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ABSTRACT

When using an organic liquid scintillator such as NE213 for neutron spectrometry, the light output as a function of proton energy is needed in order to unfold the neutron spectrum from the scintillator's pulse height distribution.

We have measured this function for several detectors over the range 1.5 – 16 MeV approximately, using monoenergetic neutrons from the Harwell 5 MV Van de Graaff accelerator.

Results were obtained for a wide variety of sizes and shapes of scintillator cell, and were found to be essentially in agreement within errors. The results were also compared with those of several other workers (amongst whom there is considerable disagreement). Below 10 MeV, there is excellent agreement with one worker and moderate or poor agreement with others; above 10 MeV, agreement is moderate in all cases.

We conclude that workers wishing to unfold neutron spectra from NE213 pulse height distributions would be advised to make measurements with their own particular detector configuration, rather than use published functions.

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INTRODUCTION

Neutrons incident on an organic scintillator produce light indirectly, mainly via the knock-on protons from elastic collisions with hydrogen. In order to interpret a measured pulse height spectrum, therefore, the relationship between proton energy and light output must be known. For the widely used liquid scintillator NE213 [1], several workers have reported such determinations, but there are significant differences between their values.

One aim of the present work was to measure (in view of the uncertainties attached to taking values from the literature) the proton light output function for the types of detector used in two neutron diagnostic systems [2,3] at the Joint European Torus fusion experiment. The other was to investigate whether the discrepancies in the literature could be explained by some hitherto unrecognised dependence of the light output on the shape, size or age of the scintillator. To this end, a wide variety of different scintillator cells was included in the measurement programme.

DETECTORS

Table 1 sets out the dimensions of the scintillator cells in the detectors used. Detector G has a cell with a low mass encapsulation, consisting of a simple glass envelope with a nitrogen bubble at one end to take up thermal expansion of the scintillator. The other cells are all bubble-free, and have double-skinned aluminium side walls to accommodate a coiled thermal expansion tube.

These cells cover a factor of 50 in volume, and a factor of 5 in the ratio of length to diameter.

Table 1 Details of the scintillator cells used in the present work. The neutron energy range covered for each detector is also given.

Detector Identifier	Cell Diameter / mm	Cell Length / mm	Year of Purchase	Energy Range / MeV
A	50	20	1990	1.41 - 3.95
B	50	10	1987	1.11 - 17.3
C	50	10	1984	1.61 - 3.23
D	50	10	1984	1.51 - 3.22
E	25	10	1990	1.49 - 17.3
F	10	10	1987	1.49 - 16.2
G	10	10	1990	3.02 - 15.7

ELECTRONICS

Each photomultiplier was connected to a Pulse Shape Discrimination (PSD) module [4]. These modules integrate the photomultiplier pulse, to give an analogue signal proportional to the area under the pulse, and can be set so that only pulses identified by their time profile as neutrons are processed as far as the analogue output. Finally, the analogue output from the PSD modules was passed to a multi-input Multichannel Analyser (MCA).

The PSD modules have the useful property that, when they are idle, internal stabilisation circuitry generates an artificial output pulse corresponding to a notional input event of zero amplitude.

LIGHT OUTPUT UNITS (MEVEE)

It is convenient to express light output in terms of the scintillator's response to electrons, as this can be taken to be linear (at least above about 100 keV [5]). That is, if $L(E)$ is the light produced by an electron of energy E stopping in the scintillator, then

$$L(E)=\alpha(E-E_0) \tag{1}$$

where α is a constant, and E_0 a small energy offset parameter. In the present work, a signal that appears in the same MCA channel as that from an electron of energy E MeV is said to be of amplitude E 'MeV electron equivalent' (MeVee).

Some authors [e.g. ref. 6] adopt a different convention, in which the relevant energy is the 'effective electron energy' $E-E_0$ rather than the actual energy E. Such differences are ignored in the present paper, on the assumption that E_0 is sufficiently small compared to typical light output values (see the results below and Ref. 7).

CALIBRATION

To establish the MeVee calibration for a given detector, the MCA channel numbers corresponding to two different known electron energies must be found. This was done by observing the 511 and 1274 keV gamma rays from a ^{22}Na source.

In the absence of resolution effects, this spectrum would exhibit two sharp Compton edges corresponding to electron energies of 341 and 1061 keV, but in practice these edges are smeared out. The position of the half-height of the smeared edge is often assumed to correspond to the true Compton edge position, but in fact the two can differ by several percent. Dietze and Klein [6] have studied this problem in detail. They calculated ideal (resolution-free) spectra by Monte Carlo techniques, and systematically broadened them with known resolutions. They then deduced the relationship between the true position L_c of the Compton edge, and the positions of observable spectral features, namely the peak position L_{max} and the half-height position $L_{1/2}$ (see Fig.1). A different relationship exists for each different combination of detector size and gamma energy.

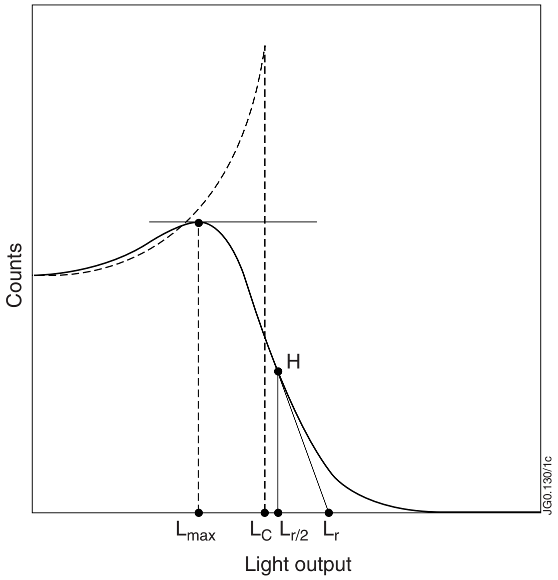

Fig.1: The upper part of a typical broadened Compton spectrum (solid line), compared with the unbroadened ideal spectrum. (Schematic.)

L_{max}: *position of peak in observed spectrum.*
L_c: *true position of Compton edge.*
$L_{1/2}$: *position of half-height of observed edge.*
L_T: *intercept of horizontal axis and tangent at H to observed spectrum, where H is the point half way down the Compton edge.*

We used Dietze and Klein's results in the calibration of detectors A – E. For the smallest scintillators (F and G), however, the technique could not be used directly with the higher Compton edge, because the spectra from those detectors do not show any peak there, so no L_{max} can be identified. A new set of calculations was therefore carried out, following essentially the same method but using the parameter L_T (defined in Fig.1) in place of L_{max}. The Monte Carlo program McBEND [8] was used to calculate the electron energy spectra, and a check was made that McBEND successfully reproduced the results of Dietze and Klein for a selected case.

For the set of detectors used, it was found that the half height was on average about 3.7% above the derived Compton edge position at 341 keV, and about 2.1% above at 1061 keV.

In the present experiment, it was easy to determine the offset parameter E_0 of Eqn. 1, because the artificial pulses from the PSD unit correspond to a zero signal from the scintillator and hence an electron energy equal to E_0. The weighted average of the E_0 values found for detectors A – F is 15 keV. (For detector G, it was necessary to assume an E_0 value in order to establish the MCA calibration, because the 341 keV edge was not visible at any of the gain settings used.)

MEASUREMENTS AND ANALYSIS

The detectors were arranged in front of the target assembly of the Harwell 5 MV Van de Graaff accelerator [9], and monoenergetic neutrons were generated by means of the T(p, n), D(d, n), ^{9}Be(α, n_0), ^{9}Be(α, n_1) and T(d, n) reactions. The neutrons were incident on the end face of detectors A – F, and the side face of G.

The ^{9}Be(α, n)^{12}C reaction [10] proved very useful in bridging part of the energy gap between the more traditional neutron-generating reactions, even though it produces neutrons at two distinct energies.

Ideal pulse height spectra from monoenergetic neutrons would show a sharp upper edge corresponding to the highest kinematically allowed proton energy (equal to the incident neutron energy). In analysing the measured spectra, the half-height of the observed (resolution broadened) edge was assumed to correspond to the true edge position. This is justified on the grounds that unbroadened n-p recoil spectra are approximately rectangular, so that smearing will shift the half height by a much smaller amount than is the case for Compton spectra.

The mean energy of the neutrons incident on each detector was calculated from the kinematics of the nuclear reaction, after correcting the beam energy to allow for slowing down in the target (using published stopping powers [11, 12]).

Spectra obtained with blank copper targets showed that the background from copper target backings was not significant near the proton edge.

RESULTS AND DISCUSSION

Results from all detectors over the complete energy range are shown in Fig.2, and those for the energy interval 0 - 4 MeV are shown in Fig.3. Agreement between the detectors is generally excellent. There is a suggestion of a slight systematic difference in the results for detector A in the energy range 1 - 3.5 MeV approximately (Fig.3). The only obviously unique feature of this detector is its thickness, which at 20 mm is twice that of any of the others.

Results from other workers (Verbinski et al. [13], Smith et al. [14], Dekempeneer et al. [15], and Batchelor et al. [16]) are also shown in Figs 2 and 3. The curves shown are trend curves (polynomial, order 5) generated by the Microsoft Excel spreadsheet program, to data points reported by the authors named, or to points derived from formulae given by them. The data of Verbinski et al. were converted to MeVee by multiplying by 1.2307. There are many other response functions in the literature also.

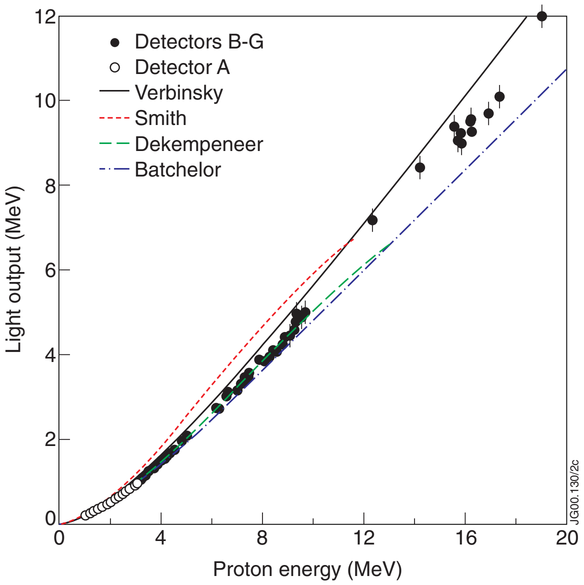

Fig.2: Measured Light Output Function for protons, 1 - 20 MeV. Present data compared with those of Verbinski et al. *[13], Smith* et al. *[14], Dekempeneer* et al. *[15], and Batchelor et al. [16].*

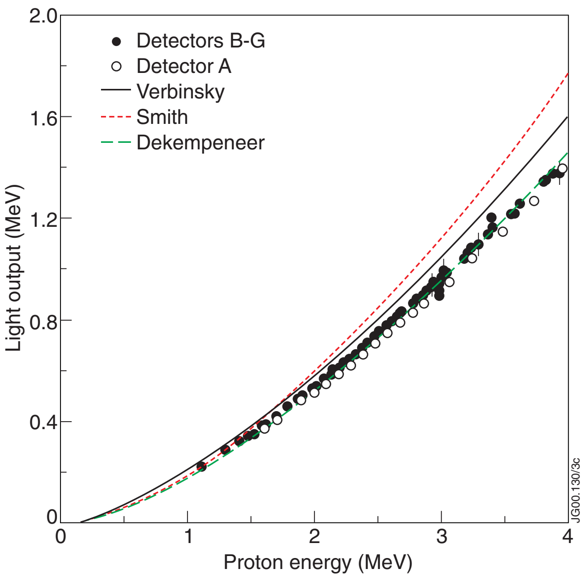

Fig.3: Measured Light Output Function for protons, 1 - 4 MeV. Present data compared with those of Verbinski et al. *[13], Smith* et al. *[14], and Dekempeneer* et al. *[15].*

Up to about 10 MeV (and particularly to 4 MeV), agreement between the present data and the curve of Dekempeneer et al. is excellent, while agreement with the other curves is moderate or poor. Above 10 MeV, the present data lie significantly above the apparent extrapolated trend of Dekempeneer's results, and instead appear to favour Smith or Verbinski.

CONCLUSIONS

The present data give no indication of any dependence of light output on the diameter of the scintillator, or the age or cell type (simple envelope or bubble-free). There is a possible slight dependence on scintillator thickness. The data can therefore offer no explanation for the wide variation [17] of light output functions reported in the literature. Furthermore, they indicate that agreement between two determinations over one energy range may not persist into another energy range. While these problems remain unresolved, it is prudent to measure the light output function from new detectors rather than accept published values.

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