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LIQUID SCINTILLATOR FILLED CAPILLARY ARRAYS FOR PARTICLE TRACKING

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Abstract:

Coherent arrays of glass capillaries filled with liquid scintillator offer interesting possibilities in high resolution particle tracking. We describe the preparation and filling of capillary targets with 20 μm and 120 μm diameter light guides, as well as the performance of capillary targets in a 5 GeV test beam exposure. Considerations are given concerning choice and optimization of solvents with high refractive index and fluorescence dyes. Furthermore results of systematic studies of liquid scintillators in beam tests are reported.

(submitted to Nuclear Instruments and Methods A)

1. INTRODUCTION

Glass capillaries with inner diameters ranging from 1 mm down to 50 μm and filled with liquid scintillators of high refractive index, have been shown recently by us to be efficient optical light guides. In particular the effect of reflection losses at the core / cladding interface was found to be small, resulting in attenuation lengths substantially longer than one meter [1]. A coherent array of such scintillating light guides offers interesting possibilities for fast, fully active detectors for high resolution particle tracking. Attractive applications have been suggested, e.g. in heavy flavor detection, high and low energy neutrino physics and for tracking at high luminosity colliders [2-7].

In continuation of our investigations on capillary targets we investigated systematically suitable binary liquid scintillators and started attempts to optimize our test scintillators with respect to light yield and attenuation. In addition we studied preparation techniques and the performance of targets made of highly regular arrays of 20 μm and 120 μm diameter capillaries. Results obtained in test beam exposures confirm our earlier findings with UV-light excited single microcapillaries.

2. HIGH REFRACTIVE LIQUID SCINTILLATORS WITH LARGE STOKES SHIFT

2.1 Solvents with high refractive index

The production of stable liquid scintillators for use in capillary detectors of about 1 m length requires a careful choice and optimization of solvent and fluorescent dye. Concerning the selection of the solvent several properties are mandatory. Apart from a high refractive index, the position of the absorption edge of the solvent is of importance. The only interesting solvents are those, which are transparent at wavelengths longer than 350 nm. The requirement of meter long attenuation lengths can only be fullfilled, if the transmittance in the spectral range of the dye emission is larger than 99% in 1cm of traversed liquid, that is for absorption coefficients smaller than a = 0.0044 cm^{-1} ($a = \varepsilon \cdot c$, where ε is the molar decadic absorption coefficient and c is the concentration in mole l^{-1}). Problematic in all investigated solvents are impurities, which also can be reaction products of the solvent itself, like e.g. dissolved oxygen, and which absorb in the visible part of the spectrum. Assuming a molar absorption coefficient of $\varepsilon = 10^4$ 1 $mole^{-1}cm^{-1}$ in the visible region [8], impurity concentrations of 10^{-6} mole l^{-1} result in absorption coefficients of 0.01 cm^{-1}.

We concentrated our investigations on a selection of pure solvents. Refractive indices and absorption coefficients at 400 nm and 500 nm of different solvents are shown in tab.1, together with the geometric trapping efficiencies expected for light guides made of borosilicate glass as described in sect.5.

1-Methylnaphthalene $C_{11}H_{10}$ (1MN) is a well known high refractive solvent. The density of the liquid is 1.02 g/cm^3. It is only commercially available with poor optical quality in the visible and ultraviolet region and has to undergo several

purification steps. After purification including washing with sulfuric acid, neutralization and careful vacuum distillation under inert gas (2-3 times) we obtained results of satisfying optical transmittance. In fact, the final product has the same quality, obtained as if 1-methylnaphthalene is synthezised directly from purified naphthalene [9]. It is interesting to note that measurements of the fluorescence spectrum of the pure solvent show a superposition of a monomer fluorescence peaking at 330 nm with a broad excimer fluorescence at 400 nm [10].

1-Chloronaphthalene $C_{10}H_7Cl$ (1ClN) belongs to the high refractive naphthalene derivates, which are in the liquid state at room temperature. Its density is 1.19 g/cm^3. Purification by vacuum distillation is possible without problems and the liquid already shows excellent transmittance after two distillations. The absorption coefficient of 0.008 cm^{-1} at 400 nm is the lower limit for absorption due to heavy atom induced singlet-triplet transitions [11]. However, being a heavy atom solvent, 1ClN can influence strongly the fluorescence properties of dyes, which leads in the case of 1-phenyl-3-mesityl-pyrazoline (PMP) to a drastic reduction of fluorescence quantum yield by about a factor 20, and in the case of diketone derivates [12] to an enhancement, when compared to standard solvents (e.g. benzene).

Isopropyl biphenyl $C_{15}H_{16}$ (IBP) is despite of its relatively low refractive index of n = 1.58 an interesting solvent, since it is already commercially available with a relatively high purity [13]. Its density is 0.979 g/cm^3 and the maximum of its fluorescence is found at 318 nm.

Several other solvents are interesting candidates, like *1-phenylnaphthalene* (1PN), *1-naphtoic-acid -ethylester* (1NE), *benzylalcohol* (BA), *2-methylbenzthiazole* (2MBZ) and *1-acetylnaphthalene* (1AN). All of them were found to need further optimization of synthesis and purification techniques.

Excellent transmission in the visible part of the spectrum has been obtained with saturated solutions of high refractive aromates. However, so far, the achieved refractive indices are not yet sufficient for practical applications.

2.2 Fluorescence dyes

Suitable dyes for liquid scintillators are characterized by a high fluorescence quantum efficiency in the respective solvent and by a small overlap of emission and absorption spectra. Moreover high molar concentrations of dyes are needed in order to guarantee locality of light emission, which is essential for light transport in capillaries with diameter smaller than 100 μm. For this reason binary compositions with one solvent and one dye are favorable. The wavelength of the dye emission maxima, fluorescence quantum efficiencies and fluorescence decay times are summarized in tab.2 for various dyes in different solvents. With increasing refractive index we observed for most solutions the expected bathochromic shift of the wavelength of the fluorescence maximum.

The fluorescence properties of dissolved dyes depend on their molecular structure,

concentration and type of interaction with the solvent. In case of high dye concentration the formation of aggregates and direct energy transfer among the dye molecules lead to a decrease of fluorescence yield. Quenching also can occur by impurities or by oxygen dissolved in the solvent. Apart from the unspecific solvatation, specific solvent/ solute interactions occur via hydrogen bonds and donator-acceptor interactions, which can also involve ground and excited states. In the case of 3-hydroxyflavone (3HF) intramolecular proton transfer occurs after dye excitation and leads to an extremely large Stokes shift. PMP and its derivates belong to the class of most efficient dyes with large Stokes shift [14]. In this case the Stokes shift is due to the differences in steric arrangement of the molecule in the ground and excited state.

3. TEST OF LIQUID SCINTILLATORS IN SINGLE CAPILLARIES

Light yield and attenuation of various liquid scintillators were determined in test beam exposures with 5 GeV pions from the CERN PS accelerator. For this purpose the scintillators were filled in about 70 cm long single capillaries made of SCHOTT glass 8250, the same as employed in fabrication of capillary arrays, as described in sect.5. The capillaries had circular cross section and an inner diameter of 2 mm. One end of each capillary was equipped with a window to make optical contact with an adiabatic lightguide matching the diameter of the photomultiplier, the other end was sealed with a non-reflecting cap. In order to suppress glass-air reflections the entire capillary was covered with black acrylic paint. The target was mounted horizontally on an optical bench, which could be moved transverse to the particle beam between two trigger counters in coincidence. The pulse height spectra and, in case of small light output the probability of no-photon detection (pedestals), were recorded at different target positions. Together with the known single photon response, the obtained pulse height spectra were converted into the number of photoelectrons detected at the photocathode.

Depending on the color of the emitted scintillation light either a photomultiplier with a bialkaline (EMI 9939B) or a S20 (EMI 9203B) photocathode were used. Fig.1 shows for several scintillators the number of photoelectrons detected at the photomultiplier, normalised to 1 mm of traversed pathlength in the liquid. For comparison data were also taken with a 1mm diameter plastic fiber (UA2-type, Polystyrene/butyl-PBD and POPOP) with well known properties [15].

As a general feature the green emitting scintillators yield substantially less detectable photoelectrons than the blue emitting dyes. Although self absorption is smaller in 3HF-doped scintillators, the longer attenuation length cannot compensate for the smaller light output within the considered target length. The best results have been obtained with 1MN+PMP 0.01mole/liter, with on average 8 p.e./mm detectable in a 1m long target and 80 cm attenuation length.

4. SYSTEMATIC STUDIES OF THE COMBINATIONS IBP/PMP AND 1MN/PMP

From all solvent/solute combinations considered by us so far, IBP/PMP and 1MN/PMP gave the best results with respect to fluorescence quantum efficiency and transmittance. The optical quality of the solvents and the influence of a high dye concentration were studied in absorption measurements with a two beam spectrophotometer (PERKIN ELMER Lambda 15), with a relative accuracy of 10^{-3} in the range from 300 nm to 700 nm. Difficulties in this type of measurements usually arise from differences in reflectivity in the sample and reference beam, as well as from the varying quality of the cuvette material itself. In order to reduce systematics, the measurements were repeated several times with two cuvettes of the same glass composition (Hellma, Quartz SUPRASIL). Both cuvettes were always filled with the same liquid. The optical pathlength in the sample cuvette was 10 cm and in the reference cuvette 1 cm. From the measured spectral absorption a_λ the attenuation length can be inferred using the relation $L_\lambda = d / (a_\lambda \ln 10)$, where d is the difference in optical pathlength of sample and reference beam. The offset of the instrument was calibrated by measuring the attenuation at 700 nm in 70 cm long samples following UV excitation and by comparing the attenuation lengths observed for the same liquids. The obtained attenuation lengths as a function of wavelength are shown in fig.2 for the pure solvent and with a high dye concentration of 0.1 mole/liter PMP.

In order to determine the absolute light output of the scintillators as a function of dye concentration and following particle excitation, samples were filled in glass cuvettes and exposed to a 5 GeV pion test beam. The cuvettes were optically coupled by a lucite light guide to a photomultiplier with bialkali photocathode (EMI 9939B). A plastic scintillator of type NE102A with the known light yield of 10 γ/keV was cut and polished to cuvette dimensions and used as a calibration standard. For comparison the pulse height spectra measured for the test scintillators still had to be corrected for the slightly different emission spectra and geometric light collection efficiencies. For both solvents the light output was found to be comparable to the plastic standard, as soon as the dye concentration was raised above 0.01 mole/liter. The obtained light yields as a function of dye concentration are shown in fig.3a. These results are consistent with measurements of the concentration dependence of the fluorescence intensity following UV excitation in the solvent absorption bands, where for 1MN/PMP, Benzene/PMP and IBP/PMP a plateau is reached above 0.1 molar solutions [1].

Assuming no reflection losses at the capillary walls, the overall attenuation expected in long capillaries can be calculated from the wavelength dependent transmission of the pure solvent, the molar extinction of the dye, its emission spectrum and the spectral response of the detecting photocathode. The result is given in fig. 3b. Indeed, comparable results have been obtained in test beam measurements with 70 cm long capillaries of 2 mm inner diameter: for 1MN as solvent attenuation lengths of 80cm/71cm/ 45cm (+-5 cm) were found for concentrations of 0.01/0.025/ 0.1 mole/liter of PMP. The agreement of calculation and measurement is, within the existing uncertainties, satisfying.

The knowledge of the concentration dependence of scintillation light output and observable attenuation length, can finally be used to optimize the performance of the solvent/solute combination for a certain detector length. In order to estimate the number of photoelectrons detectable in capillaries after 1m light propagation, the trapping efficiency has to be taken into account. The result of a Monte Carlo simulation of light propagation in a circular fiber with n_{wall} = 1.49 (SCHOTT glass 8250) and assuming a reflectivity of R = $1 \cdot 10^{-5}$ is shown in fig.3c for a 2mm capillary and for the scintillators under consideration. Optimum performance is expected at dye concentrations around 0.01 mole/liter and the higher refractive index in 1MN translates into an overall higher light output of the capillary. The experimental results from beam exposures of capillaries filled with 1MN/PMP 0.01 molar are similar, as evident from fig. 1 and give values of 4 detected photoelectrons per mm of traversed liquid scintillator at 1m distance on a standard bialkali photocathode.

5. CAPILLARY TARGETS AND THEIR PREPARATION

The coherent capillary bundles used in our investigations were produced as described in more detail in [1] from a multicomponent borosilicate glass (SCHOTT type 8250), with an index of refraction n = 1.49 [16]. The glass is transparent above 380 nm. The remaining small absorbance of light travelling for some wavelengths in the capillary walls at each reflection translates into an effective absorption lengths of longer than 13 m in 20 μm diameter capillaries.

Three types of targets have been used; individual capillaries with 2.0/2.7 mm inner/outer diameter and hexagonal bundles with capillaries of 120/144 μm and 20/24 μm inner/outer diameter. The size of the capillaries is the result of several fiber drawing steps, e.g. bundles of 20 μm lightguides are obtained after three drawing steps. Cross sections of filled bundles are shown in fig.4a and 4b. In order to reduce cross talk between individual lightguides an extramural absorber can be introduced. Two techniques have been successfull. In the case of 20 μm capillaries, black stained glass fibers were placed in each of 1/6 of the available interstices. This put one black fiber in contact with each capillary tube. The size of the black fibers in the final capillary array is about 5 μm. The density of the black glass is nearly identical to 8250 glass, except for about 3 wt.% of iron to make the glass black. In case of 120 μm capillaries, individual lightguides were covered by a 2 μm thick layer of absorbing glass.

The filling factor determines the physical properties of a capillary target. It is defined as the fraction in volume of liquid scintillator, and for a hexagonal close packed geometry it is given by the relation

$$f = (1 - \pi/2\sqrt{3}) + \pi/2\sqrt{3} \cdot (d_i/d_o)^2$$

where d_i , d_o are the respective inner and outer capillary diameters. The first term describes the contribution of the space between the light guides, which has to be

taken into account, if no interstitial absorber is applied. The resulting physical parameters of the targets, i.e. density, radiation length and energy loss are shown in tab.3 for a filling with a liquid scintillator of density 1.02 g/cm^3 (1MN).

Several preparation steps are necessary in order to achieve a satisfying performance of capillary targets. First a clean surface of the target, with unobstructed capillaries is produced at both ends by cutting at the outer rim with a sharp diamond knife and by breaking the bundle to the approximate size. In order to protect the outer capillaries from damage during handling the bundle is mounted on rubber inside of a rod, only the ends sticking out. Then the ends are cut with a precisely mounted diamond saw [17]. Best results were achieved with a sawblade covered with 3.3 carat/cm^3 of synthetic 10 to 20 μm diamonds and an attacking grain size between 3 to 6 μm. The saw is kept rotating at a speed of 5500 turns/min clockwise and the target with 37 turns/min counterclockwise. During sawing the target is continually cleaned by a stream of pressurized nitrogen entering from the opposite end. In order to prevent excessive heating and eventually melting of the thin glass walls during cutting, the heat is removed by rinsing the saw blade with distilled water. After cutting, water collected in the capillaries is removed by baking the target for 12 hours at 120^0 C under constant nitrogen flow. In fact it was found, that a large part of the water present in the 20 μm capillaries is due to condensation from ambient air humidity.

After preparation of the end faces the capillary bundles are equipped with small fluid recipients at both ends, which carry 1mm diameter tube connections for filling and purging and an optical window at a close distance of about 100μm to the target ends.

To fill the capillaries several procedures proved successful. For short targets of several cm length and made of 20 μm diameter capillaries, filling by capillary effect is effective and sufficient. In the case of 120 μm capillaries and of longer targets the liquids were pressed from a recipient with slight nitrogen overpressure into the capillary array. Care has to be taken that a steady, laminar flow of liquid develops, without production of microbubbles. Under front illumination a well filled capillary bundle without extra mural absorber has then the transparent appearance of a single capillary without visible scattering centers. The filling could be accomplished with close to 100 % efficiency for both 20 μm and 100 μm capillaries, resulting in a neglectable amount of blemishes apparent in the image transported by the coherent light guides.

The optical coherence of a 1 m long 20 μm capillary array has been tested by taking photographic pictures of the image of the endface under a microscope. By sequentially cutting the bundle, relative distortions of the image could be detected by overlaying the microphotographs and by inspecting the resulting Moiree patterns. Over the most part of the bundle cross section gross distortions, i.e. distortions which cause straight line objects to be imaged as continuous curves of varying degree, are smaller than 5 μm. Shear distortions appearing at multifiber edges are of the same size. At the bundle edges, down to a depth of 250 μm, a chickenwire effect is apparent. In this type of distortion small gaps of one or more capillary diameters

open and give dark line patterns creeping from the border into the bundle. The pattern is varying from short lines to regular patterns following the contour lines of multifibers.

6. PERFORMANCE OF CAPILLARY TARGETS

The performance of the targets was tested in a 5 GeV pion beam exposure and a scintillator filling of IBP+3HF 0.006 mole/liter. Depending on the quality of filling, attenuation lengths of up to 105 cm were achieved with coherent arrays of 127 capillaries of 120 μm inner diameter. These results, which were recorded with a photomultiplier with S20 photocathode, have to be compared to the attenuation length of about 130 cm obtained in 2 mm capillaries under the same conditions (fig.5). From this observation we conclude that light propagation in 120 μm capillary targets is essentially limited by the transparence and self absorption of the liquid scintillator. Additional losses introduce a partial attenuation length of about 550cm. By further improvements of the filling technique we expect the deteriorating influence of imperfect reflectivity and impurity scattering out of the light guide to become negligible.

The performance of targets with 20 μm diameter capillaries depends more critically on optical transparence and high reflectivity at the core/cladding interface. The large surface exposed to the scintillator liquid and the high number of reflections (~ 32 /mm) render the microscopic light guides very sensitive to impurities. Although the capillary arrays have been produced under cleanroom conditions, it was observed, that after the first complete filling, light transmission in the target is bad, with attenuation length of a few cm only (curve c in fig.6). Moreover the originally water clear liquid at the inlet exits the target with a greenish colour at the outlet. However the performance could be substantially improved after abundantly flushing the capillaries with scintillator solvent. A final inspection under the microscope showed, that close to 100% of the total of individual capillaries (about 25000) are optically active with about equal brightness. The obtained result after a fourfould exchange of scintillator liquid in the target is shown on curve b in fig.6. An attenuation length of 45cm was found for a scintillator composition with a self absorption length of about 80 cm. From this we can derive a partial attenuation length of about 100cm, which has to be attributed to the imperfections in light transport in the capillaries themselves. Although this is the best result obtained so far in coherent arrays of microscopic light guides, we expect from our results with 49 μm single capillaries [1], that with increased purification efforts, further improvement will be possible.

7. CONCLUSIONS

In conclusion, our investigations have shown that high resolution tracking targets of coherent capillary bundles can be prepared up to 1 m in length and with diameters of the individual light guides ranging from 20 μm to 120 μm. Blocking of individual capillaries can be avoided by suitable preparation techniques and a homogeneous optical performance of all light guides in a bundle can be achieved.

From our experience we consider the transmittance of the liquid scintillator core material as an essential limiting factor. In this respect further improvements in purification could help and highly efficient, green emitting dyes would be desirable. In addition scintillators based on solvents like 1PN (with high trapping efficiency) and 1ClN (with excellent transmittance) should be studied systematically.

In view of the satisfying results achieved so far with capillary arrays, we are setting up first tests with a complete image intensifier chain to study particle tracking in detector submodules.

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8. TABLES

Solvent	refr. index	ε_{trap}(%)	a_{400} (cm^{-1})	a_{500} (cm^{-1})
1MN	1.617	4.4	0.015	0.002
1ClN	1.632	4.9	0.008	0.001
1PN	1.664	5.7	0.118	0.014
IBP	1.582	3.4	0.018	0.004
BA	1.545	2.3	0.01	
2MBZ	1.617	4.4	0.041	0.005
1AN	1.628	4.8	0.5	
1NE	1.586	3.6	0.1	
NA/Toluene	1.533	2.0	$<$0.004	
NA/BA	1.547	2.4	$<$0.004	

Table 1) Optical properties of high refractive index solvents. The abbreviations of chemical compounds are explained in the main text. ε_{trap} is the trapping efficiency in meridional approximation for $n_{cladding} \Rightarrow 1.49$, i.e. borosilicate glass. a_{400} and a_{500} are the absorption coefficients (cm^{-1}) at 400 nm and 500 nm, respectively.

Dye/Solvent	λ_{em}(nm)	Φ_F	τ(nsec)
PMP/1MN	435 +3	0.90	2.65
PMP/1PN	435	0.80	3.45
PMP/1ClN	455	0.05	3.6
PMP/IBP	438	1.0	2.5
3HF/1MN	542	0.25	3.0
3HF/1ClN	550	0.34	3.8
3HF/IBP	532	0.32	3.2

Table 2) Fluorescence properties of scintillating solutions. All quantities have been measured with dye concentrations of 0.1 mole l^{-1}. λ_{em} is the wavelength of the maximum of the dye emission spectrum in the given solution. Φ_F is the fluorescence quantum efficiency of the energy transfer from solvent to dye (with a precision of +-10%). τ is the decay time of the fluorescence light. In case of 1ClN the decay is not single exponential; only the shortlived component is quoted.

Filling factor	0.63
Ave. density (g cm^{-1})	1.49
Radiation length (cm)	23
Interaction length (cm)	61
dE/dx (MeV cm^{-1})	1.98

Table 3) Physical parameters of a capillary target filled with a liquid scintillator based on 1MN as solvent. The capillary walls are made of borosilicate glass. In this example we assume individual capillaries of 20/24 μm inner/outer diameter in a hexagonal packing arrangement and interstitial extramural absorber. The filling factor is the fraction of scintillator volume in the target. The specific energy loss refers only to the active core material.

9. FIGURES

Fig.1) Light output of liquid scintillators in single capillaries. The light yield is given in photoelectrons recorded per mm of traversed liquid scintillator. The measurements were done in a 5 GeV pion beam. (a) 1MN/PMP 0.01 mole l^{-1}, (b) IBP/PMP 0.06 mole l^{-1}, (c) for comparison 1 mm diameter plastic fiber polystyrene/butyl-PBD/POPOP (UA2-type), (d) 1MN/PMP 0.1 mole l^{-1}, (e) IBP/3HF 0.08 mole l^{-1}, (f) IBP/BBQ 0.06 mole l^{-1}. A bialkaline photocathode was used for the blue emitting scintillators a)-d), S20 for the green emitting dyes of scintillators e) and f).

Fig.2) Attenuation lengths as a function of wavelength. Results of spectrophotometric measurements are shown for IBP and 1MN. The effect of an additional dye concentration of 0.1 mole l^{-1} PMP is apparent.

Fig.3) Scintillator performance as a function of dye concentration. a) Result of light yield measurements with 5 GeV pions. b) Open symbols: measured attenuation length in 2 mm capillaries. Curves with filled symbols: Result of a Monte Carlo simulation of light propagation in a single 2 mm diameter fiber assuming the measured absorption properties of the scintillators. c) Expected light yield in capillaries after 1 m light pathlength. The result is based on a Monte Carlo simulation of 2 mm diameter capillaries. The quoted hit density is understood as the number of detectable photoelectrons per mm traversed scintillator. An optimum PMP dye concentration is found around 0.01 mole l^{-1}.

Fig.4) View of the endfaces of capillary bundles filled with liquid scintillator. a) The inner diameter of individual light guides is 120 μm, the wall thickness 12 μm. The bundle is 60 cm long and illuminated from the other end. b) The inner capillary diameter is 20 μm, the wall thickness 2 μm. In 1/6 of the interstices between the capillaries thin black fibers have been introduced for cross talk reduction.

Fig.5) Comparison of light attenuation in a 2 mm diameter single capillary to that in a bundle of 120 μm diameter capillaries. The attenuation lengths are 130 cm and 105 cm, respectively. Data were taken with 5 GeV pions.

Fig.6) Light attenuation in a 2 mm diameter single capillary compared to attenuation in a bundle of 20 μm capillaries. In (c) the bundle has been filled without special treatment. After cleaning of capillaries a drastic improvement in performance could be observed (b). A higher dye concentration translates into overall smaller attenuation lengths as compared to fig.5. Attenuation lengths of 80 cm and 45 cm were found for the single capillary (a) and the bundle (b), respectively. The difference is attributed to remaining impurities in the bundle.

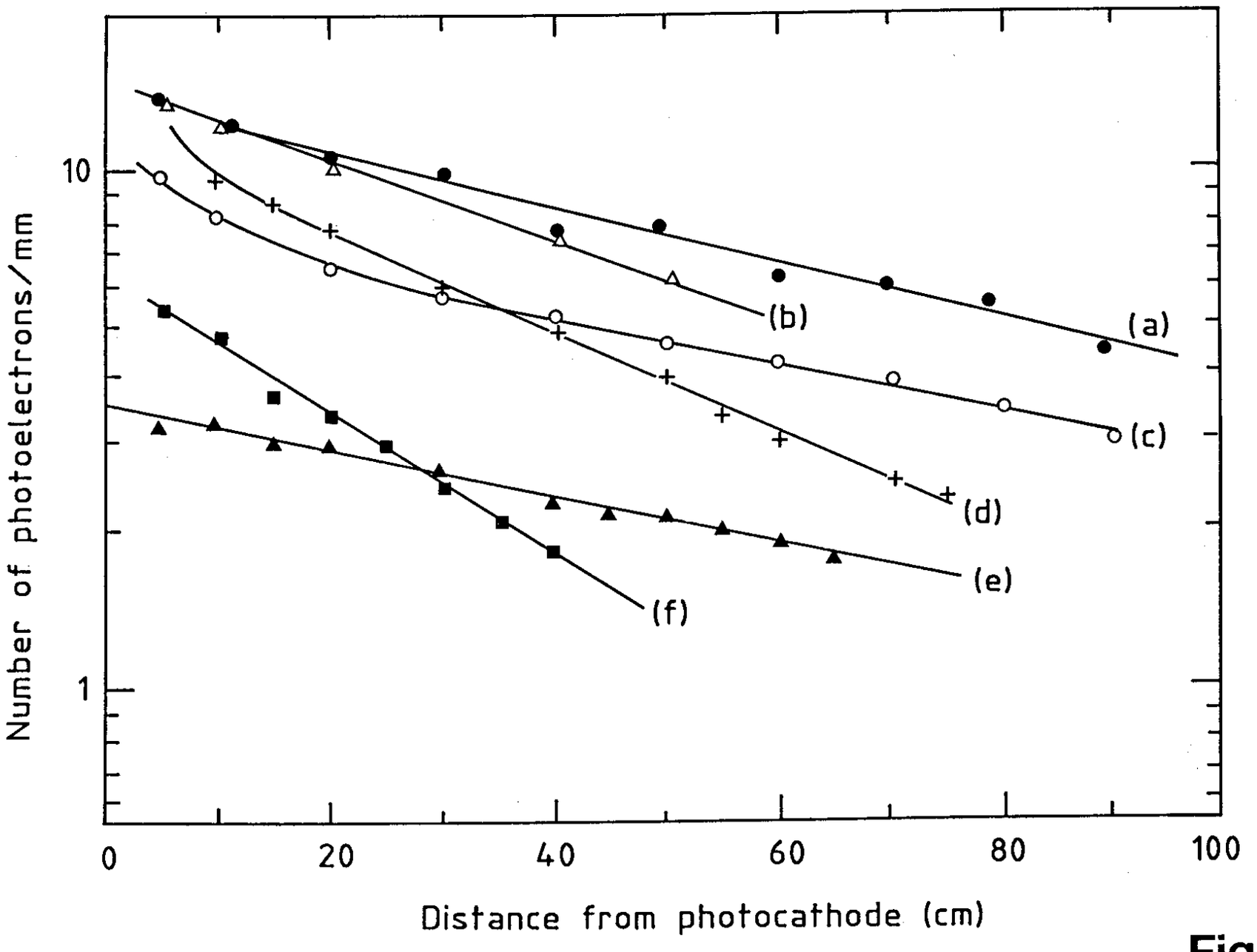

Number of photoelectrons/mm
10
1
0
20
40
60
80
100
Distance from photocathode (cm)
(a)
(b)
(c)
(d)
(e)
(f)

Fig.1

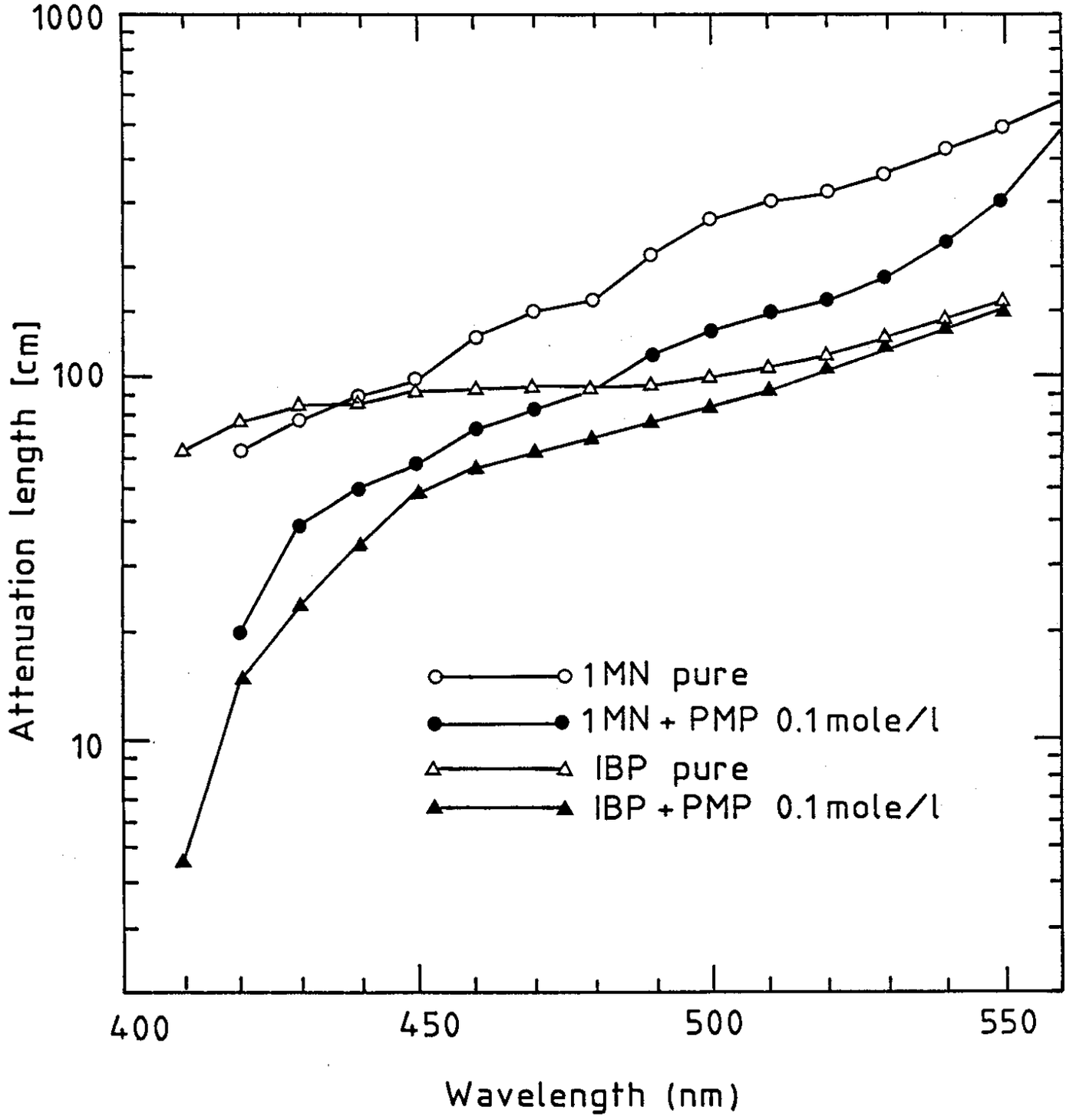

1000
100
10
Attenuation length [cm]
400
450
500
550
Wavelength (nm)
1MN pure
1MN + PMP 0.1mole/l
IBP pure
IBP + PMP 0.1mole/l

Fig.2

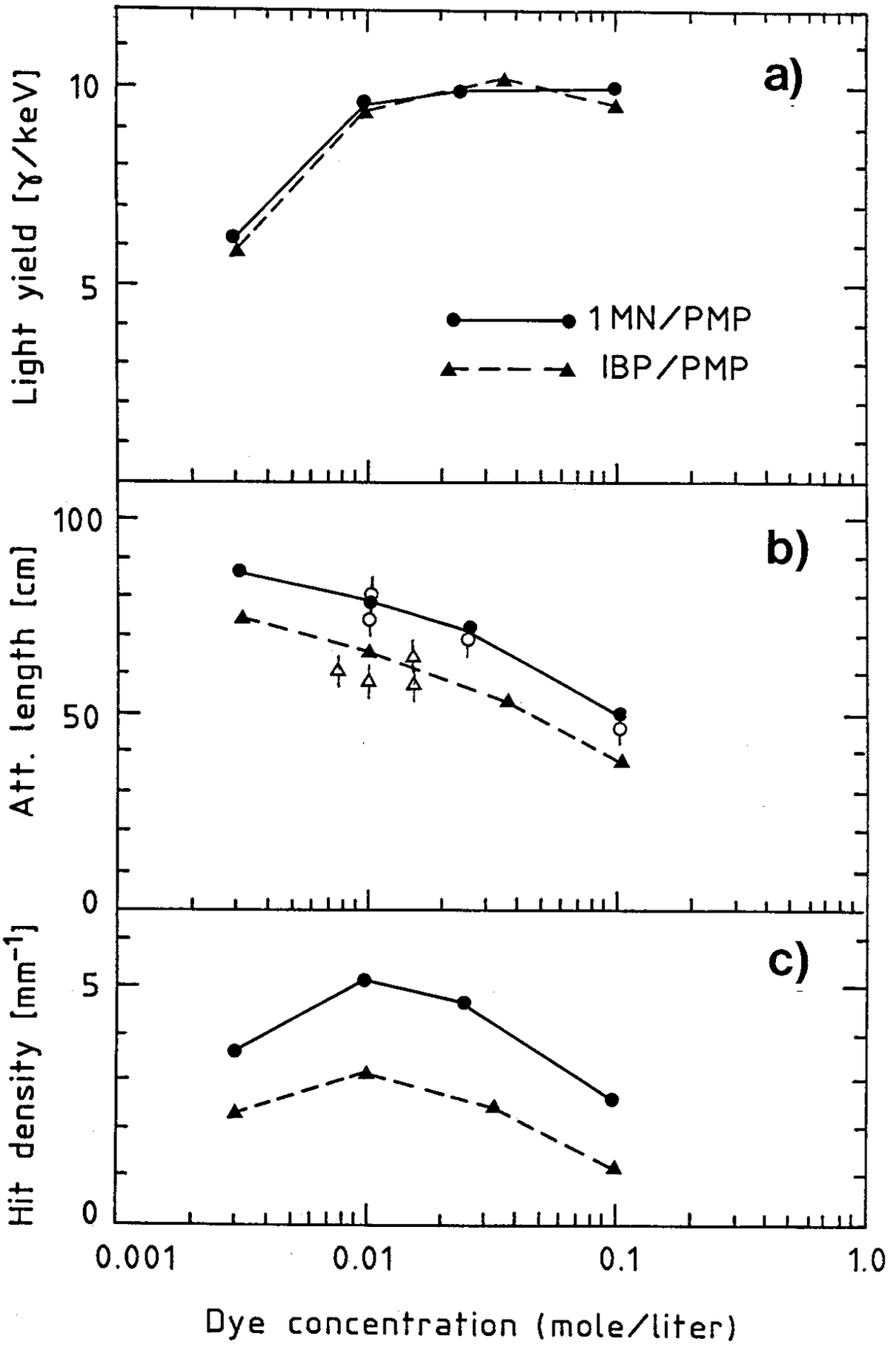
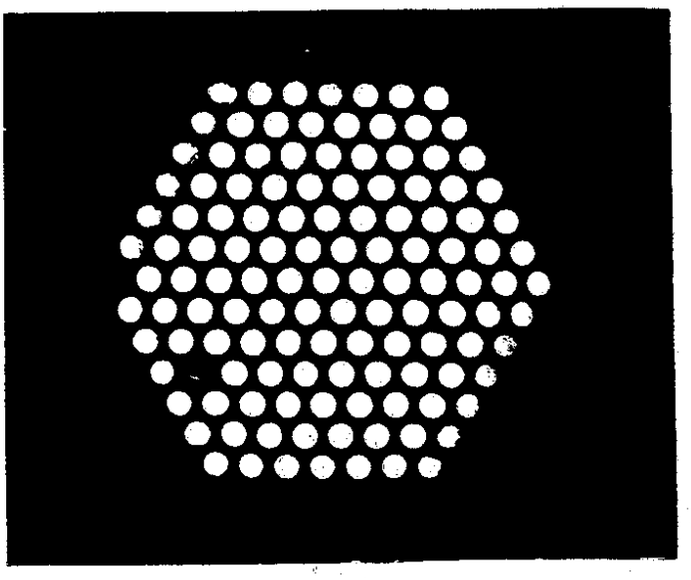
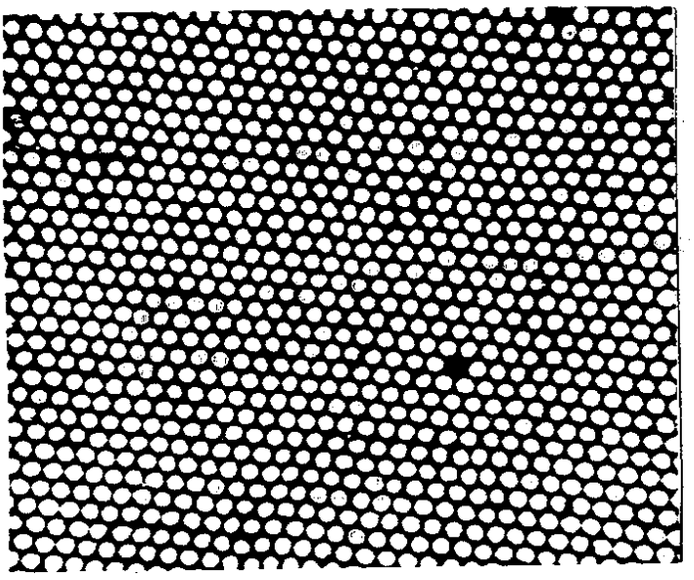

a)
b)
c)
Light yield [γ/keV]
10
5
1 MN/PMP
IBP/PMP
Att. length [cm]
100
50
0
Hit density [mm⁻¹]
5
0
0.001
0.01
0.1
1.0
Dye concentration (mole/liter)

Fig.3



a)



b)

Fig.4

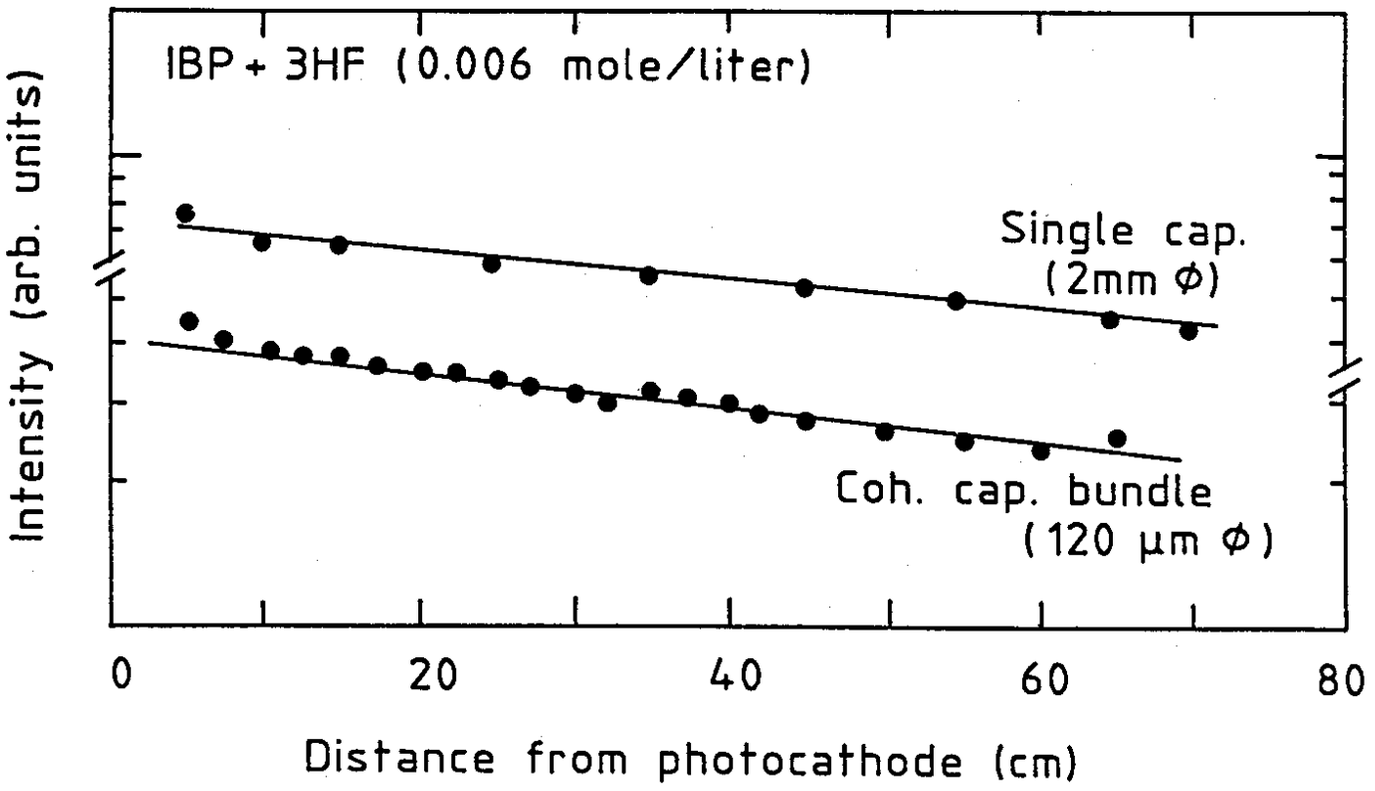

IBP + 3HF (0.006 mole/liter)
Single cap.
(2mm φ)
Coh. cap. bundle
(120 μm φ)
Intensity (arb. units)
0
20
40
60
80
Distance from photocathode (cm)

Fig.5

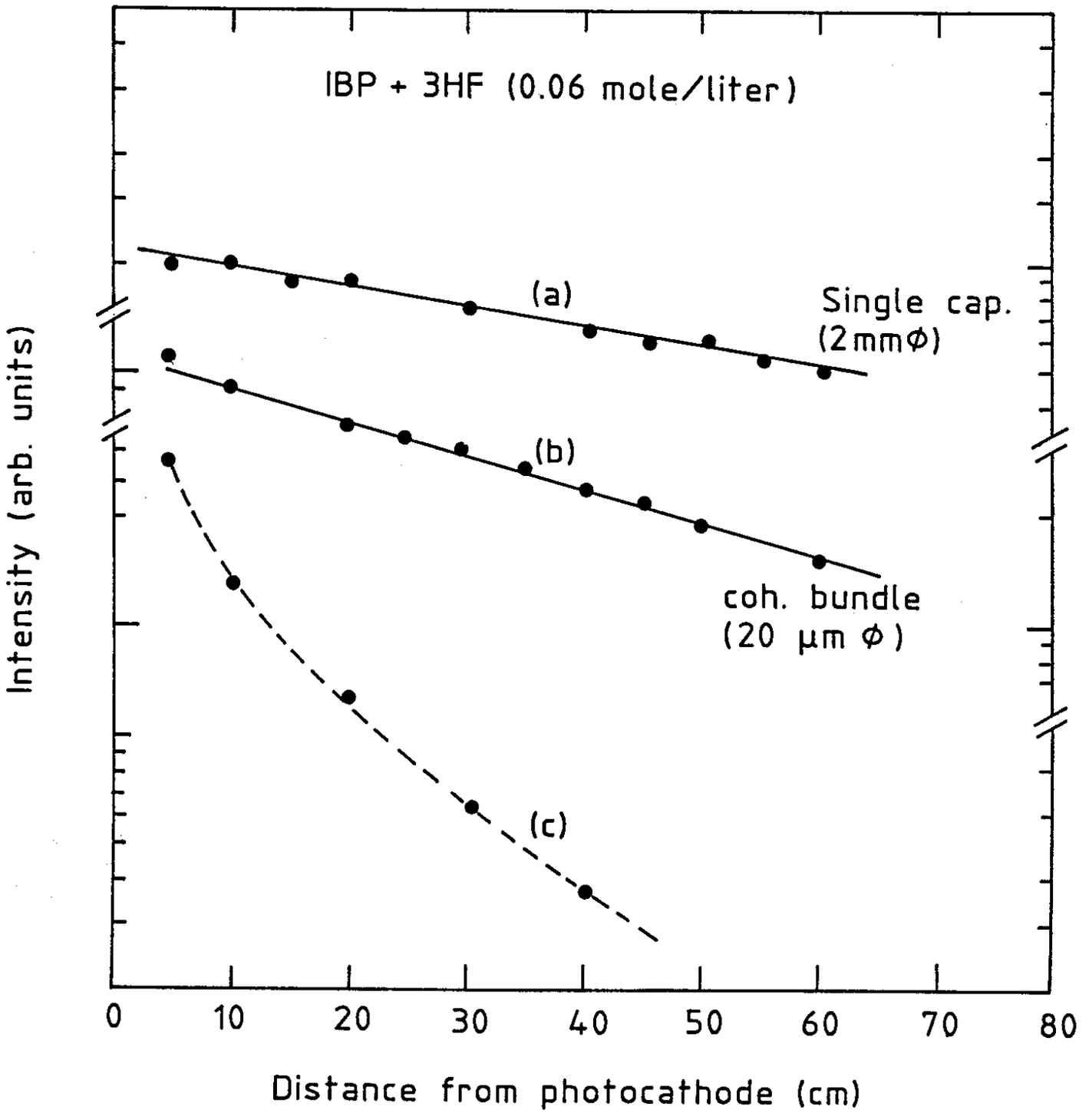


Fig.6

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