THERMALIZATION OF ACCELERATOR-PRODUCED NEUTRONS IN A CONCRETE ROOM

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Abstract

We investigated a thermalization of neutrons, which were produced by an accelerator in a concrete room, by experiments and calculations. It was clarified that the widely-used simple empirical formula[1] $\phi_{th}=c \cdot Q/S$, where Q is neutron source intensity and S is total surface area of a room, gives about 1/3 underestimated value to our experimental and calculated results and the coefficient, c, is not a constant, but dependent to the source neutron energy.

Introduction

In a concrete room, high energy neutrons which produced by an accelerator, lose their energy by the multiple collision with the wall, the floor and the ceiling, and are reflected from their surfaces as thermal neutrons. These thermal neutrons generate a radioactive nuclide ^{41}Ar by the $^{40}Ar(n,\gamma)$ reaction in the air. The ^{41}Ar isotope causes gamma-ray exposure to the workers in accelerator facilities and to the outdoor public through the ventilation. For this reason, the estimation of ^{41}Ar generation and then of thermalized neutrons is one of the important problem in the accelerator shielding design. Very few studies hitherto exist on this neutron thermalization, and the following simple empirical formula has generally been used for the estimation of the thermalized neutrons in the accelerator room.[1]

$$\phi_{th} = c \cdot \frac{Q}{S} \qquad (n/cm^2/sec) \qquad (1)$$

where

- c : coefficient (The value of 1.25 was recommended in the Ref.1.)
- Q : neutron source intensity, i.e. total number of neutrons generated at the target (n/sec)
- S : total surface area in a concrete room (cm^2).

Equation(1) gives that ϕ_{th} is independent of a room shape, a detecting position and a source neutron energy. The theoretical background of this coeffient c=1.25 is, however, not clear. The validity of this equations has never checked by experiments and calculations.

A purpose of this study is to investigate the accuracy of Eq.(1) by experiments and calculations.

Experiment

We made the experiments at the Cyclotron facilities in the Cyclotron and Radioisotope Center, Tohoku University (CYRIC) and at the Fast Neutron Laboratory, the Department of Nuclear Engineering, Tohoku University (FNL). The measurement at CYRIC aimed to investigate the accuracy of Eq.(1) in actual accelerator facilities and the dependence of the coefficient 'c' to the different room shapes. Another measurement at FNL was to investigate the dependence of 'c' to the source neutron energy by using monoenergetic neutrons.

CYRIC experiment

The experiment at CYRIC was done in a broad room (Electro-Magnetic room: 1480 x 897.5 x 700cm^3, S = 5.985x$10^6 cm^2$) and in a narrow room (Beam- Extended room : 1000 x 180 x 700cm^3, S = 2.012x$10^6 cm^2$) (see Fig.1). A 30-MeV proton beam extracted from the Cyclotron, was stopped in the 32mm thick copper beam stopper in each room, in order to produce high energy neutrons. The number of protons injected to the copper was measured by a current integrator. The neutron energy spectra produced by the copper were measured with activation foils of Al, Co, Ni, In and Au which were set, 40cm away from the copper beam stopper, at 30° and 75° to the proton beam axis in the Beam Extended room (BER). More detailed spectrum measurement at 30, 45, 75 and 135 degree to the beam axis, was made at the Electro-Magnetic room (EMR).

The activities of foils were measured with a high purity Germanium detectors coupled to a multi-channel analyzer. Their activition rates were unfolded by the SAND-2 code[2] to obtain the angular-dependent neutron energy spectra $\phi(\theta,E)$ generated from thick copper target. As an initial guess spectrum for unfolding, the spectrum measured with the NE-213 scintillator by T.Nakamura et al.[3] was used. The source intensity Q was obtained by integrating $\phi(\theta,E)$ over whole solid angle and energy.

Thermal neutron fluence distribution in two rooms was measured by the "cadmium difference method"[4] with 0.1mm thick gold foils. Nine pairs of a bare gold foil and a Cd-covered gold foil were set at various points in EMR and BER, respectively. These gold foils were exposed by the neutron at the same time as the above activation foils and their activities were measured by a high purity Germanium detector. Thermal neutron fluence ϕ_{th} was obtained from these activities by the cadmium difference method[4].

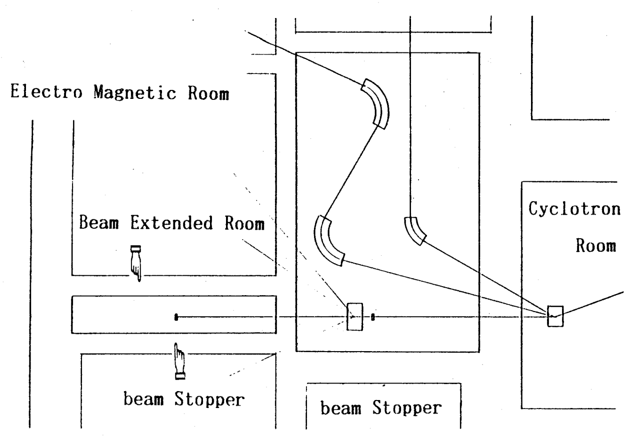

Figure 1. Plan of CYRIC

FNL experiment

The experimental arrangement in a lager room(2300 x 1900 x 960cm^3, S=1.680x10^{7}cm^2) at FNL is shown in Fig.2. Three kinds of semi-monoenergetic neutrons with their average energies of 14.1, 3.35 and 0.523 MeV were generated from the d-T, d-D and p-T reactions by the Dynamitron accelerator, respectively. The neutron intensities were monitored by the fission chamber set at 0 degree to the beam axis and the hydrogen proportional counter set at 45 degree shown in Fig.5. Total neutron yield generated from the target was estimated from these measured counts and angular-dependent neutron production cross sections.[5]

Thermal neutrons were measured by the "cadmium difference method" with a 10 atm.^{3}He proportional counter. The ^{3}He proportional counter was set at 4 positions as shown in Fig.2. At each position, measurement was repeated twice with a bare counter and a cadmium covered one.

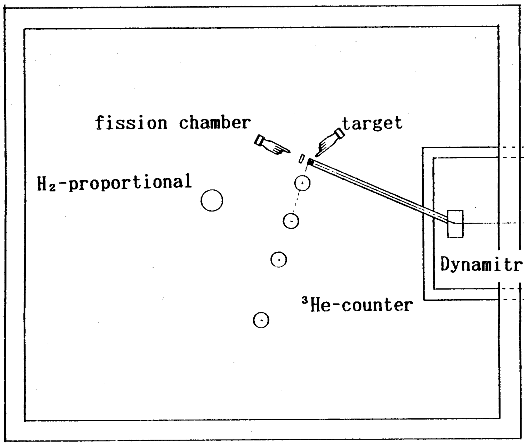

Figure 2. Plan of FNL

Calculation

For comparison with the experimental results, we calculated the distribution of thermal neutrons in these three rooms, EMR and BER at CYRIC and FNL with the MORSE-CG Monte Calro code[6] and investigated the dependence of the coefficient c to the distance from the source. Subsequently,we calculated the thermal neutron fluence in the spherical concrete room by one dimensional discrete ordinate code ANISN[7] in order to study further the dependence of the coefficient c to the source neutron energy and to the room size.

MORSE-CG calculation

The calculational condition of MORSE-CG is the followings. A neutron source is point-isotropic and its spectrum is the integration of the angular- dependent neutron energy spectra over the whole solid angle. The angular-dependent neutron energy spectra used were obtained from thick copper data cited from Ref.3 for CYRIC and from neutron production differencial cross section by charged particle from Ref.5 for FNL. A neutron fluence estimator is a"real surface crossing estimator" with a spherical shell of 100cm diameter at CYRIC EMR and FNL and 50cm diameter at CYRIC BER. The concrete wall thickness is fixed to 30cm at CYRIC and 40cm at FNL. The cross section data used are the DLC-87 libraly and the components of concrete and air are the same as those given by Uwamino et al.[8]

ANISN calculation

The ANISN calculation was performed under the calculational condition that the room used in this experiment was modeled to be a sphere sarrounded with 100-cm thick concrete wall, whose inner surface area was equal to that of the experimental room. The neutron source, the cross section library and the components of concrete and air are the same as in the MORSE-CG calculation. In the calculation, the thermal neutron fluence was almost constant inside the concrete wall. We, therefore, adopted the value of thermal neutron fluence at the center of the shere. We also calculated the dependence of c to the room size and to the source neutron energy by changing the radius of a spherical room from 1.25m to 10m and the source energy from 1keV to 400MeV, respectively.

Results and Discussion

Results at CYRIC

The value of coefficient c in Eq.(1) obtained from Q and ϕ_{th} are shown as black circles for EMR and black triangle for BER in Fig.3, respectively. The "distance from target" in the figure means the shortest distance ,t, among the passages through which neutrons from the target reach the detecting point via the reflection from the concrete surface. This passage corresponds to the case that an incident angle and a reflection angle on the concrete surface are equal. The c values decrease from about 6 to about 1 with the distance t and they are close each other for two rooms, EMR(broad room) and BER(narrow room) despite of big differences of these room sizes and shapes as shown in Fig.1. The measured values of c are larger than 1.25 in Ref.(1) except at the most distant position of 1335cm in the EMR. The average values of c are 2.09 at EMR and 2.54 at BER.

In Fig.3, the c values calculated from MORSE-CG and ANISN are also shown for comparison. The ANISN calculations give constant c values to the variation of the distance t, but c values of MORSE-CG decrease with t similarly as the measured c values. This distance dependence may be because the detecting point near the

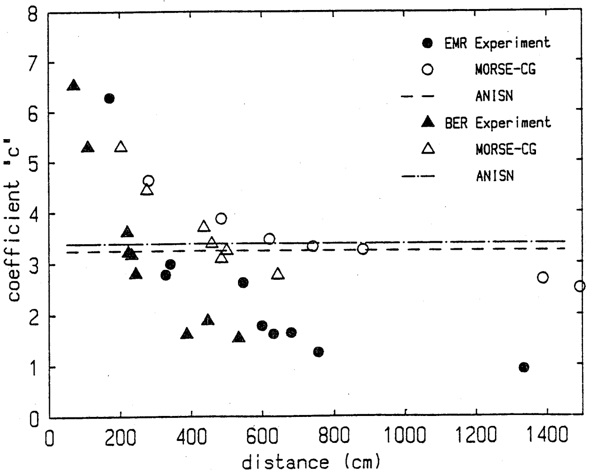

Figure 3. Coefficient 'c' at CYRIC

target are strongly influenced by the first reflected neutrons from the concrete floor or wall when the target is close to the concrete surface.

The calculated c values are all larger than the measured c values and the average c values are shown in Table 1. The ANISN and MORSE-CG results are close together and in good agreement with the measured results.

Results at FNL

The coefficient c values in Eq.(1) obtained from Q and ϕ_{th} are shown in Fig.4, as a function of average energy of neutron source, $\bar{E}_0$. In Fig.4, the c values decrease with the shortest distance,t, similarly as in Fig.3, and also with the average source neutron energy $\bar{E}_0$. The c values averaged for t are 1.33 for $\bar{E}_0$=14.1 MeV (d-T neutrons), 1.72 for $\bar{E}_0$=3.35 MeV (d-D neutrons) and 2.80 for $\bar{E}_0$=0.52 MeV (p-T neutrons). These results are also listed in Table 1 together with the calculated results.

The c values calculated by ANISN and MORSE-CG give all larger than the measured values. The ANISN results are closer (32 to 67 % higher) to the measured results.

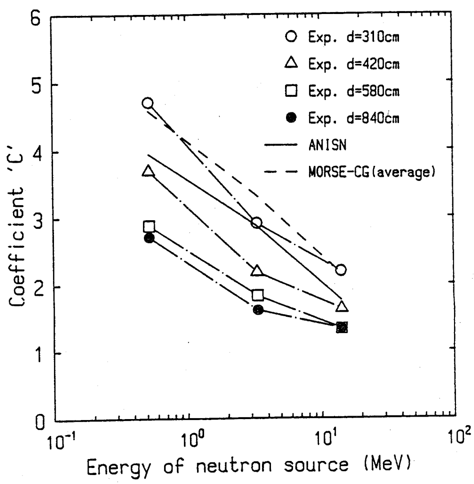

Figure 4. Coefficient 'c' at FNL

Table 1. results of measurements and calculations

laboratory		surface area of the room S (cm²)	neutron source energy [average] (MeV)	coefficient 'c' calculation ANISN	calculation MORSE-CG [average]	measurement [average]
CYRIC	EMR	5.99×10^6	2.8	3.24	3.05	2.09
	BER	2.01×10^6	2.8	3.38	3.22	2.54
FNL		1.68×10^7	14.1	1.76	2.16	1.33
			3.35	2.87	3.32	1.72
			0.52	3.95	4.58	2.80

Dependence on source neutron energy

As seen in Fig.4, the measured c values decrease with the source neutron energy $\bar{E}_0$. In order to investigate the dependence of c on E_0 in wider energy region, the ANISN calculation was carried out for E_0= 1 keV to 400 MeV, since the ANISN calculation gives closer values to the measured values. In this calculation, the room radius was 500 cm and the concrete wall thickness was 100 cm. Fig.5 shows the calculated results of c.

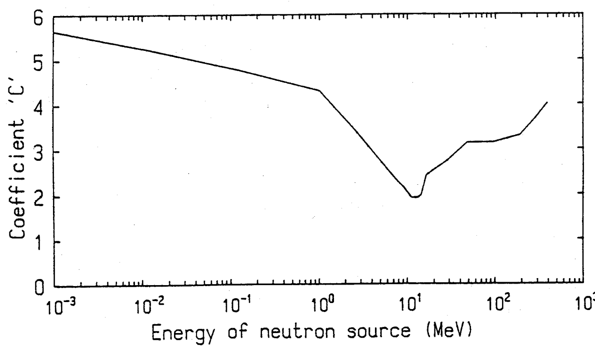

Figure 5. Coefficient 'c' Calculated by ANISN

Conclusion

Our results clarified that the thermal neutron fluence in a concrete room can be estimated by

$$\phi_{th} = c \cdot \frac{Q}{S}$$

The coefficient c is dependent on the source neutron energy and the distance from the target to the detecting position, but besides the position close to the target, the c values are almost independent to that distance. To give the safe-side estimation of Φ_{th}, we propose c = 4 for the source neutron energy between 400MeV and 1 keV, in place of c = 1.25 hitherto used.

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