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PROGRESS ON HIGH-RESOLUTION TRACKING WITH SCINTILLATING FIBRES: A NEW DETECTOR BASED ON CAPILLARIES FILLED WITH LIQUID SCINTILLATOR

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Presented by G. Martellotti

Abstract

The capabilities of a new detector based on capillaries filled with liquid scintillator have been investigated. Tests have been performed using various scintillating cocktails and readout systems. With the best combinations, and for light propagation over a few centimetres, the hit density is as high as 5 hits/mm. For propagation over distances greater than 10 cm, an attenuation length of $\sim$ 95 cm is measured. A spatial resolution of $\sigma \simeq 12\ \mu$m is obtained with capillaries of 20 μm bore.

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1. INTRODUCTION

Particle tracking using bundles of scintillating fibres (SCIFI) has been proposed since many years [1], but it is only recently that the progress in optoelectronic technology and in the chemistry of scintillating substances has allowed SCIFI to become competitive with other tracking devices.

In the last few years we have tested SCIFI devices based on bundles of 30 000–100 000 fibres, where each fibre has a diameter of 15–30 μm. The typical bundle cross-section is 5×5 mm^2 and its length is between 4 and 50 cm. Three different types of SCIFI have been examined: glass fibres, plastic fibres and glass capillaries filled with liquid scintillator.

The glass fibres had cores of GS1, which contains cerium oxide (Ce_2O_3). The fibres were drawn[a] to give a square cross-section of 25×25 μm^2. Cerium-doped glasses were originally developed because of their high resistance to radiation [2]: GS1 suffers little damage for an absorbed dose of up to $\sim 10^4$ Gy [3]. Cross-talk between fibres is largely eliminated by surrounding each fibre with an extra-mural absorber (EMA) [4]. The disadvantage of glass fibres is that the time response is slow [5] and the short-distance light attenuation is severe (attenuation length $\lambda \simeq 2$ cm [6]). The result is a low light output [6]: ~ 0.6 hit/mm after propagation over ~ 2 cm in the fibres.

The plastic fibres[b] had cores of polystyrene doped with 1-phenyl-3-mesityl-2-pyrazoline (PMP). The core cross-section was hexagonal, with a distance of 30 μm between parallel sides. Compared [6] with glass fibres, the short-distance attenuation was greatly reduced, resulting in a higher light output (~ 2 hits/mm) and the time response was fast (~ 3 ns). However, EMA could not be placed around each fibre because no black material has yet been found that does not diffuse into the neighbouring plastic fibres during the manufacturing process. The cross-talk between fibres then contributes appreciably to the noise. Also, the radiation hardness of the plastic fibres was somewhat lower than that of the glass fibres, and only doses of a few 10^3 Gy can be sustained.

Recently, bundles of glass capillaries of 20–25 μm bore, with walls of 2 μm thickness, have become available[c] in lengths of up to ~ 1 m. With such capillaries, filled with organic scintillator, it is possible to combine the best characteristics of the glass and plastic SCIFI: the time response and light attenuation are similar to those of plastic fibres, while by inserting black glass in the interstices between capillaries, the cross-talk is practically eliminated [7]. The radiation hardness that can be attained using capillaries is even better than for GS1 glass. Preliminary studies undertaken at IHEP, Protvino, show that quartz capillaries of 1 m length and 110 μm bore, filled with an appropriate liquid scintillator, can sustain several 10^5 Gy with a reduction in light yield of less than a factor 2.

In this paper we report on tests of different capillary bundles filled with various liquid scintillators, exposed to a 5 GeV/c hadron beam at the CERN proton synchrotron. Several configurations of the readout optoelectronic chain have been considered in exploring the capabilities of the new tracking device. In the best case, and for light propagation over a few centimetres in the capillaries, we observe a hit density of ~ 5 hits/mm and an attenuation length of $\lambda \simeq 15$ cm, while for propagation over distances greater than 10 cm, λ is as high as ~ 95 cm.

[a] Collimated Holes Inc., Campbell, CA, USA.
[b] Kuraray Co. Ltd., Tokyo, Japan.
[c] Schott, Southbridge, MA, USA.

2. EXPERIMENTAL SET-UP

The set-up consisted of a tracking detector optically coupled to an optoelectronic chain with a CCD readout. The detector is a 5 mm diameter bundle of capillaries, filled with liquid scintillator. Different detectors have been tested: several short bundles (6–10 cm in length) and a long bundle (45 cm in length). They were made of capillaries having circular cross-sections, with inner diameters of 20 μm and 25 μm respectively, and with wall thicknesses of ~ 2 μm. All capillaries were drawn from Schott borosilicate glass, which has a refractive index $n = 1.49$. One in six of the interstices between capillaries was filled with EMA. Light emerging from the readout end of the capillaries was amplified by a series of five image intensifiers (IIs). Most of the gain came from the fourth II, which contained a microchannel plate and was gateable. In order to preserve spatial resolution, this II was preceded by three electrostatically focused IIs that magnified the image, and followed by another electrostatically focused II, which demagnified the image so as to match the size of the CCD.

Three different optical couplings between detector and first II have been tested: direct coupling in which the readout end of the capillary bundle was pressed against the photocathode fibre-optic window of the first II, which ensures that the liquid scintillator is kept in place; coupling through a fibre-optic plate glued to the readout end of the capillaries; coupling through a transparent quartz lamina, also glued to the detector, followed by a mirror and a large-aperture lens, as described in ref. [7]. The direct coupling has a greater light-collection efficiency than the other couplings, but there is the disadvantage that the detector is not mechanically independent of the optoelectronic chain. The light-collection efficiency of the fibre-optic-plate coupling has been measured to be $\sim 65\%$ of that of direct coupling, with the light losses being due to the packing fraction of the fibre-optic plate. Coupling with the lens introduces inefficiencies because, in spite of its large aperture ($f/0.8$), the lens has a limited angular acceptance for light. In this case, the light collection efficiency, which depends on the angular aperture of the cone of light emitted by the SCIFI, is $\sim 50\%$ for plastic fibres ($n_{core} = 1.59$, $n_{cladding} = 1.49$) and lower for capillaries. The lens coupling is the only one that allows observation of particles that cross the detector at small angles with respect to its axis: with the other couplings, the particles would traverse the optoelectronic chain.

Capillaries have been filled with different scintillating cocktails. Two solvents have been used: 1-phenylnaphthalene (PN) and 1-methylnaphthalene (MN), which have refractive indices of 1.64 and 1.62 respectively. The MN has been specially purified so that its transmission below 450 nm is greatly increased. The two solvents were doped with either PMP or 1-(2′-methoxyphenyl)-3-biphenylyl-5-(4′-methoxyphenyl)-2-pyrazoline (MBMP) [8]. In fig. 1 we show the emission spectrum of these two dyes, together with the effect of purification on the transmission properties of MN.

In the tests, two different IIs have been used as first element of the optoelectronic chain. One was manufactured by Varo[d] while the other (SUII) was manufactured in the Soviet Union. Both have multialkali photocathodes but the SUII tube has a better quantum efficiency for wavelengths higher than 450 nm (fig. 2). This is evident in the experimental measurements, which show that the two tubes have practically the same response for the light emission spectrum of PMP, peaked at 420 nm, while for the MBMP spectrum, peaked at 480 nm, the sensitivity of the SUII is higher than that of the Varo tube by a factor of ~ 1.2.

[d] Varo Inc., Electron Devices Division, Garland, TX, USA.

3. RESULTS FROM ANALYSIS OF PARTICLE TRACKS

In fig. 3 we show an example of the image recorded on the CCD for a particle that crosses the capillary bundle perpendicularly to its axis. The procedure used for fitting tracks and the subsequent analysis have already been described [6]. In fig. 4a and 4b the transverse pulse-height distribution that can be obtained for particles crossing a capillary bundle is compared with that for particles crossing a plastic SCIFI detector, measured with a previous version of the optoelectronic chain [9]. The noise is reduced from $\sim$ 48% of the total pulse height to $\sim$ 15%, which is close to the physical limit imposed by δ-ray production [9]. The spatial resolution is $\sigma \simeq 14$ μm (root-mean-square value) with the capillaries (fig. 4a) coupled to the optoelectronic chain using the lens, compared with $\sigma \simeq 20$ μm [6] for the plastic fibres (fig. 4b). The improvement is due to the smaller diameter of the capillaries (20 μm) compared with the plastic fibres (30 μm) and to the high magnification of the lens, which reduces the contribution to the resolution of the following IIs. In a more refined analysis, the pin-cushion distortion introduced by the IIs has been taken into account by fitting tracks with parabolae rather than straight lines. This leads to an even better spatial resolution of $\sigma \simeq 12$ μm.

In fig. 5 we report the number of hits per millimetre obtained for particles that cross a detector at different distances, d, from its readout end. The detector was composed of capillaries with 25 μm bores and lengths of 45 cm. The capillaries were filled with MN doped with 0.3%, by weight, of MBMP and directly coupled to the SUII. At shorter distances ($\simeq$ 2 cm) the hit density is $\sim$ 5 hits/mm and the attenuation length is $\lambda \simeq$ 15 cm. At larger distances ($\geq$ 10 cm) the attenuation length increases to $\lambda \simeq$ 70 cm. With a second, nominally identical, preparation of MN and MBMP, and using the same capillaries and readout system, a long-distance attenuation length of $\lambda \simeq$ 95 cm has been measured, although with a slightly reduced hit density.

With the short capillaries, having inner diameters of 20 μm, the best attenuation length measured is $\lambda \simeq$ 23 cm, obtained when using a scintillating cocktail of PN doped with 0.5% by weight MBMP. This result was achieved despite the PN not being specially purified.

Using capillaries filled with a solution of PMP (1.5% by weight) in MN, and directly coupled to the Varo II, a hit density of $\sim$ 5 hits/mm has again been obtained at $d \simeq$ 2 cm. Here, however, the light yield is higher than for MN doped with MBMP, since the sensitivity of the Varo photocathode to the PMP emission spectrum is lower by a factor of $\sim$ 1.2 than that of the SUII photocathode to the MBMP emission spectrum.

We have found that doubling the concentration of the PMP or MBMP in MN results in a marginally increased light yield at short distances, but is accompanied by a slight worsening of the light attenuation.

Studies of radiation hardness have so far been limited to measurements for quartz capillaries filled with MN doped with MBMP. In fig. 6 we report results [10] obtained with 110 μm capillaries. Absorbed doses of up to 640 kGy can be sustained with a reduction in light yield of about a factor 2, at $d \simeq$ 1 m, and no change in scintillation efficiency. The radiation hardness of this tracking device is therefore significantly better than that of the other SCIFI we have considered.

4. CONCLUSIONS

Detectors based on capillaries filled with liquid scintillator offer better performance than those based on other types of scintillating fibres. With 20 μm capillaries we have obtained a spatial resolution of $\sigma \simeq 12$ μm. At shorter distances, attenuation lengths of $\lambda \simeq 15$–23 cm have been found, while for distances greater than ~ 10 cm, $\lambda \simeq 70$–100 cm. At distances of a few centimetres, a hit density as high as 5 hits/mm has been measured. This is equivalent to $\sim 2 \times 10^3$ hits per unit radiation length, which compares favourably with that obtained using other types of detector. The possibility of introducing EMA between capillaries practically eliminates the noise due to optical cross-talk. The use of appropriate liquid scintillators like MBMP dissolved in MN allows the construction of tracking devices that are radiation resistant up to several 10^5 Gy.

In conclusion, high-resolution tracking with capillaries filled with liquid scintillator has been shown to be a very promising technique.

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Figure captions

Fig. 1 Emission spectra of a) PMP and b) MBMP scintillators when excited at 270 nm. Absorption coefficient for a 10 cm thickness of MN: c) industry grade and d) specially purified.

Fig. 2 Photocathode sensitivity of the two image intensifiers that were placed first in the optoelectronic chain: a) Varo tube; b) SUII tube. The peak emission wavelengths of PMP and MBMP are also shown.

Fig. 3 Typical image recorded by the CCD for a particle crossing the capillary bundle perpendicular to its axis. Scales are in mm at the detector surface.

Fig. 4 Transverse pulse-height distribution for particles crossing: a) a bundle of capillaries with ~ 20 μm bores and b) a bundle of plastic scintillating fibres having core diameters of ~ 30 μm. Different optoelectronic chains were used in the two cases.

Fig. 5 Hit densities for particles crossing a bundle of 25 μm capillaries, as a function of the distance, d, of the particles from the readout end of the detector. The capillaries were filled with MN doped with 0.3%, by weight, of MBMP.

Fig. 6 Light yield of 110 μm capillaries filled with MN doped with MBMP, before and after irradiation, plotted as a function of the distance, d, between the point of light production and the readout end of the capillaries: a) no irradiation, the long-distance attenuation length is $\lambda = 118$ cm; b) 125 kGy, $\lambda = 101$ cm; c) 160 kGy, $\lambda = 93$ cm; d) 320 kGy, $\lambda = 85$ cm; e) 640 kGy, $\lambda = 64$ cm.

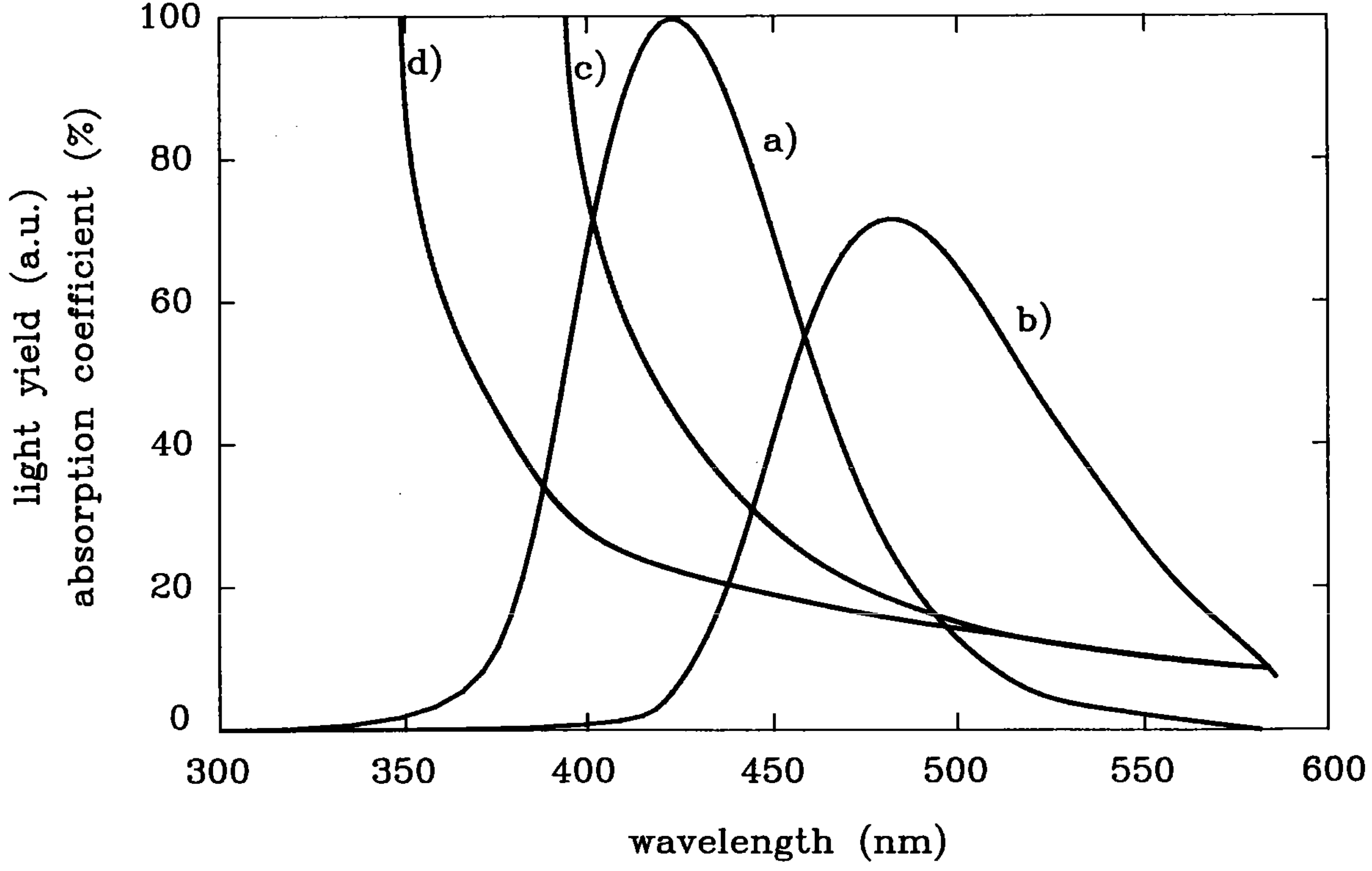

light yield (a.u.)
absorption coefficient (%)
100
80
60
40
20
0
300
350
400
450
500
550
600
wavelength (nm)
a)
b)
c)
d)

Fig. 1

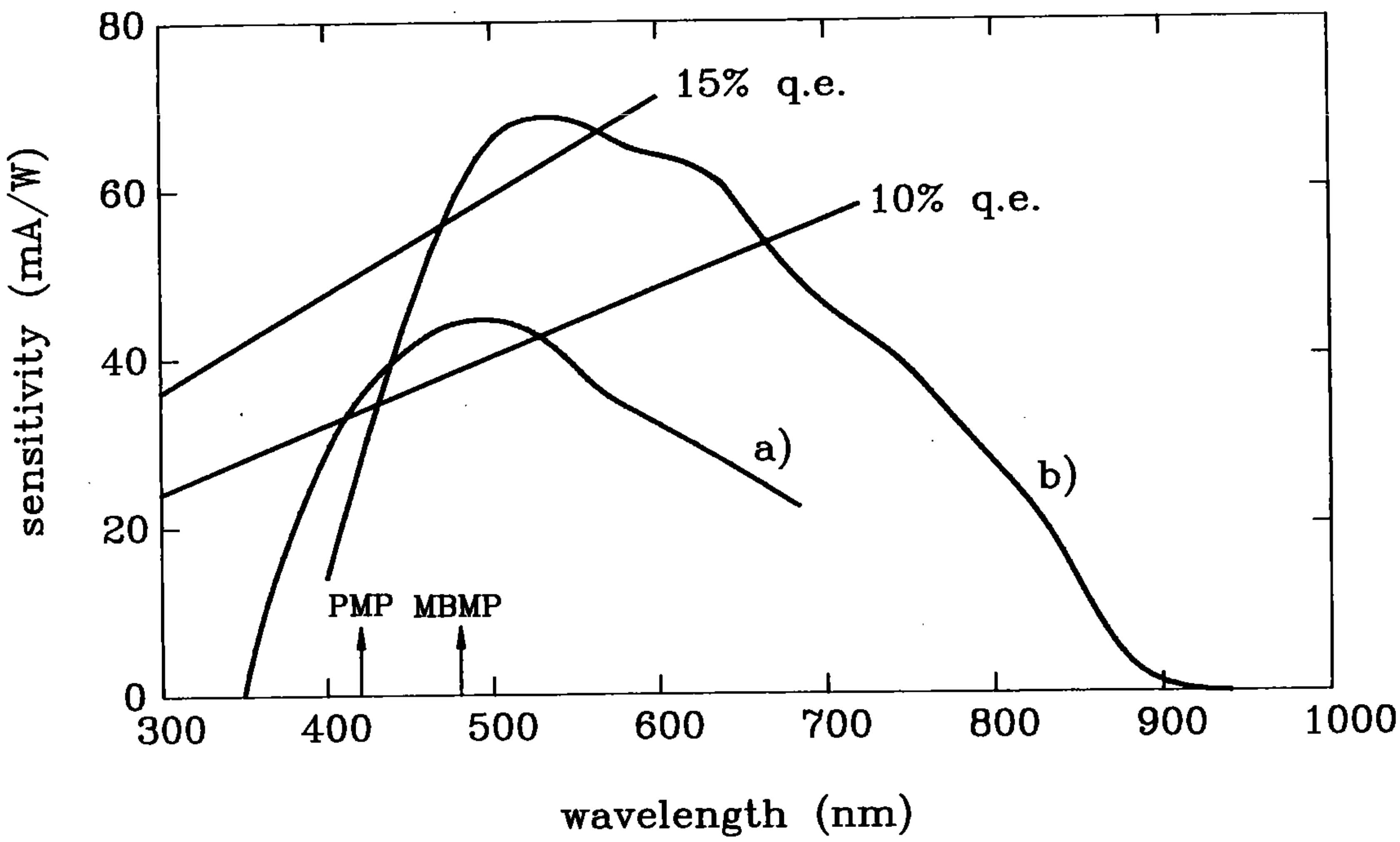

80
60
40
20
0
300
400
500
600
700
800
900
1000
sensitivity (mA/W)
wavelength (nm)
15% q.e.
10% q.e.
a)
b)
PMP
MBMP

Fig. 2

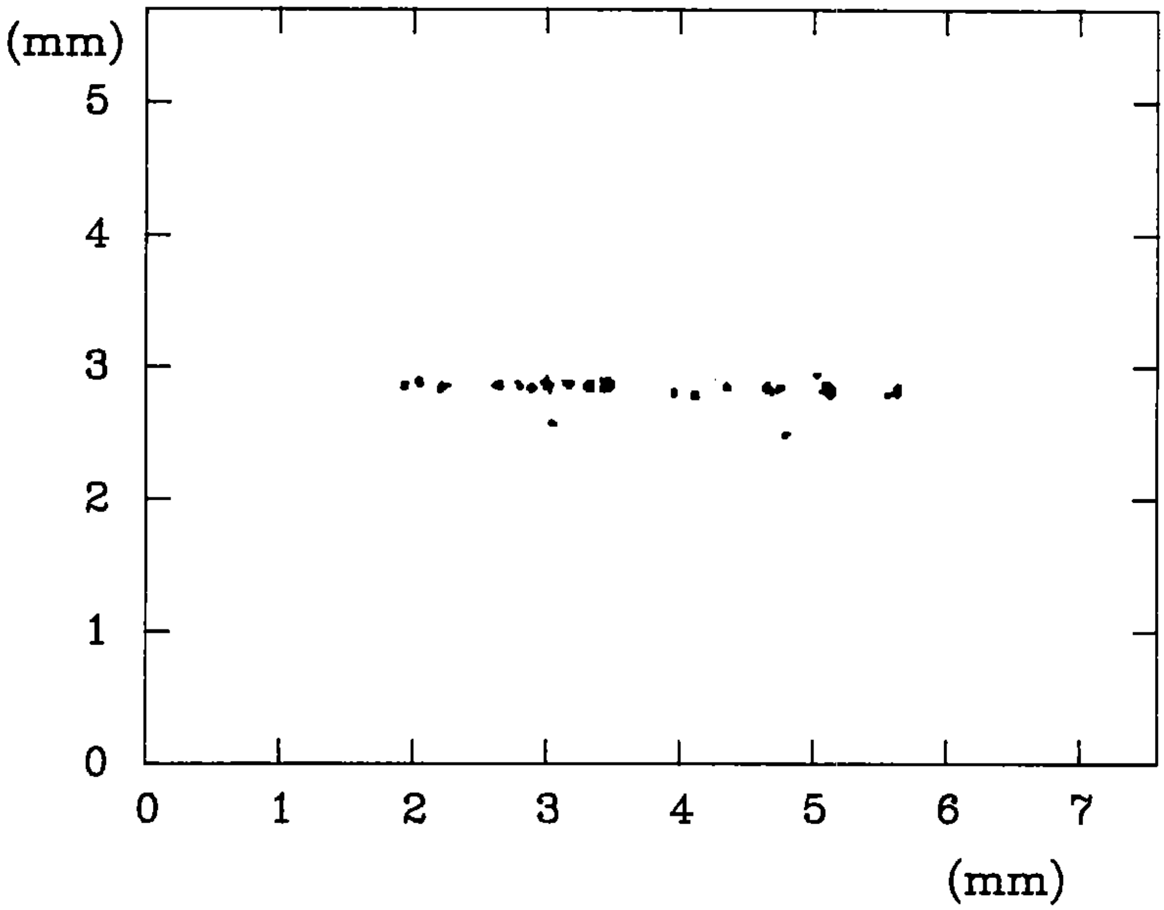
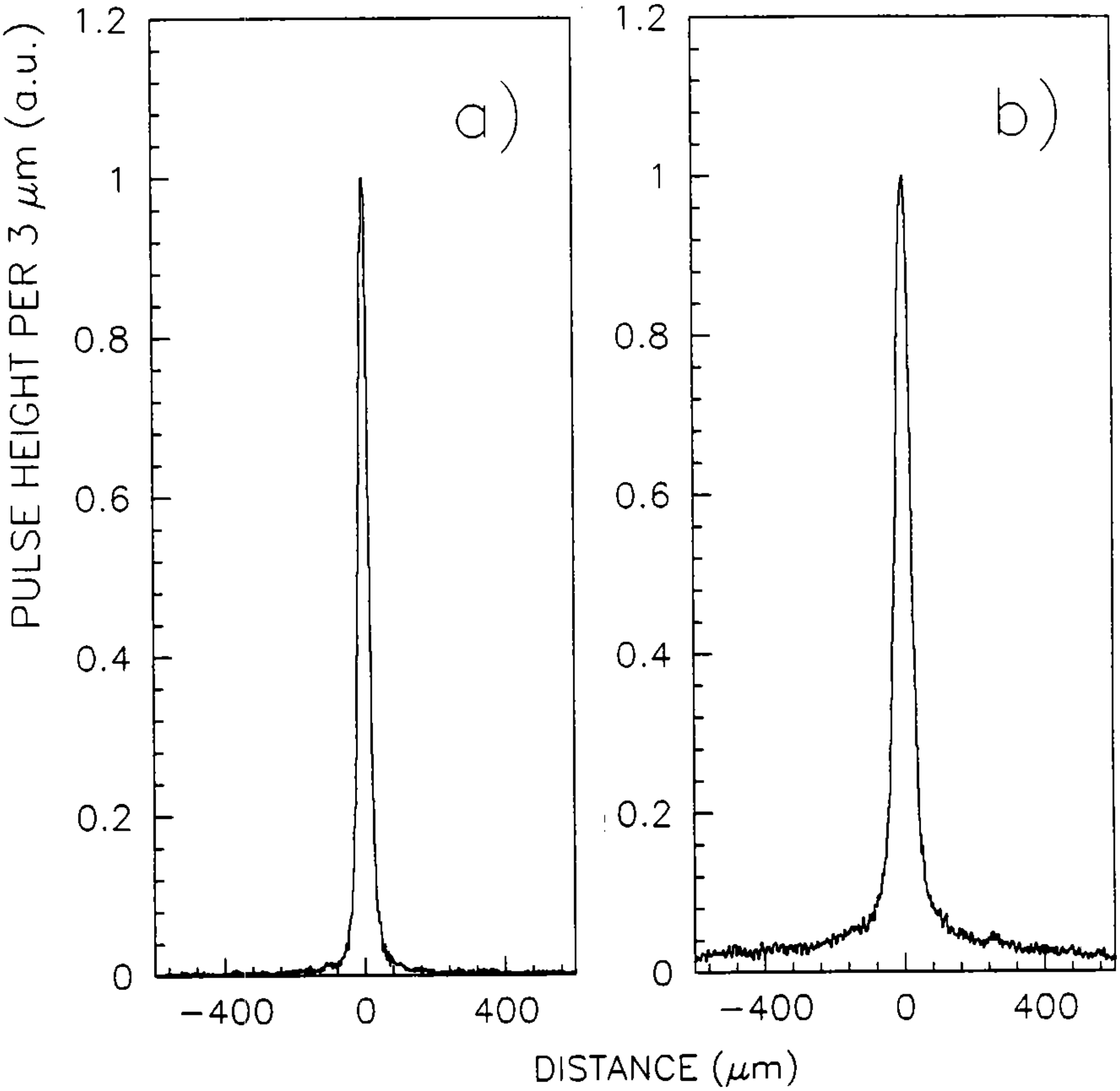


Fig. 3



PULSE HEIGHT PER 3 μm (a.u.)
1.2
1
0.8
0.6
0.4
0.2
0
a)
b)
−400
0
400
DISTANCE (μm)

Fig. 4

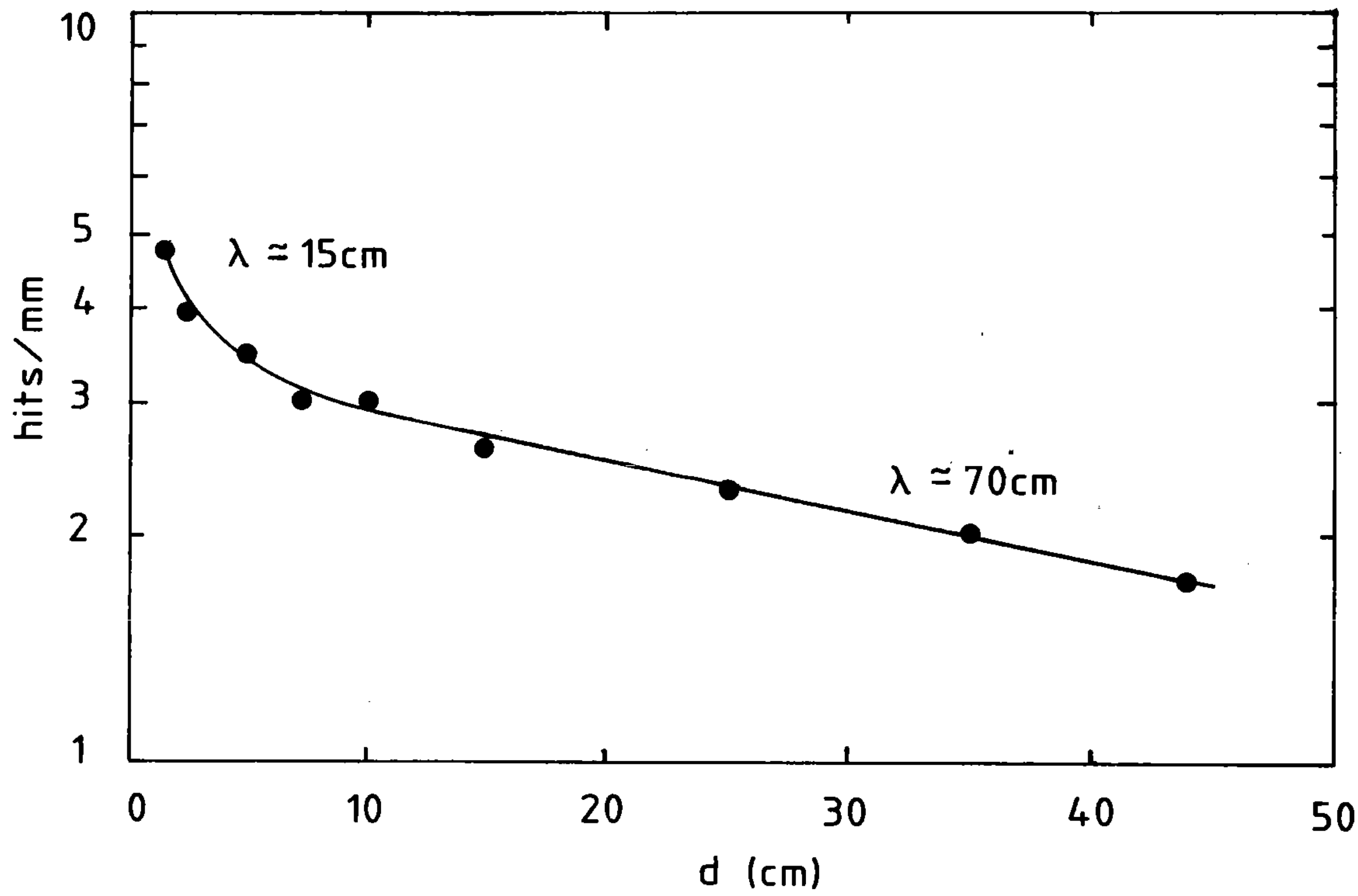


Fig. 5

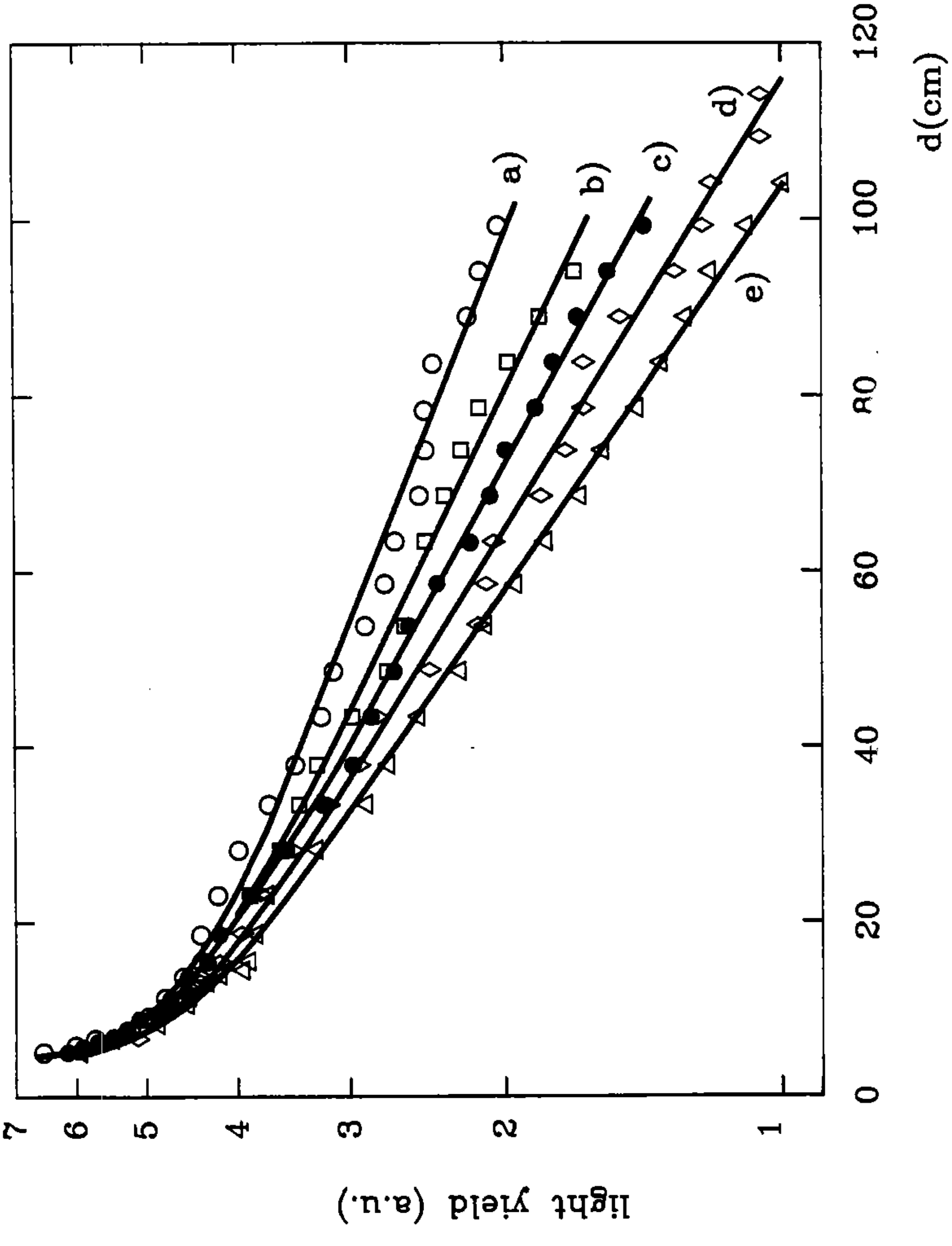


Fig. 6

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