactor spectrum to the reactor thermal flux.

The assumption that the distribution of fission neutrons in a reactor has the same shape as the uncontaminated fission spectrum can be tested by determining the ratio 'K' for different threshold energies in the energy range of interest.

3. Experimental Datails

The effective cross-sections for various (n,p), (n,α) reactions for different detectors were determined in the central thimble of TRIGA MARK-II reactor operating at 250 KW. The irradiations were done in Cd covered capsule to eliminate (n,r) reaction. Cobalt monitor was enclosed in the capsule to measure thermal flux. The details regarding amount of material, its purity, irradiation time, etc., are given in Table—1.

Table—1

Reaction	Half Life	Threshold Energy, Mev	Purity & form	weight	Irradiation Time	Waiting Time
1. Ni^{58} (n,p) Co^{58}	71 days	0. 62	Spec-pure foil	38. 3 mg	4 hrs	25. 1 hrs
2. Al^{27} (n,α) Na^{24}	15 hrs	3. 26	〃	24 mg	4 hrs	25. 16 hrs
3. Mg^{24} (n,p) Na^{24}	15 hrs	4. 95	〃	54. 3 mg	4 hrs	25. 25 hrs

The activity of the product nuclide were measured by 2″ x 2″ NaI crystal coupled with a 100 channel pulse height analyzer. The method of flux measurement is based on Westcott's convention[5]. The reaction rate R is given as

$$R=nv_o\bar{\sigma} \tag{6}$$

where

$$\bar{\sigma}=\sigma_o(g+rs) \tag{7}$$

g and r are from Westcott's convention. For cobalt, g is unity. The quantity s is temperature-dependent and since neutron temperature during irradiation is not known, $s\sqrt{\frac{T_o}{T_n}}$ is evaluated as

$$s\sqrt{\frac{T_o}{T_n}}=\frac{2}{\sqrt{\pi}}\ \frac{\varepsilon'}{\sigma_o} \tag{8}$$

where ϵ' is the resonance integral of the detector with $1/v$ subtracted. The epi-thermal contribution to the neutron flux is represented by $r\sqrt{\frac{T_n}{T_o}}$. This is evaluated from the cadmium ratio Rcd and is given as

$$r\sqrt{\frac{T_n}{T_o}}=\frac{1}{R_{cd}\left(s\sqrt{\frac{T_n}{T_o}}+\frac{1}{K_2}\right)-s\sqrt{\frac{T_o}{T_n}}} \tag{9}$$

By putting numerical values of K_2, ϵ' and σ_0 in equations (8) and (9) we get

$$\bar{\sigma}_{co}=36.4\left(1+1.7\,r\sqrt{\frac{T_o}{T_n}}\right) \tag{10}$$

4. Results and Discussions

The experimental results of (n,p) and (n,α) reactions are given in Table II. It is seen from Table-II that K shows a variation more than the experimental error on K (estimated as $\pm$ 10%) for Ni detector which has threshold energy of 0.62 Mev, whereas for detectors Al and Mg which have threshold energies of 3.26 and 4.93 Mev, respectively, K is constant within experimental errors. Thus it can be said that at the central thimble, the assumption of pure fission spectrum is certainly not valid for energies below 1 Mev, but can be considered valid for neutron energies above 1 Mev, as seen from the constant 'K' value for Al and Mg having threhold energies above 3 Mev.

In view of the fact that the validity of fission spectrum fails below the neutron energy of about 1 Mev, it is necessary to find first the spectrum and then determine fast flux. Assuming the spectrum does not differ very much from fission spectrum, we follow the two semi-empirical methods of analysis.

a) Analysis by method of effective threshold energy

The reaction rate can be written as

$$R=\int_0^\infty \sigma(E)\ \phi(E)\,dE=\sigma_o\int_{Eeff}\phi(E)\,dE \tag{11}$$

where Eeff is defined as effective threshold energy of a particular threshold reaction beyond which the activation cross-section σ(E) attains a constant value of σ_0. If σ_0. and Eeff are known, it can be seen that from the measurement of reaction rates R of various threshold detectors one can obtain the integrated flux above the threshold energy and then by differentiation of ϕ(E). Let us assume that the reactor spectrum does not deviate much from the fission spectrum.

If we choose the form[1),6)] which is a Maxwellian expression of Eq. (1), as follows:

$$N(E) = \frac{2\beta^{\frac{3}{2}}}{\sqrt{\pi}} E^{\mu} e^{-\beta E} \tag{12}$$

the values of β and μ that apply in case of fission spectrum are 0.77 and 0.5, respectively.[7) 8)]

Taking the value of $\mu=1/2$, σ_0 is calculated as a function of β for various values of E_{eff} from the relation

$$\sigma_o(\beta) = \frac{\int_0^{\infty} \sigma(E) E^{\frac{1}{2}} e^{-\beta E} dE}{\int_{Eeff} E^{\frac{1}{2}} e^{-\beta E} dE} \tag{13}$$

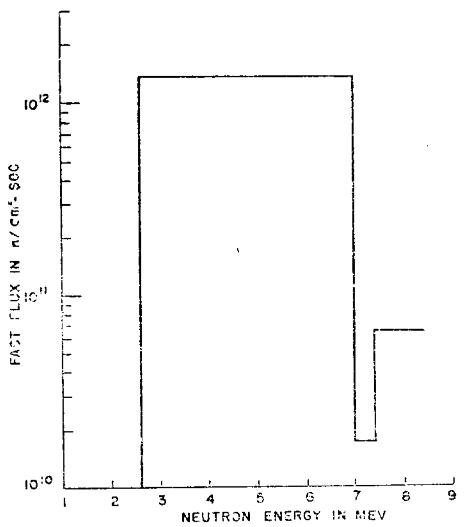
For each value of E_{eff}, we obtain a curve $\sigma_0(\beta)$. Out of this family of curves we seek that curve which satisfies the condition $\frac{\partial \sigma_0}{\partial \beta} = 0$, where $\beta = 0.77$. By plotting all the values of E_{eff}, a curve is resulted from it, and then the values of $\sigma_0(\beta = 0.77)$ are obtained out of this curve. Having abtained σ_0 and E_{eff} for various threshold detectors, ϕ(E) can be obtained from the experimental observation of reaction rates.

The values of σ_0 and E_{eff} have been calculated from the expression (13) on CDC-3600 computer and are given in Table-III along with the calculation of fluxes.

Table II

Reaction	Threshold Energy (Mev)	Reaction Rate (atoms/sec)	Thermal Flux (n/cm²-sec)	σreactor (mb)	σfission (mb)	K
1. Ni^{58}(n,p) Co^{58}	0. 62	4.83×10^{-13}		48. 33	104	0. 46
2. Al^{27}(n,α) Na^{24}	3. 26	4.83×10^{-15}	1×10^{13}	0. 4826	0. 60	0. 80
3. Mg^{24}(n,p) Na^{24}	4. 95	9.77×10^{-15}		0. 9774	1. 34	0. 73

Fig. 1 HISTOGRAM OF FAST FLUX AS FUNCTION OF ENERGY GROUP IN CENTRAL THIMBLE FOR TRIGA MARK-II REACTOR (250KW)



The differential spectrum obtained as a histogram from the three threshold reaction data is shown in Fig 1.

b) Analysis by method of spectral index[9)]

1) The total energy range of fast neutron is divided into three groups, ϕ_1 for 0.19–1.5 Mev range, ϕ_2 for 1.5–3.0 Mev, and ϕ_3 for 3.0–10 Mev, respectively.
2) The flux density ϕ (E) in the first and second groups is constant and the third group is proportional to $e^{-\beta E}$.

Fast flux ϕ_3 is determined by finding the ratio of reaction rates of Ni and Al detectors. The function K (β) defined below has been evaluated as a function of β on CDC-3600 computer.

$$K(\beta) = \frac{R_{Ni}}{R_{Al}}(\beta) = \frac{\int e^{-\beta E} \sigma_{Ni}(E) dE}{\int e^{-\beta E} \sigma_{Al}(E) dE} \tag{14}$$

The theoretical plot of K (β) versus β is shown in Fig 2. From the experimental observation of

Table III

Reaction	E_{eff}	σ_o (mb)	Fast Flux above E_{eff} (n/cm²-sec)	Differential fast (n/cm²-sec)
1. Ni^{58}(n,p) Co^{58}	2.6 Mev	340	1.42×10^{-12}	1.34×10^{12}
2. Mg^{24}(n,p) Na^{24}	7 Mev	119	8.21×10^{10}	1.69×10^{10}
3. Al^{27}(n,α) Na^{24}	7.4 Mev	74	6.25×10^{10}	6.25×10^{10}

R_{Ni}/R_{Al}, the parameter β which describes the spectrum in the third group is obtained from Fig 2. Since β is known (i.e. shape of spectrum is known), the effective cross-section is given by

$$\sigma_{eff}=\frac{\int_0^{\infty}e^{-\beta E}\,\sigma(E)\,dE}{\int_3^{\infty}e^{-\beta E}dE} \qquad (15)$$

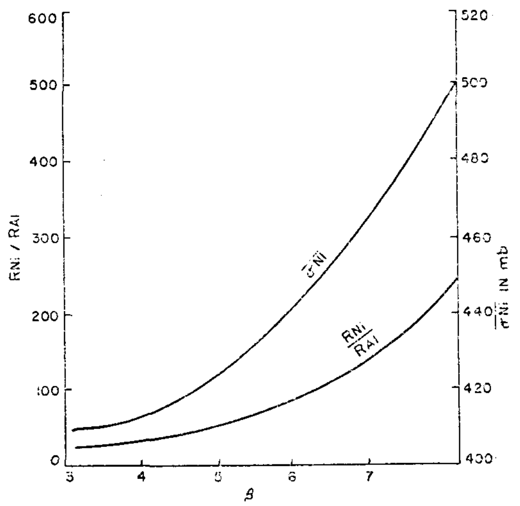
The value of σ_{eff} for Nickel as a function of β is also given in Fig. 2.

The fast flux ϕ_3 can be found from the relation $R_i=\phi_3\sigma^i{}_{eff}$ where i stands for nickel or aluminum. Since only two detectors Al and Ni having threshold above 2 Mev are used in the present experiments, we can determine flux in the energy range 3 Mev and above.

The results (β and σ_{eff}) obtained using the reaction data of Ni and Al are shown in Table-IV along with the experimentally obtained value of fast flux.

On the differential cross-sections of the threshold detectors, data were extracted from the literature[10], in which curves are drawn smoothly between the experimental data.

Fig 2 $\frac{R_{Ni}}{R_{Al}}$ AND $\bar{\sigma}_{Ni}$ AS A FUNCTION OF β



5. Conclusion

By using three threshold detectors, Ni, Al and Mg and cobalt as thermal flux monitor and analysing the data based on the method of finding and comparing reactor spectrum cross-section to fission cross-section for each of them, it has been found out that the validity of the assumption of a fission spectrum in the central thimble of TRIGA MARK-II reactor exists only for neutron energies above 1 to 2 Mev and not below the threshold energy of Nickel. Hence, in order to find the reactor spectra and fast flux in the reactor, the threshold activation data for Ni, Mg and Al were analysed by two semi-empirical methods.

The fast flux data as a function of energy group were found out by differential technique and is presented in the form of a histogram. The treatment of the experimental data by two methods shows self consistancy in the analysis

Table IV

Reaction Rate of Ni/sec	Reaction Rate of Al/sec	Ratio $\frac{R_{Ni}}{R_{Al}}$	β from Fig. 6	$\bar{\sigma}_{Ni}$ from Fig. 6	Fast Flux above 3 Mev (n/cm²-sec)
4.633×10^{-13}	4.626×10^{-15}	100	0.63	448	1.08×10^{12}

since both methods give a fast flux in the range of 1x 10^{12} n/cm^2—sec above the energy of 2.6 Mev in the central thimble of TRIGA MARK-II reactor operating at 250 KW.

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