Study of Light Output and Response Function of Liquid Organic Scintillator for High-Energy Neutron Spectrometry

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***Abstract*— In order to investigate the relationship between kinetic energy of charged particles and light output of liquid organic scintillator, response functions for proton, deuteron, triton, ^{3}He nucleus and alpha particle have been measured at Heavy-Ion Medical Accelerator in Chiba (HIMAC) of National Institute of Radiological Sciences (NIRS). The charged particles were generated by 400 MeV/u C ion bombardment with a thick graphite target. Kinetic energies were determined by time-of-flight (TOF) technique. Energy loss during their flight was calculated by PHITS code and taken into account at energy-correction. Light output for proton was also measured using mono-energy proton beam of 100 and 160 MeV supplied by accelerator. Kinetic energy of proton beam was changed by inserting Al plates onto beam axis as an energy absorber. The experimental results gave a new database of light output.**

***Index Terms*— neutron spectrometry, liquid organic scintillator, BC501A, NE213, light output, response function.**

I. Introduction

LIQUID organic scintillators, such as NE213 and BC501A, have been widely used for neutron spectrometry in the energy region above several MeV, since these scintillators have a high detection efficiency and a good capability to distinguish neutrons and gamma-rays.

In order to obtain spectral information using the scintillators, time-of-flight (TOF) technique is suitable for pulsed neutrons source, and unfolding technique is applicable to stationary neutron sources. In both methods, it is required to determine the response function of the scintillators either experimentally or computationally. In this reason, we have developed a Monte Carlo code, SCINFUL-QMD[1], for calculating the response function of the scintillator up to 3 GeV and validated the predictions of the code by comparing with experimental results measured for incident neutrons up to 800 MeV[2]. It was found from the comparison that SCINFUL-QMD fails to reproduce the response functions at the higher light output region[3]. This comes from the poor modeling for the creation of fluorescent light, especially its quantification.

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To investigate the energy dependence of light output from the scintillator for various charged particles, response functions have been measured for protons, deuterons, tritons, ^{3}He nuclei and alpha particles at the Heavy-Ion Medical Accelerator in Chiba (HIMAC) of National Institute of Radiological Sciences (NIRS), Japan. Spallation reaction by 400 MeV/u of C ion incident on a thick graphite target was utilized to produce the charged particles. Kinetic energy of the emitted particles was determined by use of TOF technique. Mono-energy proton beam supplied by accelerator was also injected to the scintillator. The energy of proton beam was 100 MeV and 160 MeV, and degraded by inserting various thicknesses of Al plates onto beam axis as an energy absorber.

In this work, we report the systematic data of light output for protons, deuterons, tritons, ^{3}He nuclei and alpha particles. Comparisons were made with the formulas[4], [5] for proton, deuteron and alpha particle.

II. Experiment and Analysis

The experiment was carried out using the PH2 beam line of the HIMAC at NIRS. Two types of experimental method were employed, hereafter we designate them as *spallation method* and *mono-energy beam method*. Spallation method is able to obtain the data simultaneously for various charged particles with a wide energy range. On the other hand, mono-energy beam method has an advantage of the accuracy for the energy determination. The detailed descriptions about each method are as follows.

1) Spallation Method: Figure 1 shows an experimental arrangement of the spallation method. Various kinds of charged particles were produced via spallation reaction by C ion bombardment with a thick graphite target. The kinetic energy of C beam was 400 MeV/u. The thickness of the target was 20

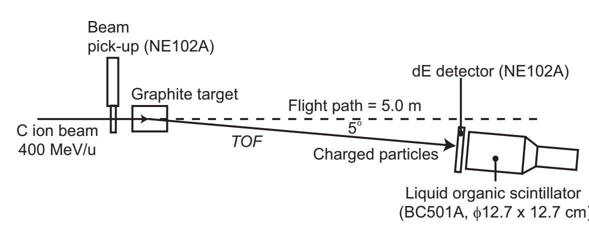

Fig. 1. Experimental arrangement of spallation method

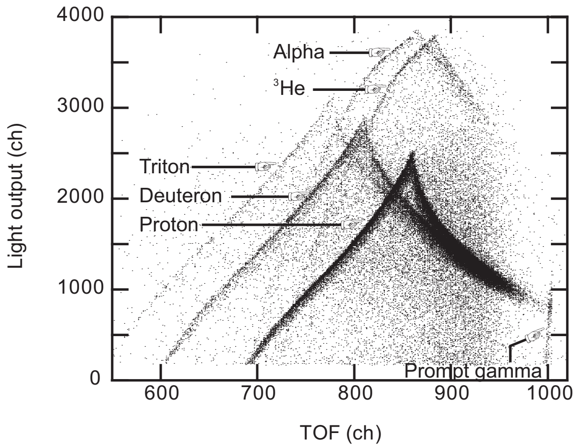

Fig. 2. Two-dimensional scatter plot of TOF and light output of liquid organic scintillator

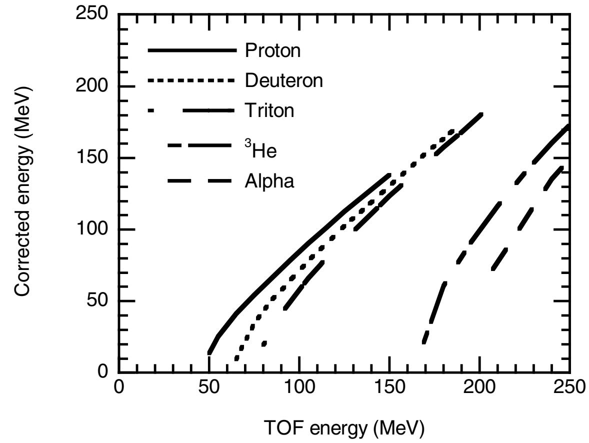

Fig. 3. Energy-correction for each charged particle. Energy loss was calculated by PHITS[6] along the flight path, and subtracted from TOF energy

cm to stop the primary ions inside it. Time-of-flight (TOF) technique was adopted to estimate the kinetic energy of charged particles. A BC501A liquid organic scintillator was placed at 5° from the beam axis. The shape was cylindrical with a 12.7 cm diameter and 12.7 cm thickness. Flight path length was 5.0 m. An NE102A plastic scintillator was set in front of the target as a beam pick-up monitor. To identify the type of particles, a dE detector was mounted in front of the BC501A scintillator.

Figure 2 shows the two-dimensional scatter plot of the TOF and the light output. The horizontal axis is inversed owing to the configuration of our electronic circuit. Higher TOF channels mean higher kinetic energies. As shown in the figure, the charged particles were separated by the difference of the mass and charge. There is a sharp bend in the tendency of light output. The light output is decreasing even though the kinetic energy is increasing. This means that the charged particles are penetrating the scintillator, and depositing only partial energy.

In the TOF measurement for the charged particles, they keep reducing the energy during their flight. we estimated these energy losses by PHITS code, and corrected the energy determined by TOF. The results shows in Fig. 3 for various charged particles.

2) Mono-energy Beam Method: Figure 4 shows a schematic view of experimental arrangement for the mono-energy beam method. Mono-energy proton beams of 100 and 160 MeV were incident on the BC501A liquid organic scintillator which is a same one used in the spallation method. The scintillator was set on beam axis. In order to change the energy of the incident beam, an energy absorber was installed into upstream of the BC501A scintillator. The energy absorber was consisted of various thicknesses of Al plates. Beam pick-up monitor was placed in front of the energy absorber. The flight path length was 50, 150 and 250 cm. Kinetic energy was determined by TOF data at these three positions.

An example of TOF spectra at 50 and 250 cm are shown in Fig. 5. The time difference between two peaks is come from the difference of the flight path. From the time and path length,

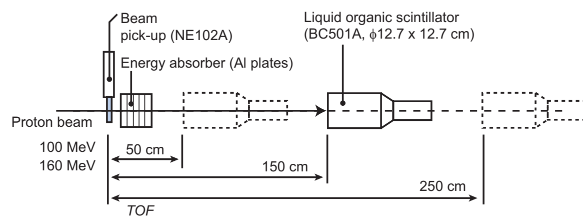

Fig. 4. Experimental arrangement of mono-energy beam method

kinetic energies were derived experimentally.

Figure 6 shows the relationship between the kinetic energy of beam and the thickness of the energy absorber. Experimental results gave a good agreement with those of calculation by PHITS. Broken lines include the energy-correction by the loss at the scintillator case.

III. Result and Discussion

Figure 7 presents the energy dependence of the light output of BC501A liquid organic scintillator for various charged particles together with the formula proposed by Nakao[4] for proton

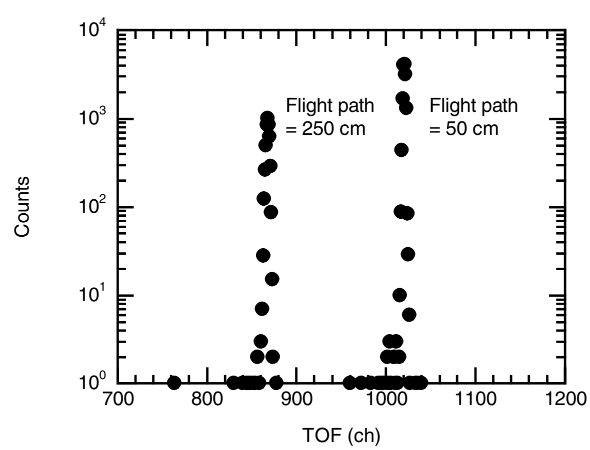

Fig. 5. TOF spectra at flight path 50 cm and 250 cm

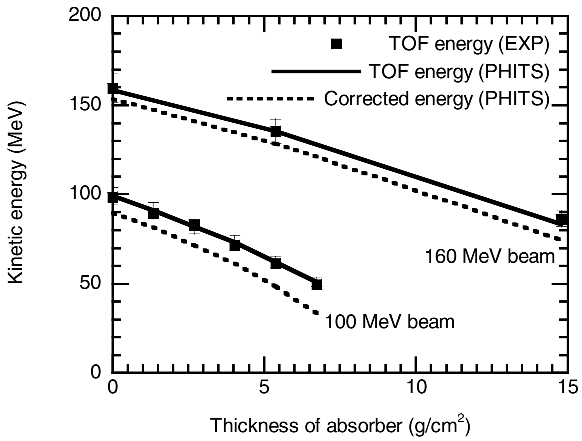

Fig. 6. Relationship between kinetic energy of incident beam and thickness of energy absorber. Marks are experimental data. Lines are calculated results by PHITS[6]. Broken lines were corrected the contribution of the energy loss at the Al case containing the liquid scintillation material

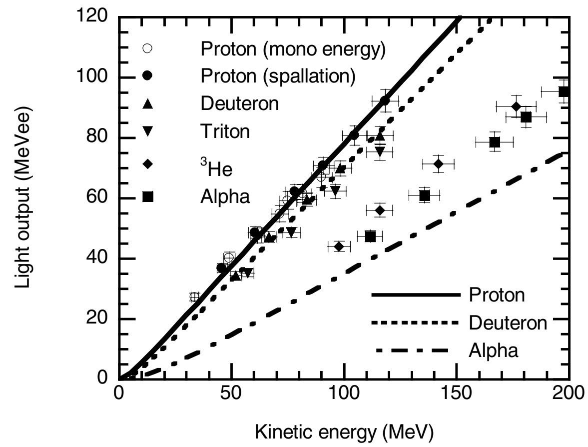

Fig. 7. Light output of BC501A liquid organic scintillator for proton, deuteron, triton, ^{3}He nucleus and alpha particle. Marks indicate experimental results. Open circles are obtained by the mono-energy beam method, and other marks are by the spallation method. Lines indicate the formulas, solid and broken lines are proposed by Nakao[4] for proton and deuteron, chain line is by Cecil[5] for alpha particle

and deuteron, and by Cecil[5] for alpha particle. Light output was converted from the channel to the electron equivalent light (MeVee) by the least square fitting with the obtained data and gamma-ray sources. Error bars were decided by considering both the energy and light resolutions (15%).

In comparison with the proton data taken by the mono-energy beam and the spallation methods, the results show fairly good agreement at the overlap region. This fact indicates that our procedure for the energy determination in spallation method is consistent and appropriate.

The data for proton and deuteron are in good agreement with the formula by Nakao. However, the data for alpha particle give larger values than those of Cecil. The formula proposed by Cecil is not based on experimental data. It was derived from the fitting of the calculation by Gooding and Pugh[7] for plastic scintillator. As described in Ref. 5, the accuracy is insufficient. For triton and ^{3}He nucleus, there are no formulas. Our systematic data are very useful for understanding the scintillation mechanism and modeling its property.

IV. Conclusion

The response functions have been measured for protons, deuterons, tritons, ^{3}He nuclei and alpha particles at HIMAC of NIRS, and light output of the liquid organic scintillator was obtained. The experiment was performed by two methods, i.e. spallation and mono-energy beam ones. The data agreed well at the overlap region. From this result, the experimental method was validated.

The experimental results for light output were compared with the existing formulas[4], [5] for proton, deuteron and alpha particle. For proton and deuteron, our results showed a good agreement. For alpha particle, on the other hand, the results deviated from the formula. Because the formula by Cecil is deduced by the calculation results for the plastic scintillator, we think that it includes some ambiguities for the liquid scintillator as BC501A.

We will construct new formulas from the systematic data obtained in this experiment. Then, the formulas will be employed in SCINFUL-QMD code to improve the accuracy of the calculation.

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References

[1] D. Satoh, S. Kunieda, Y. Iwamoto, N. Shigyo, and K. Ishibashi, "Development of SCINFUL-QMD code to calculate the neutron detection efficiencies for liquid organic Scintillator up to 3 GeV," *J. Nucl. Sci. Technol., supplement 2*, Vol. 1, pp. 657-660, Aug. 2002.

[2] D. Satoh, T. Sato, A. Endo, Y. Yamaguchi, M. Takada, and K. Ishibashi, "Study on response function of organic liquid scintillator for high-energy neutrons," *AIP Conference Proceedings*, Vol. 769, pp. 1680-1683, 2005.

[3] D. Satoh, T. Sato, A. Endo, Y. Yamaguchi, and M. Takada, "Development of dose assessment method for high-energy neutrons using intelligent neutron monitor," *2004 Annual Report of the Research Project with Heavy Ions at NIRS-HIMAC*, pp. 263-264, May 2005.

[4] N. Nakao, T. Nakamura, M. Baba, Y. Uwamino, N. Nakanishi, H. Nakashima, and Shun-ichi Tanaka, "Measurements of response function of organic liquid scintillator for neutron energy range up to 135 MeV," *Nucl. Instrum. Meth.*, Vol. 362, pp. 454-465, 1995.

[5] R. A. Cecil, B. D. Anderson, and R. Madey, "Improved predictions of neutron detection efficiency for hydrocarbon scintillators from 1 MeV to 300 MeV," *Nucl. Instrum. Meth.*, Vol. 161, pp. 439-447, 1979.

[6] H. Iwase, K. Niita, and T. Nakamura, "Development of general-purpose particle and heavy ion transport monte carlo code," *J. Nucl. Sci. Technol.*, Vol. 39, No. 11, pp. 1142-1151, Nov. 2002.

[7] T. J. Gooding and H. G. Pugh, "The response of plastic scintillators to high-energy particles," *Nucl. Instrum. Meth.*, Vol. 160, pp. 189-192, May 1960.