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Light output of EJ228 scintillation neutron detectors

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ABSTRACT

The light output of neutron detectors based on the plastic scintillator EJ228 is studied as a function of neutron energy using a time tagged ^{252}Cf source. Calibration of the light output scale is performed by fitting the experimental distribution of Compton scattering events of photons from a ^{22}Na source with a response function obtained by Gaussian smearing of the predicted line-shape. The light output curve as well as the pulse height resolution for the EJ228 scintillators is very close (within 5%) to those recently reported for NE213 type organic liquid scintillators.

1. Introduction

For several decades scintillation detectors have been useful tools employed in several fields of basic and applied science (Knoll, 1999). In particular, organic scintillators are commonly used as fast neutron detectors, taking advantage of the neutron–proton scattering inside the plastic or liquid material (Klein and Brooks, 2006). Characterization of basic parameters of such detectors as the detection efficiency is performed experimentally and/or by using Monte Carlo simulation codes (Rout et al., 2009). The use of these codes is extremely useful when the detection efficiency has to be determined for an extended range of neutron energies and for different values of energy threshold. To this end, knowledge of the scintillator light output as a function of neutron energy is needed. Consequently, several experiments have been performed in the past, providing empirical light output functions (Kornilov et al., 2009; Madey et al., 1978; Czirr et al., 1964; Kurz, 1964; Verbinski et al., 1968; Smith et al., 1968; Dekempeneer et al., 1987; Batchelor et al., 1961; Naqvi et al., 1994; Filchenkov et al., 1990; Gul et al., 1989).

We employed an array of eight fast plastic scintillators in an experimental set-up devoted to material studies via attenuation of gamma rays and neutrons (Stevanato et al., 2009). In our system, EJ228 plastics (from Eljen Technology, Sweetwater, Texas, USA) are used, for which light output functions are not available. We have thus performed this study by means of a time tagged ^{252}Cf source, as recently described in Kornilov et al. (2009). Results of our work are reported in this paper.

2. Experimental details

The experimental set-up employed in this work consists of a time tagged ^{252}Cf source and a horizontal array of 8 scintillation detectors. By placing an object between the tagged source and the detectors and measuring the attenuation of gamma rays and neutrons, the material can be identified (Viesti et al., 2008). The array of scintillators provides the possibility to reconstruct an elemental image from the vertical scan of the object as well (Stevanato et al., 2009).

All detectors used in this work are 5.1 cm in diameter, 5.1 cm thick right cylinders of EJ228 fast plastic coupled, by means of an EJ560 silicon rubber interface, to PHOTONIS XP2020 photomultipliers. A 10^6 fissions/s ^{252}Cf source is tagged by an additional EJ228 detector placed very close to the emission point, detecting the burst of neutrons and gamma-rays emitted during each fission event. The array of scintillators is placed at a distance of about 100 cm from the ^{252}Cf source. All scintillators were energy calibrated using a ^{22}Na gamma-ray source as detailed in the next section. The low energy threshold for neutron detection was measured to be about 100 keVee (i.e. in keV electron equivalent).

The typical resolution of time-of-flight system is $\delta t < 0.8$ ns [FWHM] when the ^{252}Cf source is used.

3. Experimental results

3.1. Calibration

Energy calibration of a plastic scintillator has been the matter of several studies in the past due to the special characteristics of this

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type of detector (Knoll, 1999; Klein and Brooks, 2006). First it is well known that the yield of scintillation light depends on the ionizing particle (electron, proton,…) the light output for electrons being not linear below 40 keV and beyond 1.6 MeV (Klein and Brooks, 2006). Moreover, the low average atomic number of the plastic material implies that photons emitted by typical radioactive sources interact only by Compton scattering. In this case the nominal energy of the Compton Edge is well known. However, the finite pulse resolution of the scintillation detector implies that the position of the maximum in the Compton events distribution is shifted to lower energies, with the shift depending on detector pulse resolution.

In order to solve this problem, some empirical prescriptions have been developed in the past and simulations by Monte Carlo methods are commonly used to determine the shift value by fitting the experimental distribution. In this work, a simplified method was used. We started by constructing the expected distribution of the Compton events using the Klein–Nishina formula (Klein and Nishina, 1929):

$$\frac{d\sigma}{dT} = \frac{\pi r_e^2}{m_e c^2 \alpha^2}\left(2+\frac{s^2}{\alpha^2(1-s)^2}+\frac{s}{(1-s)}\left(s-\frac{2}{\alpha}\right)\right)$$

where T is the kinetic energy of the scattered electron, r_e the classical electron radius, $\alpha = h\nu/m_e c^2$, $s = T/h\nu$ and $h\nu$ is the initial photon energy. The overall pulse height resolution of the detector was reproduced by a Gaussian smearing of the predicted distribution (Kudomi, 1999; Siciliano et al., 2008). As an example, the effect of Gaussian smearing corresponding to width values of $\sigma = 5$, 10, 15 and 25 keV is compared in Fig. 1 with the theoretical distribution. It appears, as expected, that the maximum in the Compton distribution moves to a lower energy value on decreasing the pulse height resolution.

The energy calibration of scintillators was performed by the following steps: (a) measuring a high statistics pulse height distribution using a ^{22}Na gamma ray source; (b) producing a set of theoretical Compton distributions for the 511 and 1275 keV gamma rays with Gaussian smearing for different values of width and (c) determining, by χ^2 analysis, the width that better reproduces the experimental distribution. The best-fit width value determines directly the energy shift of the nominal Compton Edge, which is then used to calibrate the spectra. Furthermore, the variance of the χ^2 distribution provides information on the sensitivity of this method.

An example of the above procedure is reported in Fig. 2 for the ^{22}Na spectrum measured by one of our EJ228 scintillators. The result of the spectrum analysis is also shown. In this case it is found that the best fit values for the width of the Gaussian smearing are $\sigma = 36$ keV ($\sigma = 64$ keV) for the 511 keV (1275 keV) photon, respectively. These resolution values imply shifts of 52 and 89 keV for the two maxima in the spectrum with respect to the nominal Compton Edge energies. The sensitivity of this method is typically 10% of the σ value.

It is worth mentioning that this method was first tested using high resolution HPGe spectra, where energy calibration was obtained either by using directly the full-energy peaks or by the method previously presented. It is found that, in this case, the two calibrations are very close within the experimental uncertainties. In the same way it was also verified that our results are very close to those of Dietze and Klein (1982), whose method makes use of a linear fitting of the falling region of the spectrum at energies higher than the Compton maximum to get an estimate of detector resolution.

3.2. Light output determination

The method recently proposed by Kornilov et al. (2009) has been used to determine the light output of the EJ228 scintillator

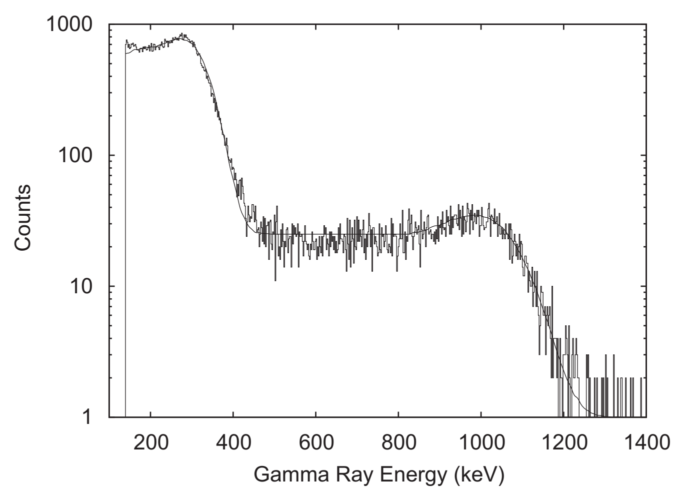

Fig. 2. Experimental energy spectrum of a EJ228 scintillator after calibration using the predicted smoothed distribution. The best-fit curve is also reported (line).

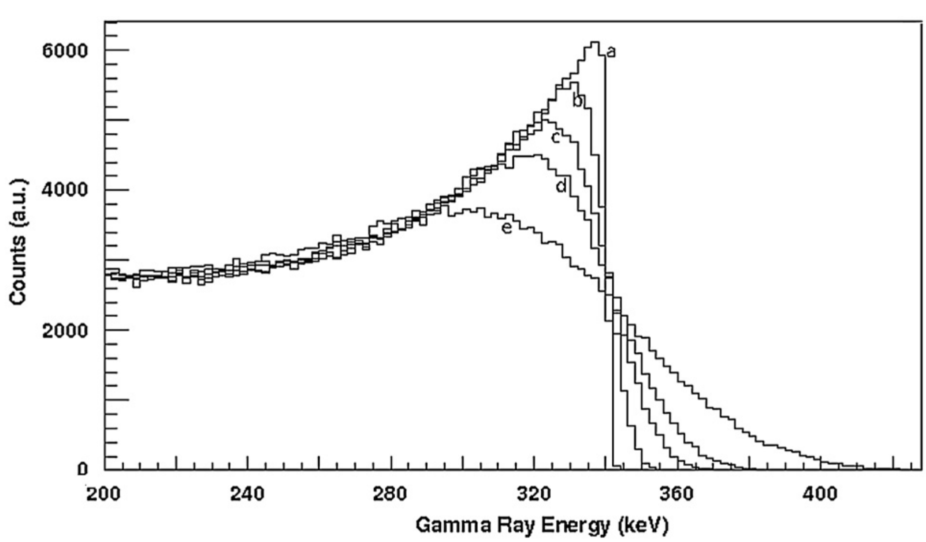

Fig. 1. Computed distributions of Compton scattered events without (a) and with different Gaussian smearing corresponding to 5 (b), 10 (c), 15 (d) and 25 (e) keV pulse resolution.

detectors. By employing the neutron fission spectrum from a ^{252}Cf source, the pulse height distributions corresponding to different neutron energies were obtained by setting narrow windows on the measured time-of-flight.

The pulse height distribution corresponding to quasi-mono-energetic neutrons selected by time-of-flight presents a problem similar to that of the Compton scattered photons. The proton recoil distribution generated by the interaction of neutrons inside the scintillator extends, indeed, from the energy corresponding to the complete transfer of the neutron kinetic energy to very low energies for small angle scattering and is affected by the finite energy resolution of the detector and by multiple scattering events.

An example of the pulse height distribution measured for $E=2.5$ MeV neutrons is presented in Fig. 3 after applying a smoothing function. To determine the pulse height corresponding to 2.5 MeV protons in an energy scale calibrated using photons (i.e. in MeV electron equivalent, MeVee), the first derivative method is used.

As discussed in Kornilov et al. (2009), the first minimum in the derivative function is associated with multiple scattering events, whereas the second one determines the maximum of the proton recoil distribution that corresponds to the neutron energy in the time-of-flight window. We have fitted the second minimum of the derivative function with a Gaussian distribution to determine the position of the minimum as well as the value of sigma, taken as a measure of pulse height resolution of the detector. By analyzing in this way the pulse height distribution for different neutron energies, the light output–neutron energy correlation has been derived up to 8 MeV neutrons. Results in terms of light output as a function of proton recoil energy are presented in Fig. 4 for one of our detectors. The error bars reported in Fig. 4 have a two-fold origin—on one end the error associated with the Gaussian fit of the second minimum in the derivative providing the light output value and, on the other side, the uncertainty in determination of neutron energy from the time-of-flight. The latter quantity is evaluated by taking into account the uncertainty in flight path (determined by the scintillator thickness) as well as the time of flight resolution of the system, which for the detector reported in Fig. 4, is $\delta t=650$ ps [FWHM]. A further source of error is the width of the time-of-flight window used to construct the pulse height distribution.

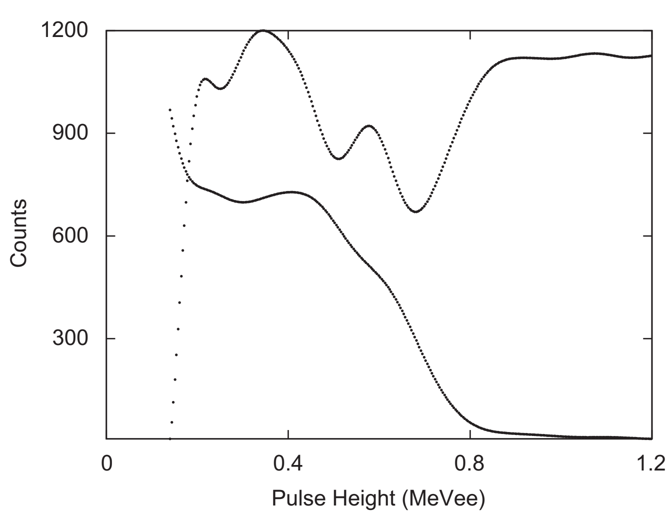

Fig. 3. Calibrated pulse height distribution for 2.5 MeV neutrons (lower curve) after smoothing using the function available in the ROOT package (http://root.cern.ch/root/html/TH1.html). The derivative is also shown (upper curve). For details see the text.

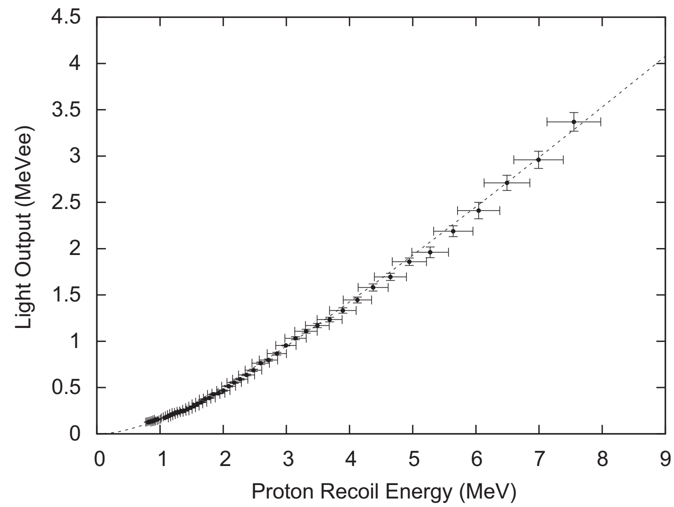

Fig. 4. Light output for one of our EJ228 scintillators compared with the data from Kornilov et al. (2009) relative to LS301 liquid scintillators (dashed line).

Table 1
Fit values for some of our EJ228 scintillators compared with results from Kornilov et al. (2009) for NE213-type detectors.

Detector	L_0	L_1 (MeV)
EJ228 #1	0.582 ± 0.005	2.70 ± 0.06
EJ228 #2	0.602 ± 0.11	3.09 ± 0.13
EJ228 #3	0.601 ± 0.007	2.96 ± 0.09
EJ228 #4	0.606 ± 0.008	2.97 ± 0.11
EJ228 #5	0.597 ± 0.008	2.84 ± 0.11
LS301 (Kornilov)	0.579 ± 0.008	$2.510 \pm .11$

The experimental light output data can be described by the equation

$$L(E_e) = L_0 \frac{E_e^2}{E_e + L_1}$$

where E_e is the electron equivalent energy in MeV; L_0 and L_1 are fitting parameters. Within the reported uncertainties, our light output determination for the EJ228 detectors fits well with the curve reported by Kornilov et al. (2009) for some liquid scintillators (LS301, BC501A and NE213). This is shown in Fig. 4 as well as in Table 1, where numerical results in terms of the fitting parameters are reported for a selection of five EJ228 detectors. The maximum deviation between our data and those in Kornilov et al. (2009) is indeed about 5% at low energies, below 2 MeV, and about 2% in the range 2–8 MeV.

Our data are also well described by the empirical formula proposed by Katz et al. (1972):

$$L(E_p) = c(0.83E_p - 2.82[1 - \exp(-0.25E_p^{0.93})])$$

where c is a fitting parameter. The value $c=0.835 \pm 0.004$ is obtained for the EJ228 scintillator in Fig. 4. This c value results to be equal for EJ228 detectors within the experimental errors.

It is also worth mentioning that our data are in fair agreement (within 4%) with the light output data reported by Naqvi et al. (1994) as measured for a NE102A plastic scintillator using a tagged ^{241}Am–Be neutron source.

Finally, the pulse height resolution σ/L, determined as the ratio of the width to the center values obtained by the Gaussian fit of the second minimum in the derivative curve, is reported in Fig. 5 as a function of light output L after correction for the time-of-flight windows. The calibration points from ^{22}Na gamma-rays are also

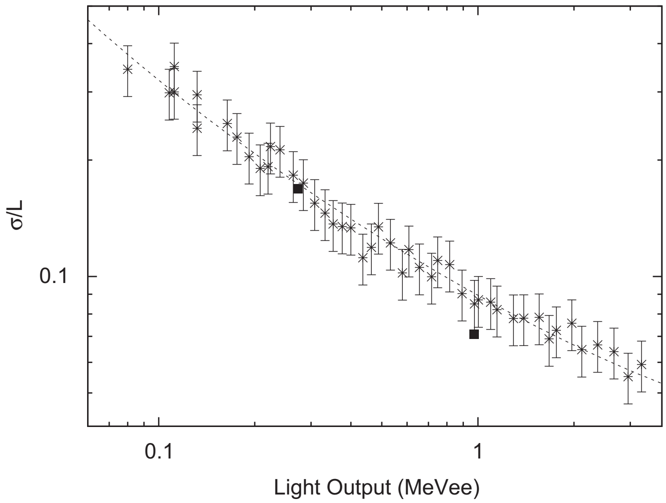

Fig. 5. Measured pulse height resolution vs. light output for a EJ228 detector (stars) after correction for the time-of-flight window. Full squares represent ^{22}Na photons. An interpolation line is also reported to guide the eye. For details see the text.

reported. Also in this case our data are very close to those reported in Kornilov et al. (2009).

4. Summary and conclusions

The light output of the plastic scintillator EJ228 has been measured using a time tagged neutron source (a ^{252}Cf source in our case) as reported in other works (Kornilov et al., 2009; Naqvi et al., 1994; Filchenkov et al., 1990; Gul et al., 1989). A simple method used to derive the correct energy of the maximum in Compton distribution of scattered photons is presented. This method makes use of predictions of the Kleine–Nishina formula (Klein and Nishina, 1929) with a Gaussian smearing function that accounts for the finite pulse resolution of the detector.

The EJ228 light output function derived in this work is very close (within 5% below 2 MeV and about 2% in the range 2–8 MeV) to that recently reported for liquid scintillators (Kornilov et al., 2009), the latter curve being compatible with light output data obtained in other works on liquid scintillators (Madey et al., 1978; Czirr et al., 1964; Kurz, 1964).

It is worth mentioning, however, that in several works it was shown that the light output of a given type of organic scintillator might depend on specific characteristic of the detector (Verbinski et al., 1968; Smith et al., 1968; Dekempeneer et al., 1987; Batchelor et al., 1961). Consequently, direct experimental characterization of all detectors employed in an experiment might be needed. In this respect, the use of a time tagged ^{252}Cf source allows the accomplishment of this goal up to energies of about 8 MeV with a simple experimental set-up. In our case, it is also verified that the light output curve presented in this work applies well to all our EJ228 scintillation detectors.

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