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Measurements of the light output functions of plastic scintillator using ^{9}Be(d, n)^{10}B reaction neutron source

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Abstract The light output functions for protons of ST-401 and BC-408 plastic scintillators were measured using white neutron source produced by the ^{9}Be(d, n) ^{10}B reaction at the HI-13 Tandem Accelerator at China Institute of Atomic Energy (CIAE). The LOFs of plastic scintillators for protons in the energy range of 0.5–16.5 MeV were obtained by the time-of-flight (TOF) technique and an iterative procedure. Two parameters (kB and C) were deduced by fitting the experimental data.

Key words plastic scintillator, light output function, ^{9}Be(d, n) ^{10}B reaction, ST-401, BC-408

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1 Introduction

Plastic scintillators such as ST-401 have been widely used in fast neutron diagnostics because of their fast time response, high detection efficiency and favorable mechanical properties [1–5]. They are very useful in the pulsed fission neutron measurements in the neutron and gamma mixed fields. Since the energy spectra of fission neutrons are not monoenergetic, it is very important to obtain the energy response to neutrons of the detectors before they are used to detect the fission neutrons. The light yields to charged particles are usually calculated by using Birks' formula [6] or the extended version of Birks' formula which was carried out by Chou [7]. Hence, light output functions (LOF) of the plastic scintillator are very significant the energy response of when calculating the plastic scintillation detector before it is used for neutron flux measurements.

Usually the light output as a function of proton energy was measured using monoenergetic neutrons which were produced via nuclear reactions such as the T(d, n) ^{4}He, T(p, n) ^{3}He, and D(d, n) ^{3}He reactions [8, 9]. In some cases, the LOF measurements were carried out using a continuous spectrum of neutron energies produced with a ^{252}Cf fission source [10]. In this work, the LOF was measured using the white neutron source produced by the ^{9}Be(d, n) ^{10}B reaction, which covers a wide energy range. The experiments and an iterative procedure for precisely determining the LOFs of BC-408 (manufactured by Saint-Gobain) and ST-401 (manufactured by Beijing Nuclear Instrument Factory in China) plastic scintillators are described in this paper.

2 Parameterizations

The response of organic scintillators to charged particles can be well described by a relation between dL/dx, the fluorescent energy emitted per unit path length, and dE/dx, the specific energy loss for the charged particle. Birks [6] uses a parameterization that relates the differential light output dL/dx to the energy loss dE/dx, the following expression is obtained:

$$\frac{\mathrm{d}L}{\mathrm{d}x}=S\frac{\mathrm{d}E}{\mathrm{d}x}\left[1+kB\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)\right]^{-1}, \tag{1}$$

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where S is the absolute scintillation efficiency, and B is a constant relating the density of damaged molecules to $\mathrm{d}E/\mathrm{d}x$, kB is treated as a single adjustable parameter.

In order to match the experimental light output for scintillators at lower energies more closely, Chou [7] has proposed a modified form of Eq. (1) with one additional adjustable parameter:

$$\frac{\mathrm{d}L}{\mathrm{d}x}=S\frac{\mathrm{d}E}{\mathrm{d}x}\left[1+kB\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)+C\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)^2\right]^{-1}, \quad (2)$$

where C is again treated as an empirically fitted parameter. This expression approaches Eq. (1) for small values of $\mathrm{d}E/\mathrm{d}x$.

We can write Eq. (2) in the form

$$\frac{\mathrm{d}L}{\mathrm{d}E}=S\left[1+kB\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)+C\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)^2\right]^{-1}. \quad (3)$$

The integral of Eq. (3) with respect to the particle of energy E is

$$L(E)=S\int_0^E\left(1+kB\frac{\mathrm{d}E}{\mathrm{d}x}+C\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)^2\right)^{-1}\mathrm{d}E, \quad (4)$$

where $L(E)$ is the total light output by a charge particle which expends all of its energy E within the scintillaor.

For a fast electron of energy E_e that stops in the scintillator, the total light output can be calculated from

$$L(E_\mathrm{e})=\int_0^E\frac{\mathrm{d}L}{\mathrm{d}E}\mathrm{d}E=SE_\mathrm{e}. \quad (5)$$

Because of the dependence of the light output of the organic scintillator on the type of particle, it is usually impossible to determine the absolute scintillation efficiency for a given scintillator. Therefore, the light output $L(E)$ is expressed in terms of MeV equivalent electron energy (MeVee), which is the light output given by the energy of an electron. The particle energy required to generate 1 MeVee of light by definition is 1 MeV for fast electrons but is several MeV for heavy charged particles because of their reduced light output per unit energy. Usually a detector is calibrated with the energy deposited in it by electrons such as Compton electrons when a photon source is used. Then the total light output $L(E_\mathrm{e})$ may be defined by

$$L(E_\mathrm{e})=E_\mathrm{e}-E_0, \quad (6)$$

where $L(E_\mathrm{e})$ is the total light output for a Compton electron of energy E_e, E_0 is the offset energy [11]. Since the response of a scintillator to electrons in the energy range from 0.04 MeV to 3 MeV is essentially linear [12], we define $L(E_\mathrm{e})$ to be in units such that it is equal to the Compton electron energy E_e.

The relationship between the pulse-height (PH) channel number ch and the Compton electron energy E_e in PH scale using a set of photon sources is obtained by

$$ch=ch_0+GL(E_\mathrm{e}) \quad ch_0\ll ch. \quad (7)$$

When a particle other than an electron deposits energy E into the scintillator, the light output $L(E)$ in relation to the electron light output scale described by Eq. (7) is given by

$$L(E)=GL(E_\mathrm{e})=L(\mathrm{MeVee}), \quad (8)$$

where $L(E)$ is the light output for that particle which is equal to the MeV equivalent electron energy (MeVee), the same light output given by the energy of a Compton electron E_e, G is the calibration constant. Inserting Eq. (5) and Eq. (6) into Eq. (4) we obtain

$$\left[1+kB\frac{\mathrm{d}E}{\mathrm{d}x}+C\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)^2\right]\mathrm{d}L(E)=\mathrm{d}E. \quad (9)$$

From Eq. (8) and Eq. (9), we get

$$\sum_{i=1}^{N}\left[1+kB\frac{\mathrm{d}E}{dx}+C\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)^2\right]\Delta L_i=E, \quad (10)$$

where ΔL_i is the measured value of the response for the particle energy E_i, i.e. the scale of equivalent electron energy (MeVee). The specific energy losses for protons $\mathrm{d}E/\mathrm{d}x$ can be calculated by the Stopping and Range of Ions in Matter (SRIM) procedure.

3 Experiments and data analysis procedure

3.1 Gamma calibration

In our measurements, a plastic scintillator with 5 cm in diameter and 2 cm in length covered with a cylindrical aluminum container was used. It was coupled to the photocathode of a photomultiplier tube via a lucite light guide.

The energy calibration of the PH spectra was established using the ^{22}Na,^{137}Cs, ^{54}Mn and ^{65}Zn photon sources. The position of the Compton edge near to half height of this maximum at the upper part of the Compton distribution was used for energy calibration. The position of the Compton edge can be precisely determined by fitting the PH spectra calculated with the GRESP-code [13] to the experimental one. The constant G can be determined according to Eq. (6) and Eq. (7).

3.2 Neutron experiments

The measurement was performed with the neutron TOF spectrometer at the HI-13 tandem accelerator of CIAE. The neutron TOF spectrometer was described in detail in Ref. [14]. A white neutron beam was produced by bombarding a 3 mm thick Be target with 20 MeV deuterons. The Be target was composed of Be (98.5%), BeO (0.5%), Be_2C (0.022%), Fe (0.065%), Al (0.04%), Si (0.015%), Mg (0.003%), Mn (0.0015%) and others (0.85%). It can provide high intensity neutrons in the energy range of 0.5 MeV and 16.5 MeV.

The detector used in the measurements was positioned at an angle of 0° with respect to the beam direction as well as a distance of 6.29 m from the Be target during the experiment. The neutron PH spectra for different neutron energies were acquired for selecting the appropriate windows in the TOF spectrum measured by TOF technique (Fig. 1). The charge of the single event for the plastic scintillator was measured with a charge ADC (Philips PS7166 CAMAC QDC). The TOF branch (TAC, ADC) was calibrated by a precise pulse generator.

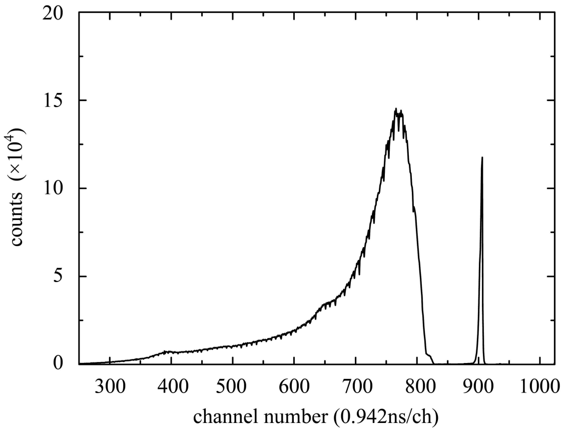

Fig. 1. A typical neutron TOF spectrum of the ^{9}Be(d, n) ^{10}B reaction measured with the BC-408 scintillator at an angle of 0°, for a flight path of 6.29 m and a deuteron energy of 20 MeV. The peak with the center around channel 900 is prompt gamma rays and the part below channel 825 is the net neutron spectrum from the ^{9}Be(d, n) ^{10}B reaction.

3.3 Proton light output function

In this work, we selected 29 PH spectra for neutron energies from 0.5 to 16.5 MeV in ±0.15 or ±0.30 MeV bins. An iterative procedure led to the final LOFs of plastic scintillators to protons [15]. The LOF was determined in the following method: the neutron PH spectra were calculated with the NRESP7-code [16] with the so-called "standard" LOF which was the default one of the NRESP7-code, and then the calculated neutron PH spectra were fitted to the measured ones at edge region to determine the edge precisely. This fit yielded the light output for protons in terms of equivalent electron energies using the gamma calibration mentioned above. The iterative correction resulted in the LOF of each plastic scintillator. Fig. 2 shows the good agreement between the measured and the calculated PH spectra.

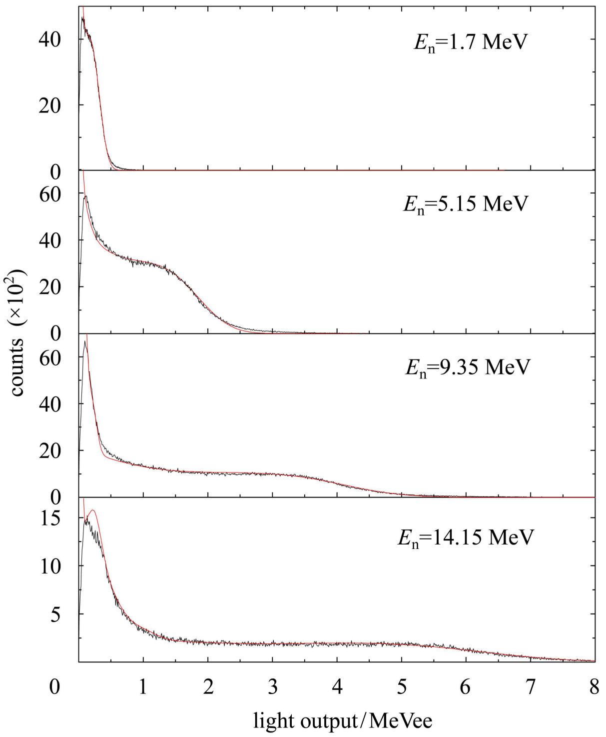

Fig. 2. Typical light output spectra (histogram) measured for 1.7 MeV, 5.15 MeV, 9.35 MeV and 14.15 MeV neutrons compared with the simulation (line) with the NRESP7-code. The neutron energies were determined by TOF.

4 Results and discussion

For the present work, we can get a set of equations with regard to parameters kB and C using Eq. (10) with the experimental data. Then the values of kB and C can be calculated by least-squares fit. The fits to the experimental data within uncertainties of about 5% are exhibited in Fig. 3. The dash and dot curves are calculated from Eq. (4) using the values of kB and C deduced from this work (listed in Table 1). It can be seen from Fig. 3 that Eq. (4) can accurately describe the energy response to neutrons of the plastic scintillator over a wide particle energy range. Our experimental LOF data are 11%–16% lower than the default LOF data of the NRESP7-code in the energy range of 0.5–16.5 MeV.

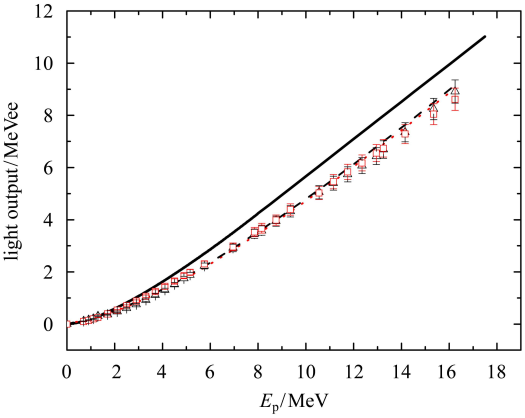

Fig. 3. The LOFs of ST-401 (△ the experimental data points) and BC-408 (□ the experimental data points) scintillators. The dash and dot line are the calculation results using Chou's parameterization for ST-401 and BC-408 scintillator respectively. The solid line is the default light output function of the NRESP7-code.

Table 1. Parameters obtained from least-square fit using Eq. (10) to the experimental data.

scintillator	$kB/$ $10^{-2}(\mathrm{g{\cdot}cm^{-2}{\cdot}MeV^{-1}})$	$C/$ $10^{-5}(\mathrm{g^2{\cdot}cm^{-4}{\cdot}MeV^{-2}})$
ST-401	1.17	1.09
BC-408	1.15	0.84

All organic scintillators contain carbon as well as hydrogen. Because of the decreased scintillation efficiency for high $\mathrm{d}E/\mathrm{d}x$ particles, carbon recoils produced by neutron elastic scattering do not contribute much to the detector output. For neutron energies below 4.81 MeV, only elastic scattering has to be considered. Above this threshold, inelastic scattering occurs and in addition, once the neutron energy exceeds 8 or 9 MeV, two competing reactions ^{12}C(n, α)^{9}Be and ^{12}C(n, n$'$)3α must be considered in the overall response of organic scintillators. The threshold energies for these reactions are 6.19 and 8.81 MeV, but they become significant only above about 10 MeV, for which alpha fractions are visible in the PH spectra. Having alpha sub-spectra for different reaction channels and summing up all to one “alpha spectrum”,

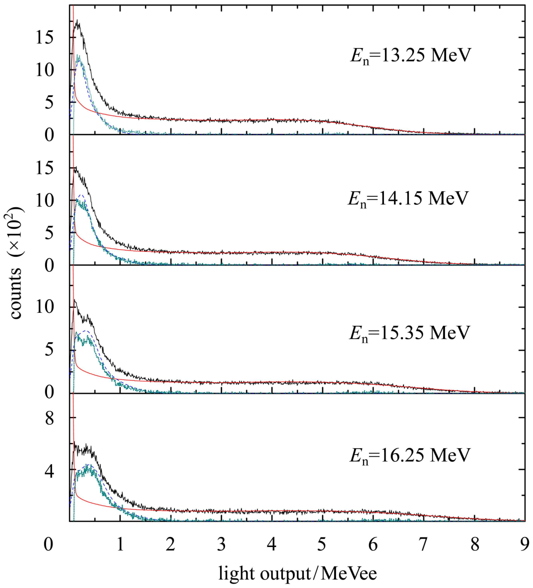

Fig. 4. Typical light output spectra (histogram) measured for 13.25 MeV, 14.15 MeV, 15.35 MeV and 16.25 MeV neutrons. The solid line is proton recoil spectra simulated with the NRESP7-code using the LOF determined in this work. The dot line is alpha spectra subtracted proton recoil spectra from experimental spectra. The dash line is alpha spectra simulated with the NRESP7-code.

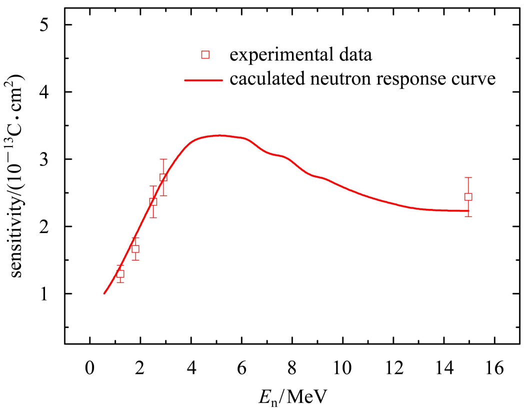

Fig. 5. Comparison of the calculated neutron energy response curve and the experiment data.

the combined effects of multiple scattering and competing reactions can be seen in Fig. 4. It shows that there is good agreement between simulation and experiment light output produced by alpha particles.

In order to test the calculation of the energy response to neutrons for the thin plastic scintillation detector [5] with the LOF determined in the present work, one experiment was carried out for 2.9 and 14.9 MeV neutrons from D(d, n) ^{3}He and T(d, n) ^{4}He reactions at the neutron generator at CIAE. Another experiment was carried out for 1.2, 1.8, 2.5 MeV neutrons from T(p, n) ^{3}He reaction at the 5SDH-2 Accelerator at CIAE. The good agreement between the experimental data and the calculated neutron energy response is shown in Fig. 5. The uncertainty of the experimental data is about 8%.

5 Summary

The LOFs of ST-401 and BC-408 plastic scintillators were measured in the neutron energy range from 0.5 MeV to 16.5 MeV using white neutron source produced by the ^{9}Be(d, n)^{10}B reaction. The LOF of the plastic scintillator was a vital component of studies aimed at the energy response of the plastic scintillation neutron detector. The present work has provided an accurate data set for calculating the energy response to neutrons for ST-401 and BC-408 plastic scintillation detectors.

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