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EXTENSION OF APPLICABLE NEUTRON ENERGY OF DARWIN UPTO 1 GEV

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The radiation-dose monitor, DARWIN, needs a set of response functions of the liquid organic scintillator to assess a neutron dose. SCINFUL-QMD is a Monte Carlo based computer code to evaluate the response functions. In order to improve the accuracy of the code, a new light-output function based on the experimental data was developed for the production and transport of protons deuterons, tritons, ^{3}He nuclei and alpha particles, and incorporated into the code. The applicable energy of DARWIN was extended to 1 GeV using the response functions calculated by the modified SCINFUL-QMD code.

INTRODUCTION

In high-intensity particle-accelerator facilities, neutrons with a wide energy distribution are generated via nuclear spallation reactions, and the radiation dose outside the shielding is dominated by the neutrons of energies up to giga-electron volts. The authors have developed a new radiation-dose monitor DARWIN(1) to assess the doses in workspaces and surrounding environments at these facilities. DARWIN employs a phoswich-type detector, which consists of a liquid organic scintillator surrounded by a ZnS(Ag) scintillation sheet, and the doses are derived by use of the G-function(2) calculated from a set of response functions and dose-conversion coefficients.

The applicable energy of DARWIN is restricted to 80 MeV(3–5) due to the lack of the available data set of response functions. In order to extend the upper energy measurable with DARWIN, it is indispensable to evaluate the response functions of the liquid organic scintillator for high-energy neutrons.

The authors have developed a computer code, named SCINFUL-QMD, to calculate response functions of a liquid organic scintillator(6). It was found from the comparison with experimental results measured for neutrons up to 800 MeV(7) that SCINFUL-QMD gives slight overestimation at all incident neutron energies. This comes from the poor modeling of the creation of fluorescent light, especially its quantification. To solve this problem, the light outputs of the liquid organic scintillator have been measured for protons, deuterons, tritons, ^{3}He nuclei, and alpha particles(8). Calibration experiments were also performed using gamma-ray reference sources and light-emitting diodes (LEDs).

The paper describes the systematic data of light outputs of the charged particles. The light outputs are parameterised for each charged particle type with a simple formula, and are incorporated into SCINFUL-QMD to improve the reliability of the code predictions.

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MEASUREMENT

The measurements of light outputs were carried out at the Heavy-Ion Medical Accelerator in Chiba (HIMAC) of the National Institute of Radiological Sciences (NIRS), Japan. Since the details of the experimental procedure are described in the previous paper(8), they are only mentioned here.

The detector was a BC501A-type liquid organic scintillator, which is the same one employed in DARWIN. The shape was cylindrical with a 12.4 cm diameter and 12.7 cm thickness. Charged particles directed into the scintillator were generated by spallation reactions at a thick graphite target with 400-MeV/u C ion incidences, and distinguished by the difference of the mass and charge. The kinetic energies of charged particles were determined by the time-of-flight (TOF) method, and the energy losses during their flights were corrected according to calculation of the general-purpose particle and heavy-ion transport code PHITS(9). The uncertainty of the kinetic energies was estimated to be 15% at maximum.

CALIBRATION

The measured light-output data were calibrated by use of gamma-ray reference sources and LEDs to quantify the light in units of electron-equivalent energy (MeV_{ee}). The reference sources employed in this work were ^{60}Co, ^{22}Na and ^{241}Am–Be. Because of the low energy resolution of the BC501A scintillator for low-energy gamma rays, it is difficult to use the position of the Compton edge as a reference; the edge is unclear and the position of the maximum

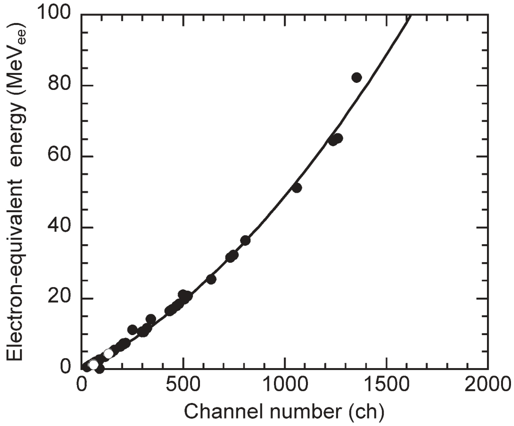

Figure 1. Calibration curve between channel number and electron-equivalent energy. Open and closed circles indicate the data by reference sources and LEDs, respectively.

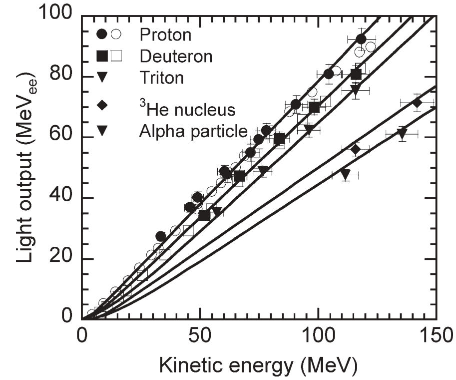

Figure 2. Light outputs of a BC501A-type liquid organic scintillator. Closed and open marks are experimental results obtained by the authors and Nakao *et al.*[(11)], respectively. Solid curves are given by light-output function proposed in this work.

depends on the energy resolution. To solve this problem, Dietze *et al.* reported that the position of the half height of the maximum ($L_{1/2\mathrm{Compton}}$) is almost independent of the resolution[(10)]. $L_{1/2\mathrm{Compton}}$ was, therefore, used to relate the channel number to the corresponding electron-equivalent energy in the present analysis.

LEDs were also utilised for calibration. The LED light, whose peak wavelength is 400 nm, was directed into the photomultiplier tube. By changing the number and current of LEDs, calibration points were obtained over the wide channel numbers, and then the data were normalised with those of the reference sources. Figure 1 presents the relationship between the channel number and the electron-equivalent energy. A calibration curve was derived from fitting the data points to a quadratic formula with the least-square method.

RESULTS AND DISCUSSION

At first, the reliability of the experimental results is examined by comparing them with other data. Then, the new light-output function is constructed on the basis of the experimental results. Light-output curves given by this function are compared with the original database compiled in SCINFUL-QMD, and finally the contribution of changing the light-output routine in the code is discussed.

Figure 2 shows the measured light outputs for protons, deuterons, tritons, ^{3}He nuclei and alpha particles in the unit of electron-equivalent energy. Error bars (equal to one standard deviation) reflect the energy and light-output resolutions. The experimental results were compared with those obtained by Nakao *et al.*[(11)] for protons and deuterons. The results of the authors and Nakao *et al.* show quite a good agreement over the wide energy range. From this comparison, the reliability of the present experimental data was confirmed.

Table 1. Coefficients in Equation (1) for proton, deuteron, triton, ^{3}He nucleus and alpha particle.

Particle	Coefficient		
	a_1	a_2	a_3
p	0.81	2.43	0.29
d	0.74	3.45	0.20
t	0.72	7.19	0.07
^{3}He	0.54	3.97	0.20
α	0.51	6.42	0.08

In order to represent the light outputs for various charged particles in a simple way, a light-output function has been developed by using the following formula[(11)];

$$L = a_1E - a_2\{1.0 - exp(-a_3E)\} \qquad (1)$$

where L (MeV_{ee}) is the light output, and E (MeV) is the kinetic energy of the charged particle. The coefficients of a_1, a_2 and a_3 were evaluated from the present experimental data by fitting to Equation (1) with the least-square method. The data measured by Verbinski *et al.*[(12)] for neutrons up to 22 MeV were also used in the fitting at the low-energy region. The values of the coefficients are listed in Table 1, and the light-output curves given by this function are shown in Figure. 2. As evident from the figure, the function reproduces the experimental data well.

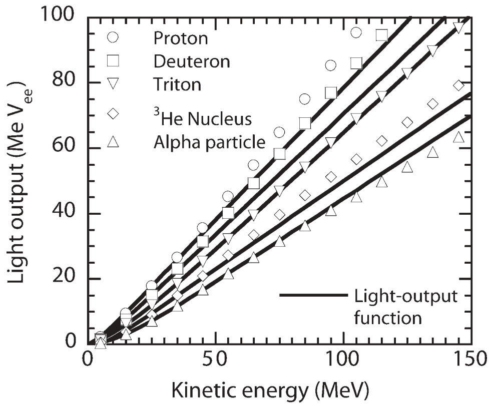

Figure 3. Comparison of light outputs between the function and SCINFUL-QMD. Marks are the data employed in SCINFUL-QMD.

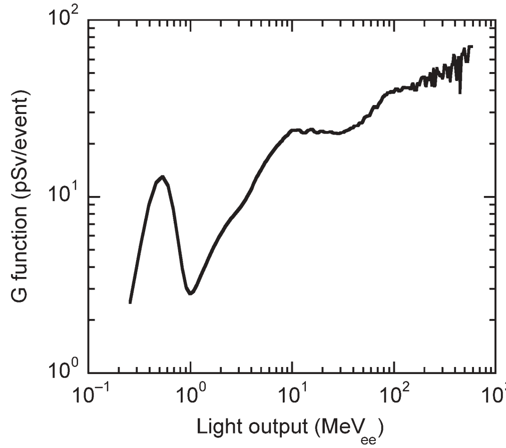

Figure 5. Evaluated G-function for isotropic neutron irradiation using the response functions calculated by modified SCINFUL-QMD.

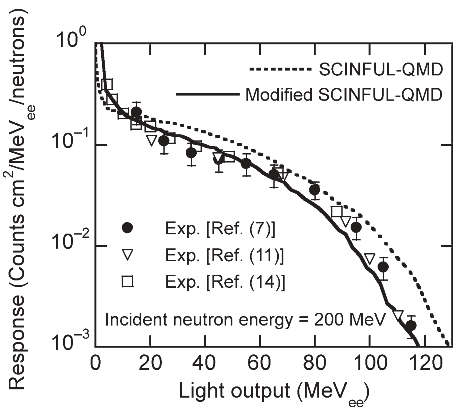

Figure 4. Response functions of a BC501A-type liquid organic scintillator calculated by the former and the modified SCINFUL-QMD codes.

In Figure 3, the light-output curves given by the function were compared with the original database compiled in SCINFUL-QMD. Below 50 MeV, the results of the function show a good agreement with the data of SCINFUL-QMD. At higher energy region, however, they show slight disagreements, excepting those for triton. The light-output database of SCINFUL-QMD is based on the data measured by Verbinski *et al.*, and extended by using Birks' formula(13) in the neutron energy region above 22 MeV. Therefore, the ambiguity becomes larger at the high-energy region where no experimental data were available.

The light-output function was incorporated into the SCINFUL-QMD code instead of the original database; it is designated as modified SCINFUL-QMD here. Figure 4 shows the response functions for 200-MeV neutrons calculated by the former and the modified SCINFUL-QMD. The experimental data obtained in the near neutron energies(7,11,14) are also depicted. The figure indicates that the modified SCINFUL-QMD is capable of reproducing the response functions better than the former one. The accuracy of SCINFUL-QMD was improved by updating the light-output routine.

Figure 5 depicts the evaluated G-function for isotropic neutron irradiation using the response functions calculated by the modified SCINFUL-QMD. The neutron-dose rate has been measured with DARWIN adopting this G-function in the background radiation field, which includes neutrons above several hundred MeV. DARWIN indicated 0.0077 μSv/h, and a model calcualtion(15) gave 0.0066 μSv/h. This result is very reasonable, because DARWIN is set to give a slightly conservative value compared with an actual one.

CONCLUSION

Light outputs of a BC501A-type liquid organic scintillator have been measured systematically for protons, deuterons, tritons, ^{3}He nuclei, and alpha particles. The experimental data were calibrated with the gamma-ray reference sources and LEDs in the unit of electron-equivalent energy. A new light-output function was constructed on the basis of the present experimental data. The accuracy of SCINFUL-QMD was improved by incorporating this function. The evaluation of the G-function using response functions calculated by the modified SCINFUL-QMD enables one to measure the neutron dose up to 1 GeV with a sufficient precision by DARWIN. The performance test of DARWIN for high-energy neutrons is reported in another paper[16].

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