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Section A

Plastic scintillators in magnetic fields

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The dependence of the light yield and the transmission on magnetic fields has been measured with different methods up to 0.45 T for the plastic scintillators NE-102A, SCSN-38 and Polivar. The scintillators were excited by 25 MeV protons, 5.9 keV X-rays and UV light. When excited with ionizing radiation an increase of light yield is observed. For SCSN-38 of 2.6 mm thickness it amounts to 0.3%, 0.9%, 1.1%, and 3.3% at 1, 10, 100 and 450 mT, respectively. NE-102A behaves similar, whereas an acrylic scintillator shows a stronger field dependence. The effect is independent of the direction of the field but increases for the acrylic scintillator with its thickness. No change in the decay time of the scintillator has been observed. The response of the scintillators did not change when excited by UV light in a magnetic field.

1. Introduction

It is known that the light emission of plastic scintillators depends on the magnetic field [1]. In previous work [2–4], a quick rise of the relative light yield at the percent level has been seen within the first 10 mT followed by a constant gain up to about 0.1 T. The magnitude of this light yield increase is material dependent. The effect is an intrinsic property of the scintillator and cannot be explained by electrons which leave the surface of the scintillator, curl in the magnetic field and reenter, or by instrumental effects like photomultiplier gain. The effect is not fully understood up to now, but two reasons or an overlap of them might be responsible for it: The magnetic field separates the tracks of nearby electrons of slightly different energies and consequently reduces a saturation effect [5] in excitation of the molecules or the magnetic field influences the delayed fluorescence [1]. The calorimeter of the ZEUS detector at HERA [6], composed of depleted uranium and plastic scintillator (SCI) plates, read out via wavelength shifters (WLS), will work in magnetic fields up to 0.9 T. Knowledge of the absolute energy scale to about 1% is being aimed at.

The calibration of the calorimeter modules has been done using the radioactivity from the uranium plates, cosmic ray muons and particle beams without magnetic field. Thus the effect of magnetic field on the light yield of the scintillator has to be known. We have investigated this effect for the ZEUS SCI SCSN-38 [7] and also for other plastic SCI as well as for the ZEUS WLS Y-7 dissolved in PMMA [7].

2. Experimental methods

The scintillators studied were excited with

a) a xenon flash lamp which enabled us to excite separately the first or second fluor of SCSN-38 (b-PBD at $\lambda \cong 300$ nm or BDB at $\lambda \cong 360$ nm).

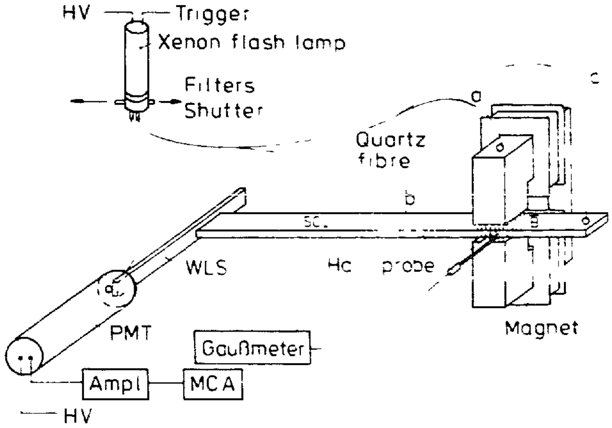

Fig. 1. Schematic view of the measurement device for UV light excitation of the scintillators in a magnetic field.

b) a 25 MeV proton beam from the Hamburg isochronous cyclotron,
c) a 5.9/6.5 keV X-ray source (^{55}Fe).

The layout used for method a) is shown in fig. 1 [8]. The UV light is guided via a quartz fibre (a) to the SCI, which is placed in between the 5 cm × 5 cm pole shoes of an electromagnet whose field is measured with a Hall probe. The UV light can be injected into the SCI either parallel or vertical to the magnetic field direction. For transmission measurements the SCI can also be excited outside of the magnet (fibre c). The light then has to travel through the field region and is recorded via a wavelength shifter by a photomultiplier (PMT) outside the magnetic field. To ensure that there is no direct influence of the field on the xenon lamp and the PMT and to control the stability of the system, the UV light can also be transported directly by a fibre to the PMT. The spectra were recorded by a multichannel analyzer (MCA). Gaussian fits allowed a determination of the mean pulse heights to a statistical accuracy of 0.1%. The reproducibility of the measurements was better than 0.2%.

Method b) [8] used the 25 MeV proton beam of the Hamburg isochronous cyclotron focused to about 1 mm diameter (fig. 2). To reduce pileup effects the beam current was reduced to some fA corresponding to a rate of about 6 kHz protons. The beam left the vacuum pipe through a 20 μm Kapton foil. For the thinner SCI samples (2.6 mm) the protons traversed the SCI and were caught in a Faraday cup while they were stopped in the thicker SCI (9.7 mm). To study the effect of δ electrons reentering into the surface of the SCI by curling in the magnetic field, the SCI in some cases were placed in between thin lead sheets. The deflection of the protons by the magnetic field, which was normal to the proton direction, was small (≈ 1 mm). Its influence on the light yield due to a changed readout distance in the SCI was corrected by reversing the field. The setup was monitored by UV light pulses from a xenon lamp which were fed into the SCI. The influence of the field on the PMT was below 0.2%. Again the spectra were recorded by a MCA and the mean pulse height was determined to an accuracy of 0.1% with a total error on the relative change in light yield of 0.3%.

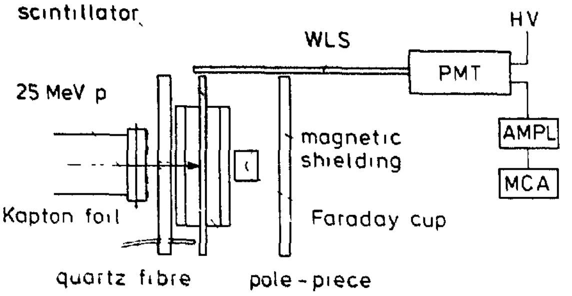

Fig 2 Setup to measure the light yield of SCI as a function of the magnetic field using 25 MeV protons

The layout of method c) [9], which used a 5.9/6.5 keV X-ray source (^{55}Fe) of 107 MBq, is shown in fig. 3. Single and coincidence rates of two photomultipliers looking at the same SCI were used to determine the light yield. The small SCI sample (4 × 2 × 0.5 cm^3) was glued to two long (70 cm) light guides which were read out by two RCA 8854 Quantacon photomultipliers with good separation of single photoelectrons from noise. From the single counting rates N_l and N_r and the coincidence rate N_lr, corrected for accidentals, losses and background, the photon interaction rate N_x, the detection efficiencies η_l and η_r, and the mean number of photoelectrons $\bar{N}_\mathrm{pe}$ are determined

$$N_\mathrm{x} = \frac{N_\mathrm{l} N_\mathrm{r}}{N_\mathrm{lr}}, \tag{1}$$

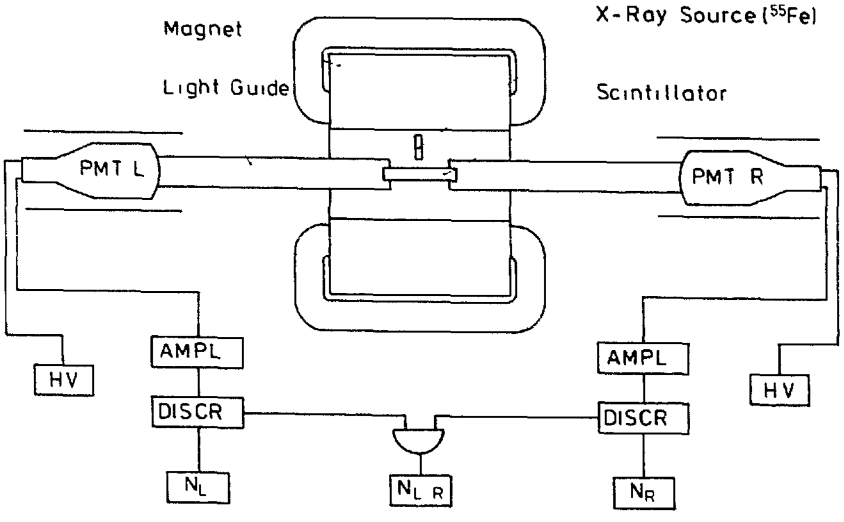

Fig 3 Setup to measure the light yield of plastic scintillators as a function of the magnetic field using a ^{55}Fe source.

$$\eta_l = \frac{N_{lr}}{N_r}, \tag{2}$$

$$\eta_r = \frac{N_{lr}}{N_l}, \tag{3}$$

$$\bar{N}_{pe} = -0.5[\ln(1 - \eta_l) + \ln(1 - \eta_r)]. \tag{4}$$

The relative change in light yield due to the magnetic field B is given by:

$$\frac{\Delta L}{L} = \frac{\bar{N}_{pe}(B) - \bar{N}_{pe}(B=0)}{\bar{N}_{pe}(B=0)}. \tag{5}$$

Grey filters have been put between light guides and photomultipliers so that typical values for η were 2% and $\bar{N}_{pe} \cong -\ln(1 - \eta_i)$. Typical statistical errors of this method were 0.1% with a reproducibility of about 0.2% after reconstruction of the entire apparatus.

The 5.9/6.5 keV X-rays from the ^{55}Fe source produce (quasi) monoenergetic electrons in the SCI via photoeffect. Their range of 1 μm is small compared to the attenuation length of the X-rays (900 μm) and the dimensions of the SCI. Thus edge effects from electrons which leave the SCI surface and reenter by curling into the magnetic field can again be neglected. A direct influence of the magnetic field on the photomultiplier was prevented by a proper shielding between light and magnetic field. The light transmission in the SCI is also unaffected by the magnetic field. The WLS Y-7 in PMMA also showed no effects.

3. Results

3 1 UV excitation

For the scintillators SCSN-38 (fig. 4), NE-102A [10] and a PMMA based Polivar [11] the light yield is independent of the magnetic field, within the measurement accuracy of 0.2%, when illuminated with UV light exciting the first ($\lambda \cong 300$ nm) or the second fluor ($\lambda \cong 360$ nm). It also does not depend on the angle

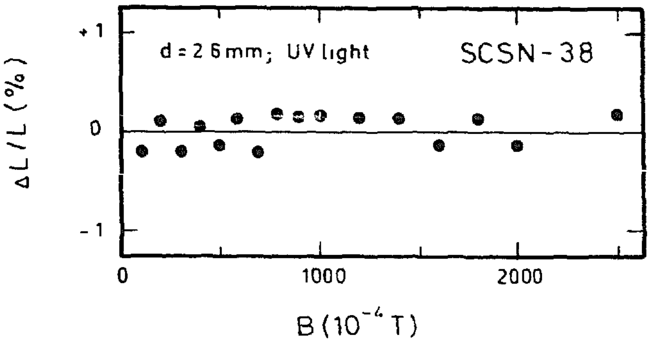

Fig 4. Relative change in light yield of SCSN-38 versus magnetic field. Here the first fluor b-PBD was excited by UV light of about 300 nm and the light was vertical to the magnetic field Within the errors no change of the light yield is to be seen.

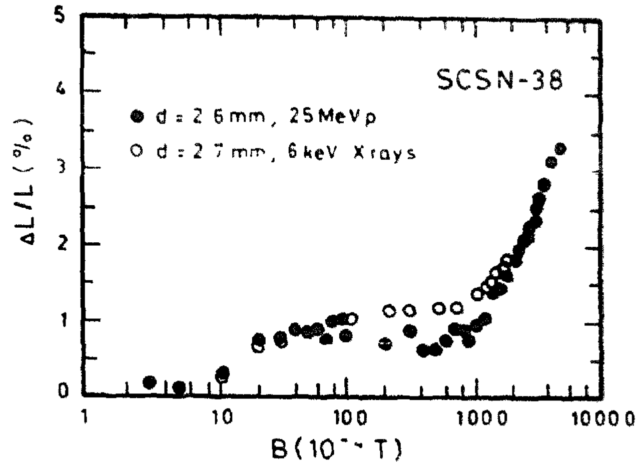

Fig. 5. Relative change in light yield of SCSN-38 (thickness 2.6 or 2 7 mm) versus magnetic field when excited by 25 MeV protons and 6 keV X-rays Within the errors the results are compatible

3.2. Proton and X-ray excitation

For protons and X-rays the same dependence of the light yield on magnetic field has been found For SCSN-38 (fig 5, table 1) it rises to 1% at 2 mT, is constant for fields of 2-100 mT and then increases linearly up to 3 3% at 450 mT. The results did not change when, in the case of the proton excitation, the SCI piece was clad with lead or SCI material. For 0 05 T < B < 0 45 T the experimental values can be well fitted by

$$\Delta L/L = (6T^{-1}B + 0.6)\%. \tag{6}$$

Other measurements [12] indicate that the linear behaviour is valid for fields up to 1 T. This further increase of the light yield gain in strong magnetic fields is not consistent with a pure saturation model [4] because, due to the separation of Compton-electron paths, the greatest effect would be at low fields while at high fields a large increase in field strength would only affect a low increase in light yield. The behaviour of the NE-102A SCI (fig. 6) is quite similar to that of SCSN-38

The results for the PMMA based Polivar SCI are more complicated. From the measurements with protons, the relative light increase is higher for thicker SCI samples (fig. 7) Several repetitions of these measurements, with different SCI types and thicknesses, always showed this unexpected behaviour. This might also be the reason for the different result of the ^{60}Co measurements [2] (fig. 8): The shapes of the SCI samples used for the proton and X-ray experiments were

Table 1
Relative light yield increase of scintillators SCSN-38 in magnetic field. The sample thicknesses were 2.6 mm (proton measurements) and 2.7 mm (X-ray measurements). The errors are 0.3% (protons) and 0.2% (X-rays)

Magnetic field B [mT]	25 MeV protons ΔL/L [%]	6 keV X-rays ΔL/L [%]
0.3	0.16	
0.5	0.08	
1	0.32	0.28
2	0.74	0.59
3	0.80	0.67
4	0.90	
5	0.86	0.78
6	0.90	
7	0.75	
8	1.02	
9	1.02	
10	0.81	0.94
20	0.71	0.97
30	0.88	1.05
40	0.63	
50	0.63	1.07
60	0.75	
70	0.90	1.11
80	0.90	
90	0.75	1.17
100	0.93	
110		1.36
120	1.03	
130		1.31
140	1.40	
150		1.55
160	1.44	
170		1.61
180	1.61	
190		1.80
200	1.81	
220	1.95	
240	2.05	
260	2.16	
280	2.25	
300	2.35	
310	2.51	
320	2.66	
360	2.83	
400	3.12	
450	3.33	

similar and the results compatible with fig. 7 while the sample for the ^{60}Co measurements had quite different dimensions (10 × 5 × 1 cm^3).

The higher light gain for the thicker Polivar SCI (fig. 7), measured with the proton beam, might be due to the fact that the range of the 25 MeV protons just exceeds the thickness of the 7.5 mm sample and the specific energy loss, on the average, is smaller in the thinner sample. If the magnetic field reduces the Birks'

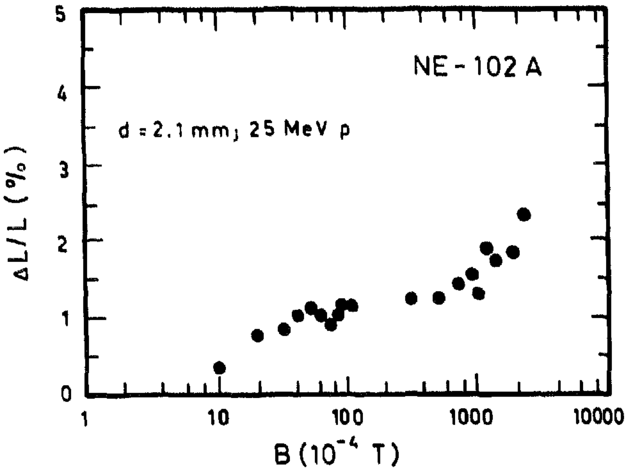

Fig. 6. Relative change of light yield of the polytoluene based SCI NE-102A in a magnetic field when excited by protons. The curve is very similar to that of the polystyrene based SCI SCSN-38 (fig. 5).

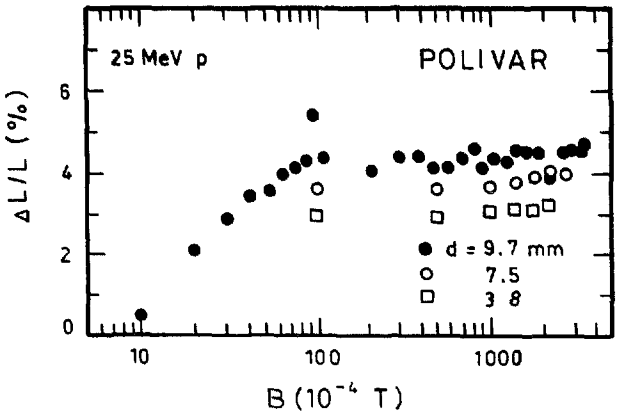

Fig. 7. Relative change of light yield of the PMMA based Polivar SCI in a magnetic field for different sample thicknesses when excited by protons. The gain in light yield increases with the sample thickness.

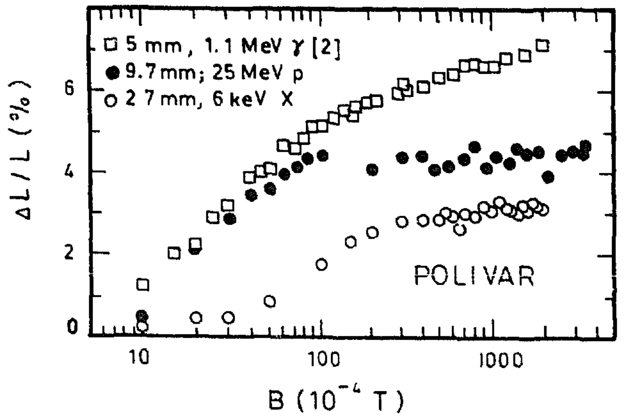

Fig. 8. Relative change of light yield of a PMMA based Polivar SCI in a magnetic field excited by 1.1 MeV γ [2], 25 MeV protons and 6 keV X-rays. The results of the X-ray and proton excitation are compatible due to the thickness dependence of the relative light yield (fig. 8). The scintillator of ref. [2] had quite other dimensions.

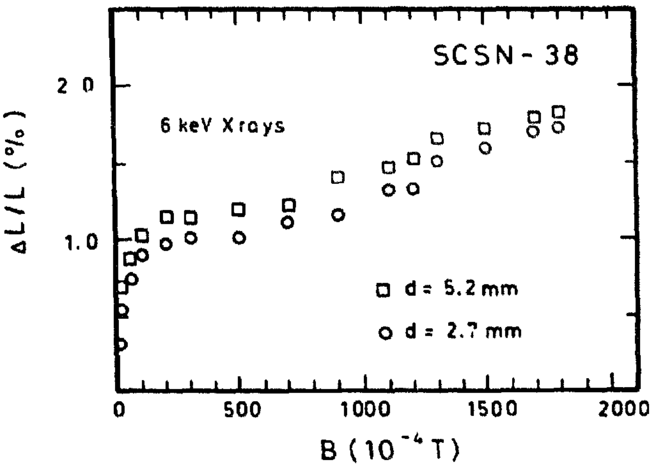

Fig. 9. Relative change in light yield of SCSN-38 in a magnetic field when excited by X-rays for different sample thicknesses of 2.7 and 5.2 mm. Within the errors no difference is to be seen.

saturation effect [5], the relative light yield increase should be higher for the thicker samples. Cumulat et al. [4] have measured slightly higher gains in the magnetic field when exciting an acrylic SCI with an alpha source or fission products instead of a ^{60}Co source. This also supports the preceding interpretation.

No thickness effect has been seen with protons, within the measurement accuracy of 0.3%, for SCSN-38 with sample thicknesses of 2.6, 5.0, and 10.0 mm and for NE-102A. This might be due to the fact that SCSN-38 has an about 15% lower Birks' kB-Value [13] than an Altulor SCI [14] which is very similar in composition compared to the Polivar SCI studied.

The X-ray measurement of SCSN-38 (fig. 9) shows a 0.2% higher relative light yield increase for a 5.2 mm thick sample compared to a 2.7 mm. This is just at the limit of the measurement accuracy.

4. Decay time

A magnetic field dependence of the decay time spectrum will influence the calibration of the ZEUS calorimeter and change the response ratio of the calibration to electrons relative to hadrons

Setup (c) [9] was modified to measure the decay time spectrum. A 2.9 MBq ^{60}Co source (320 keV β and 1170/1330 keV γ) has been used resulting in a 30 times increase of deposited energy. PMT$_L$ (left photomultiplier, see fig. 3) provides the start signal for the time measurement. A two level discriminator (energy threshold of 10 photoelectrons and timing threshold of 0.3 photoelectrons) defined the event time to 0.1 ns The signal from PMT$_R$ served as stop signal. A grey filter in front of PMT$_R$ reduced the light yield to an average of 0.02 photoelectrons. It has been verified that the measured spectra did not depend on the energy threshold of PMT$_l$ Rebuilding the setup with the role of PMT$_R$ and PMT$_l$ exchanged did not change the results.

Fig 10 shows the measured spectra for fields of 0 T and 0.15 T. A shoulder around $t = 18$ ns is seen By changing the high voltage (HV) and HV distribution of PMT$_R$ the position of the shoulder moves in time. Similar changes on PMT$_l$ had no effect. Thus the cause are rare events for which PMT$_R$ shows a pulse before the expected signal This effect is also described in the literature [15] and we were not able to cure it. The same effect occurs when PMT$_R$ and PMT$_l$ are interchanged. Thus the spectrum is distorted, but the comparison field/no field should nevertheless be valid.

The decay time spectra have been fitted by the function $L(t)$:

$$f(t) = \frac{1}{\tau_2^{(1)} - \tau_1}\left(e^{-t/\tau_2^{(1)}} - e^{-t/\tau_1}\right)$$

$$+ \frac{r_2}{\tau_2^{(2)} - \tau_1}\left(e^{-t/\tau_2^{(2)}} - e^{-t/\tau_1}\right),$$

$$g(t) = \frac{1}{\sqrt{2\pi}\sigma_t} e^{-t^2/(2\sigma_t^2)},$$

$$L(t) = A\int_0^{\infty} f(t')g(t-t')\,dt'.$$

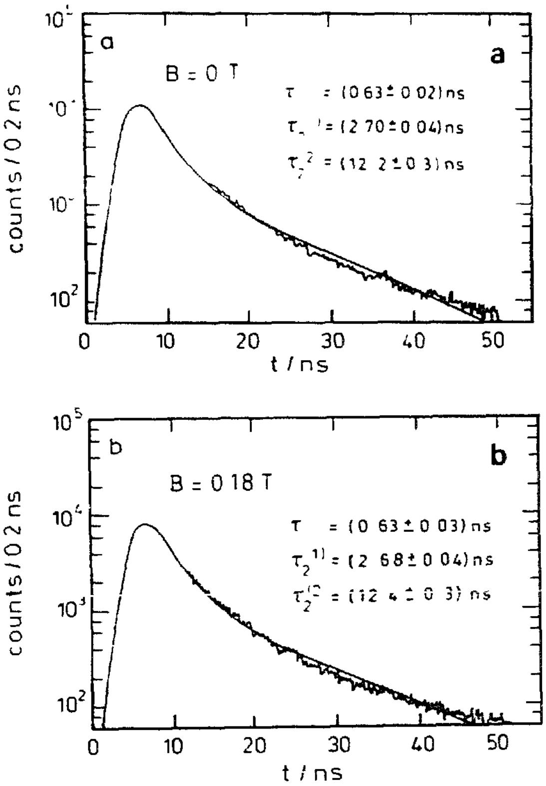

Fig 10 Decay time spectrum of SCSN-38 without magnetic field (a) and in a field of 0.18 T (b) for ^{60}Co excitation The experimental data are fitted by a function given in the text The corresponding decay constants are summarized in table 2

Table 2
Decay constants from the fit function of fig. 11. Shown are measurements without magnetic field and in fields of 0.10 and 0.18 T

B[T]	τ_1[ns]	$\tau_2^{(1)}$[ns]	$\tau_2^{(2)}$[ns]	r_2
0	0.63 ± 0.02	2.70 ± 0.04	12.2 ± 0.3	0.48 ± 0.01
0.10	0.61 ± 0.03	2.67 ± 0.05	12.4 ± 0.3	0.51 ± 0.01
0.18	0.63 ± 0.02	2.67 ± 0.05	12.4 ± 0.3	0.52 ± 0.01

The function $g(t)$, with $\sigma_t = 0.7$ ns is the timing response function. It has been determined experimentally from measurements with the grey filters removed from both PMTs. $f(t)$ describes a two step decay chain, with the single decay constant τ_1 for the first step, feeding into the second decay, described by the two decay constants $\tau_2^{(1)}$, $\tau_2^{(2)}$, and relative strength r_2. The values of the best parameters of the fit for the measurements at 0, 0.1, and 0.18 T are given in table 2. Within the statistical errors we find no dependence on magnetic field.

5. Summary and conclusions

1) The light response of different plastic scintillators to ionizing radiation depends on the magnitude of an external magnetic field. For the polystyrene based SCSN-38 and the polyvinyltoluene based NE-102A, which contain aromatic rings with low excitation energies, the light increase is about 1% between 2 and 100 mT, with a further increase for higher field values. For the PMMA based Polivar scintillator the relative increase of light yield is somewhat larger and depends on the scintillator dimensions. At a value of 100 mT it is about 2% for 2.5 mm thick samples and 4.5% for 10 mm samples.

2) No magnetic field dependence is observed, when scintillators or wavelength shifters are excited by UV light. Thus the magnetic field affects the excitation or deexcitation of the base molecules or the energy transfer to the first fluor.

3) The magnetic field does not influence the transmission of the light in scintillator or wavelength shifter material.

4) The decay time spectrum up to decay times of ≈ 40 ns does not depend on an external magnetic field.

5) The magnetic field dependence of the light yield has to be taken into account for precision calorimeters close to or inside magnetic fields like the uranium scintillator calorimeter of the ZEUS collaboration. Fig. 11 shows the change in energy calibration of the calorimeter due to the SCI magnetic field effect for the electromagnetic section of the ZEUS forward (a) and rear calorimeter (b) [16].

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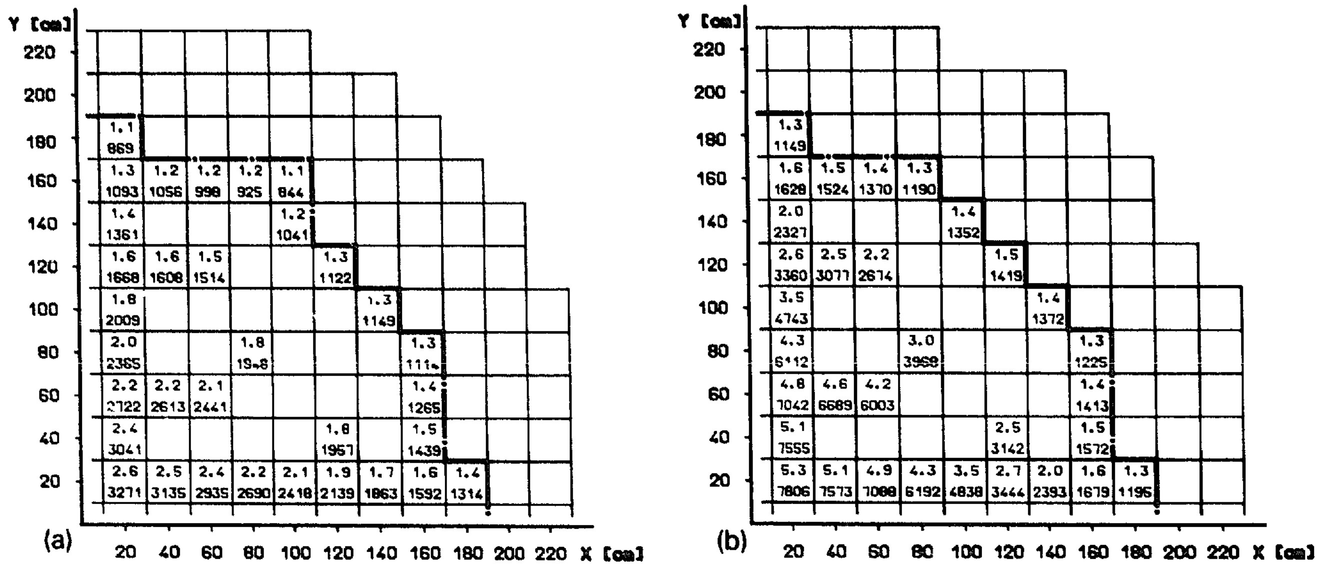

Fig. 11 One quarter of the ZEUS forward calorimeter (a) and backward calorimeter (b) seen from the interaction point x and y denote the distances from the beam line Shown are for several electromagnetic towers, the averaged (over z) magnetic field (at the bottom, in 10^{-4} T) [16] and the corresponding relative light yield increase (at the top, in %)

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