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**INVESTIGATIONS ON CAPILLARIES FILLED WITH LIQUID SCINTILLATOR FOR
HIGH RESOLUTION PARTICLE TRACKING**

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Abstract: - Glass capillaries filled with liquid scintillators of high refractive index are shown to be efficient optical light guides with surface reflection losses at the core/cladding interface of less than one part in 10^5 . In addition new binary liquid scintillator compositions are presented, which are suitable as capillary core medium. Coherent arrays of 20 μm diameter capillaries filled with liquid scintillators are technically feasible and could find interesting applications in particle tracking and vertex detection. In particular a massive vertex detector for τ -lepton detection in ν_τ charged current interactions is under investigations.

(submitted to Nuclear Instruments and Methods A)

1. Introduction

The concept of high resolution active targets based on scintillating glass and plastic fibers has been investigated by various groups [1-6]. We report here on a study of optical properties of thin glass capillaries, which are light guides of excellent quality, when filled with a transparent liquid scintillator of suitably high index of refraction and consequently can be used in high resolution active target detectors and particle tracking. This new type of optical lightguide has the good quality of the core/cladding interface as encountered in optical communication glass fibers and the high photon yield obtained in scintillating plastic fibers. Moreover, the scintillation light pulse is fast (≈ 5 nsec) and the scintillator is replaceable. Therefore, capillaries can be particularly interesting for applications in high rate experiments and for detectors in environments, where heavy radiation damage of conventional scintillators is expected.

Our own development efforts are part of the experimental program of the CHARMII collaboration at CERN, which initiated a search for means of efficient tagging of ν_τ -interactions. In particular a neutrino oscillation search of the $\nu_\mu \rightarrow \nu_\tau$ appearance type was proposed in [7], with a 0.5-1 ton vertex detector exposed to the CERN-SPS wideband neutrino beam. The use of a similar detector of smaller size (200kg) is foreseen at the future 3TeV UNK proton synchrotron at Serpukhov (SU), which will be an abundant source of ν_τ [8].

While the first experiment aims at a substantial improvement of sensitivity on $\nu_\mu \rightarrow \nu_\tau$ mixing by at least an order of magnitude, the intention of the second experiment is the first direct observation of ν_τ interactions. In both cases one searches for the charged current reaction $\nu_\tau + N \rightarrow \tau + X$. The τ will decay with a mean life of 3.0×10^{-13} sec, i.e. with a mean decay length of $60 \mu\text{m}/\text{GeV}$. The purpose of the active target fiber detector is, to determine the ν_τ interaction vertex with high precision and to identify the τ -lepton with high efficiency by impact parameter measurements on secondary tracks.

An active target detector consisting of coherent scintillating fibers or capillaries with diameters $\approx 30 \mu\text{m}$, attenuation lengths larger than 1m and a hit density of more than 5 hits/mm on a track would match the requirements. Recent progress in fabrication of meter long bundles of glass capillaries of $20 \mu\text{m}$ diameter and the ongoing development of new liquid scintillators with high light yield, large Stokes shift, and long attenuation length, promise indeed the feasibility of massive particle trackers with the needed spatial resolution.

In this paper we will first describe the physical properties of capillaries and capillary arrays, as well as the state of the art of capillary bundle production. Next the light transport in scintillator filled capillaries will be discussed. The presented results are based on measurements and on a Monte Carlo simulation, which were carried out mainly to obtain a better understanding of the influence of loss processes due to imperfections at the core/cladding interface. In the framework of these model calculations we then analysed the results of our measurements with capillaries of varying thickness and filled with high refractive index liquids. From these measurements we derived estimates for absorption and reflection losses in the capillaries. Furthermore we discuss the properties of new liquid scintillators developed by ourselves and others and which could be suitable for tracking in capillary arrays.

2. Capillaries and coherent capillary bundles

The capillaries and coherent capillary bundles used in our investigations were produced from a multicomponent borosilicate glass. The physical properties of this glass are summarized in tab.1, the transmission spectrum is given in fig.1. The low index of refraction ($n=1.49$) results in reasonable numerical apertures and trapping efficiencies for a variety of scintillating liquids.

It is known that thin scintillating plastic fibers suffer from poor transmission properties due to non-perfect total reflection [9]. This can be due to absorption losses in the cladding material, as well as to scattering at the core/cladding interface. For the liquid/glass light guides used in our study the first effect should be negligible at wavelengths above 360 nm because of the high transparency of the glass in this spectral range. Scattering losses can be kept small by carefully controlling the production process to avoid the formation of microcrystals. Preparation and production of the capillaries have to be performed in clean rooms to avoid contamination with dust particles.

Single capillaries are produced by drawing directly from the glass melt using a specially designed nozzle. By variation of the nozzle geometry, the drawing temperature and the drawing speed a wide range of capillary diameters and wall thicknesses can be produced. So far tests with single capillaries have been made with diameter/wall thicknesses between $49\text{ }\mu\text{m}$ / $5\text{ }\mu\text{m}$ and $900\text{ }\mu\text{m}$ / $50\text{ }\mu\text{m}$.

Coherent capillary bundles are produced using a multiple drawing procedure.

In the last drawing steps a hexagonal coherent bundle is obtained of about 5 mm diameter and a length of 100 cm. These bundles consist of about 28000 single capillaries with an inner diameter of 20 μm and an outer diameter of 27.5 μm . The pore area for these bundles is 58% of the total cross-section area including the wedges. Fig.2 shows the endface of such a bundle, which can already be considered as a submodule of a future massive vertex detector. Capillary bundles with other geometries can be obtained using glass preforms and multibundles of appropriate sizes. In this way honeycomb like structures with a bigger filling factor or longer bundles may be produced. Open area fractions in the range from 10% to 80% are achievable, as well as capillary inner diameters from 10 μm to 1000 μm . The introduction of an extramural absorber (EMA), which reduces cross talk and improves tracking resolution is under investigation and appears feasible.

3. Light transport in capillaries filled with liquid scintillator

Light transport in a cylindrical capillary is identical to that in a step index fiber. Let us consider a capillary of diameter d , core refractive index n_{core} and cladding index n_{clad} (fig.3). If we call φ the azimuthal angle of the light ray emission direction in the (x,y) plane orthogonal to the fiber axis and with respect to the radius vector, ϑ the polar angle with respect to the fiber axis along z , and ρ the distance of the emission point from the fiber axis, measured in fiber radii ($0 \leq \rho \leq 1$), then the condition for total reflection is given as

$$\cos\vartheta \geq \cos\vartheta_c = \sqrt{(n^2 - \rho^2 \sin^2\varphi)/(1 - \rho^2 \sin^2\varphi)} \quad (1)$$

with $n = n_{\text{clad}}/n_{\text{core}} = \cos\vartheta_c$. ϑ_c is the critical angle for meridional light emission along the fiber axis. $\cos\vartheta_c$ is rapidly varying with ρ and $\sin\varphi$. For values of ρ larger than n , any value of φ such that $\sin\varphi > n/\rho$ leads to total reflection for any value of the polar angle ϑ , i.e. $\vartheta_c = 90^\circ$.

In what follows, we consider light emitted after an ionizing particle traverses a fiber. We define the light trapping probability as the fraction of the total emitted light, which is captured by total reflection on the core/cladding interface and travels towards the fiber end. The trapping probability is then

$$\varepsilon = 1/3 \int_0^1 \rho \, d\rho \int_0^{2\pi} [1 - \cos\vartheta_c(\varphi, \rho)] \, d\varphi \quad (2)$$

Numerical integration over φ and ρ gives for the trapping probability a value of $\varepsilon = 0.059$, if n is taken to be $1.487/1.583 = 0.939$ which is applicable to glass capillaries as described in sect.2 and filled with a liquid scintillator based on isopropyl biphenyl as solvent (as described in sect.4). Total reflection on the capillary exit window may occur for skew light rays emitted near the core/cladding interface at large polar angles. An additional condition for light to emerge from the fiber is thus

$$\sin\vartheta \leq n_{\text{ext}}/n_{\text{core}} \quad (3)$$

where n_{ext} is the refractive index of the external medium. Assuming this to be air, the fraction of detectable light reduces to 0.046. This number should be compared to the value $0.5 \times (1 - n) = 0.030$, valid in the purely meridional emission approximation.

The distance Δl_z between two reflections, projected along the fiber axis, is given by

$$\Delta l_z = d \cot\vartheta \sqrt{1 - \rho^2 \sin^2\varphi} \quad (5)$$

The mean number of reflections n_{ref} per unit of length measured along the capillary cannot be described correctly in the meridional ray approximation ($\rho = 0$). In fact skew light rays have to be included, which undergo a large number of reflections on their helical path inside the light guide. In case of a uniformly excited core cross-section and isotropic light emission, the n_{ref} distribution can only be obtained by Monte-Carlo simulation. A mean value of 0.64 in units of the capillary diameter is found for n_{ref} when the integration is limited to those light rays which do not suffer total reflection on the exit window of the capillary (fig.4). This has to be compared with $n_{\text{ref}} = 0.18$ in the meridional ray case. The actual mean path length of the light rays in the capillary is only 1.067 times the length of the capillary traversed. However, values of n_{ref} as large as 1.5 and of $\cos\vartheta$ as small as $[1 - (n_{\text{ext}}/n_{\text{core}})^2]^{1/2} = 0.777$ may occur.

Because of the very large number of reflections occurring in a long capillary of small diameter, the quality of the inner glass wall plays a very significant role for the signal transmission in the light guide. It is characterized by the reflectivity $R = 1 - A$, where A is the surface loss coefficient per reflection. If L_s is the absorption length of light in the liquid scintillator, the overall transmission for a light ray emitted at relative radial distance ρ along direction (ϑ, φ) can be written as

$$T(\rho, \vartheta, \varphi, l) = R(\vartheta)^{n_{\text{ref}}(\rho, \vartheta, \varphi) l/d} e^{-l/L_s \cos\vartheta} \quad (7)$$

The evolution of the transmission T with l for fixed values of d , R and L_s can be calculated by simulation. Assuming a perfectly transparent core ($L_s = \infty$), Fig.5 shows the variation of the transmission as a function of l/d for various values of $A = 1 - R$ ranging from 10^{-2} to 10^{-5} . In order to keep the transmission above 37% after 1 m, a surface loss $A < 5 \times 10^{-4}$ will be needed for a 20 μm diameter capillary ($l/d = 5 \times 10^4$).

Within this model it is possible to derive a unique parameter pair R and L_s from a set of transmission measurements on capillaries supposedly differing only by their diameter. Using the transmission function described by (7), one can extract by an iterative optimization method the best set of values for R and L_s from the measurements.

In practice, at sufficiently long distances, depending upon d , R and L_s , the evolution of the transmission is experimentally well represented by a single exponential. In fact a strong correlation between the small values of $\cos\theta$ and the large values of n_{ref} exists and the skewest light rays vanish already at short distances. Under this simplification, the transmission may be rewritten as

$$T = \exp(-l/L_s^* - l/L_{\text{ref}}) \quad (8)$$

where $L_s^* = L_s/\cos\theta$ is the apparent scintillator absorption length and where

$$L_{\text{ref}} = d / (n_{\text{ref}} \ln R) \quad (9)$$

characterizes the attenuation by reflection losses. The mean values of $\cos\theta$ and n_{ref} should be taken at large distances and therefore depend themselves upon R and L_s . An iterative procedure using the overall means as starting values may conveniently overcome this difficulty.

4. Influence of absorption losses in the capillary walls

The reflectivity R can be affected by various loss processes: Absorption in the cladding material of the light guide, Rayleigh scattering by imperfections of the core/cladding interface, losses due to distortions in capillary shape and diameter. The last two processes strongly depend on the fabrication process and its quality control. However absorption losses are an intrinsic material property and can be avoided by a suitable choice of the capillary glass

composition. They matter even in the case of total reflection, since light penetrates several wavelength deep also in the cladding material. Assuming for simplicity meridional light rays, it is possible to evaluate the importance of absorption losses in the cladding material on the overall transmission of liquid filled capillaries of a given glass type.

Is $R(\vartheta)$ the reflectivity at the core/cladding interface for a meridional ray inclined by the polar angle ϑ to the fiber axis, one obtains for the transmission in a capillary of diameter d and length l the following relation

$$T(l/d) = \int_0^{\Theta_c} R(\vartheta)^{\tan \vartheta \cdot (l/d)} \sin \vartheta \, d\vartheta / \int_0^{\Theta_c} \sin \vartheta \, d\vartheta \quad (10)$$

Direct absorption losses in the core material are not taken into account in this relation ($L_s = \infty$). If the reflectivity $R(\vartheta)$ is dominated by Fresnel losses one obtains

$$R(\vartheta) = \frac{1}{2} \cdot (|\rho_{\perp}|^2 + |\rho_{\parallel}|^2) \quad (11)$$

with

$$\rho_{\perp} = \frac{N_{\text{core}} \sin \vartheta - \sqrt{N_{\text{clad}}^2 - N_{\text{core}}^2 \cos^2 \vartheta}}{N_{\text{core}} \sin \vartheta + \sqrt{N_{\text{clad}}^2 - N_{\text{core}}^2 \cos^2 \vartheta}} \quad (12a)$$

$$\rho_{\parallel} = \frac{N_{\text{clad}}^2 \sin \vartheta - N_{\text{core}} \sqrt{N_{\text{clad}}^2 - N_{\text{core}}^2 \cos^2 \vartheta}}{N_{\text{clad}}^2 \sin \vartheta + N_{\text{core}} \sqrt{N_{\text{clad}}^2 - N_{\text{core}}^2 \cos^2 \vartheta}} \quad (12b)$$

and $N_{\text{core,clad}} = n_{\text{core,clad}} - ik_{\text{core,clad}}$, are the complex indices of refraction of the core and cladding material. The extinction coefficients $k_{\text{core,clad}}$ are related to the attenuation lengths $L_s^{\text{core,clad}}$ according to

$$k_{\text{core,clad}}(\lambda) = \frac{1}{4\pi} \cdot \frac{\lambda}{L_s^{\text{core,clad}}} \quad (13)$$

where λ denotes the wavelength of the transmitted light. Eq.10 is solved numerically for various l/d - ratios. The results as a function of the extinction coefficient of the cladding material are shown in fig.6. A liquid with an index of refraction of 1.58 is assumed as core material. The extinction coefficient of the glass type 8250 used as cladding material in our investigations is indicated for various wavelengths. According to these results the onset of absorption depends strongly on the l/d - ratio. However, for $k_{\text{clad}} \leq 10^{-7}$, which corresponds to wavelengths larger than about 380 nm in case of 8250 - glass, the transmission is only a weak function of l/d . Even

for $l/d = 5 \times 10^4$, e.g. capillaries of 20 μm diameter and 1 m length, the transmission is about 92.5%, which results in an absorption length of 12.8 m in this configuration. In conclusion, the numerical results show that the transparency of 8250 - glass is sufficient for the proposed application.

5. Systematic studies of light propagation in capillaries

The experimental study of light transport in thin scintillating light guides and in particular the study of the reflectivity of the core/cladding interface, is most conveniently performed by direct excitation of the scintillating core material by a light source with an emission spectrum, which matches the absorption band of the solute. Provided that the incident wavelength is weakly absorbed by the core dopant, the fluorescent photons are created uniformly over the capillary cross-section. In this way the conditions of light injection in the capillary are well defined and correspond closely to the light transport following excitation by minimum ionizing particles.

Investigations of the wavelength dependent transmission losses have been carried out with capillaries of 900 μm , 180 μm and 49 μm inner diameter. For these measurements the 3-HF doped scintillator NE209B with index of refraction $n = 1.58$ was used exclusively. Its properties are described in the following chapter. In practice a small dye concentration was chosen in order to reduce the effective absorption of the scintillator itself, and to ensure a homogeneous light injection in the thinnest capillaries. For UV excitation the light from a high pressure Xe-lamp was collimated into a 3 mm wide and 15 mm high parallel beam traversing either a broadband UV filter (UG11) or alternatively an interference filter centered around 366 nm. The capillaries were illuminated at various distances from the end and the transmitted fluorescence light was recorded with a diffraction grating monochromator/photometer system (PTI 01-002). The photometer was equipped with a Hamamatsu R928 photomultiplier tube.

In order to obtain well defined optical conditions, glass/air reflections were intentionally eliminated by a layer of black varnish covering the last ten centimeters in front of the spectrophotometer. To obtain enough light intensity and to average over a larger sample, the 180 μm and 49 μm capillaries were arranged in ribbons consisting of about 10 and 30 capillaries each. On one end the ribbons were fed into the nozzle of a scintillator-filled syringe, on the other end the capillaries were fitted into a tiny lucite fluid

reservoir, which provided an exit window of optical quality. Once the capillaries were filled, the lucite cuvettes were sealed. Special care had to be taken, that individual capillaries did not cross each other within the measuring range (shadowing) and no scintillator wettened the glass from outside. The thicker 900 μm capillaries were equipped individually with syringe and cuvette.

The results of several measurements are shown in fig.7. After suppression of the reflections at the cladding/air interface single exponential light decay curves were obtained. In case of the 49 μm and 900 μm diameter capillaries a set of measurements has been taken with several different samples. The obtained averaged values of the wavelength dependent attenuation lengths are summarized in table 2. It is interesting to note that the light transmission does not depend strongly on the capillary diameter at a particular wavelength. At 600 nm, where the diluted scintillator is essentially transparent, the result of the 49 μm capillary can be used directly to derive an upper limit for the size of reflection losses. With the formalism described in sect 4 and by setting $L(600\text{ nm})$ equal to L_r one obtains $A \leq 3.4 \times 10^{-5}$ as an upper limit. If the results of the 900 μm diameter capillaries are included one can derive the two unknown parameters A and L_s and obtains $A = 1.0 \times 10^{-5}$ and $L_s = 278\text{ cm}$ at 600 nm. This is a remarkable good result, which proves that thin capillaries can be produced with an excellent quality of the glass/liquid scintillator interface.

6. High refractive index liquid scintillators

For efficient light collection due to total internal reflection the capillaries have to be filled with liquid scintillators based on solvents with an index of refraction chosen as high as possible. Moreover, for thin capillaries fluorescent light emission must occur locally, i.e. at a distance from the ionizing event which is substantially smaller than one fiber diameter. Therefore scintillators with a high molar concentration of dyes are needed. Binary compositions with a solvent and one solute only are favorable. To get a large attenuation length, the most important demand is the high purity of the solvent. In order to avoid self absorption the fluorescent dye should exhibit a large Stokes shift. As an example: to obtain attenuation lengths of about 1m a transmission of about 99%, i.e. an absorption of less than 4% after 1 cm can be tolerated.

The requirement, that the index of refraction of the core material should be higher than the above value of $n=1.49$ for the capillary walls, rules out the

use of standard solvents, like mineral oil, xylene, toluene, or alcohols. In fact a couple of high refractive liquids are known together with suitably matched dyes, as described e.g. in [10,11]. Among those in particular 1-methylnaphtalene (1MN) and 1-phenylnaphtalene (1PN) are interesting solvents with indices of refraction of $n = 1.62$ and $n = 1.66$, respectively. Apart from these, new binary scintillators based on specially purified isopropyl biphenyl (IBP) as solvent have been developed with $n = 1.58$.

Together with a high index of refraction and sufficiently long attenuation length, another important quantity is the energy conversion efficiency of the scintillator which determines the brightness of the active target detector. To measure the light output of the scintillators we applied different methods that gave mutually consistent results. The scintillators were filled into cuvettes and exposed to cosmic ray muons or electrons from ^{90}Sr and ^{106}Ru β -sources. In the latter case the endpoint of the continuous β -spectrum was determined. The cuvettes were optically coupled by a lucite light guide to a photomultiplier with bialkali photocathode. After correcting for different quantum efficiencies the results were compared to that of the standard plastic scintillator NE 102.

a) Liquid scintillators based on 1- methyl- and 1- phenylnaphtalene

We studied systematically the suitability of 1MN and 1PN as solvent with 1-phenyl-3-mesityl-pyrazoline (PMP) as fluorescent solute with a standard concentration of 0.1 mole/liter [12]. For methylnaphtalene we used two different samples, 1MN (a) produced under laboratory conditions involving several purification steps [13] and 1MN (b) of the purity grade delivered by industry. The emission spectrum of PMP together with the transmission measured for 1 cm of traversed scintillator 1MN (a) in a cuvette is shown in fig.8a. The highest light output is found for 1MN (a)/PMP. With roughly 10 photons/keV it equals that of the plastic scintillator NE 102. The other two mixtures still give reasonable results with about 2/3 of the above value (table 3).

The measured extinctions for the three solvents are shown in fig.10 as a function of wavelength. As one can see, all three liquids still contain impurities. The corresponding absorption decreases with increasing wavelength. In the interesting region between 400 nm and 500 nm the best result is found for 1MN (a) produced in the laboratory with special care for high purity. Without special precaution however the liquid rapidly deteriorates. For 1MN (a)

we found e.g. after 9 weeks under normal conditions (air, daylight) an increase of the extinction of about 60%. However keeping the same liquid sealed in a blackened capillary no degradation was observed after 3 months.

From fig.10 it is evident, that the emission spectra of the scintillators will depend on the distance between excitation point and light detection. To investigate this effect, we used a capillary of 1 m length and 3 mm diameter filled with our liquids and coupled to the spectrometer. The scintillator was excited transversely at different distances by UV-light of 365 nm at increasing distance from the spectrometer. At small distances the maxima of intensity are at about 430 nm for all liquids. The resulting integral attenuation lengths are summarized in table 3. As expected from the considerations above, the best value is found again for 1MN (a)/PMP with $L_s = 40$ cm. Due to the larger impurities values smaller by a factor 2 to 4 are found for the industry grade 1MN (b) and 1PN solvent mixtures.

At the moment the only commercially available scintillator based on 1-methylnaphtalene is the experimental scintillator "Bicron B" manufactured by BICRON [14]. The emission spectrum peaks around 500 nm and is shown together with the transmission in fig.8b. The scintillator shows excellent transmission above 480 nm. The integral attenuation was measured with a PIN diode as $L_s = 110$ cm, and a high light yield of 7.5 photons/keV was found in cosmic ray and β -source measurements (table 3).

b) Liquid scintillators based on isopropyl biphenyl

The new experimental scintillators, NE 209A and NE 209B manufactured by Nuclear Enterprise [15], are loaded with BBQ (0.06 mol/liter) and 3-hydroxy flavone (3-HF, 0.08 mole/liter), with emission spectra peaking around 505 nm and 540 nm, respectively. In both cases the dye absorption bands overlap with the biphenyl emission band ranging from around 300 nm to 350 nm. The emission spectra together with the absorption measured for 1 cm of traversed scintillator in a cuvette is shown in fig.9a and b.

Again the transmission of the liquids has been measured as a function of wavelength in capillaries of various diameters. As is apparent already from the absorption/emission spectra, the large Stokes shift in the 3-HF based scintillator makes this liquid transparent to its own fluorescent light. This results in integral absorption lengths of about $L_s = 80$ cm measured with a

PIN diode. For the BBQ doped scintillator we obtain accordingly $L_s(510\text{ nm}) = 18\text{ cm}$ at the peak of emission and $L_s(540\text{ nm}) = 54\text{ cm}$ in the upper half of the emission band. At longer wavelengths above 600 nm we find attenuation lengths of several meters for both mixtures.

In the case of IBP the observed finite absorption lengths and their dependences on wavelength are entirely due to the presence of fluorescent dyes. Measurements of the transmission of the unloaded, pure solvent gave a lower limit of $L_s \geq 180\text{ cm}$ at 540 nm. The light yields obtained for both scintillators are 7.0 and 6.8 photons/keV for NE 209A and B respectively (table 3).

7. Locality of light emission

For all scintillators investigated here, the dye concentrations are chosen high enough to produce local light emission. Given the decadic molar extinction coefficients of $\epsilon = 1.17 \times 10^4\text{ liter mole}^{-1}\text{cm}^{-1}$ for BBQ and $7.8 \times 10^3\text{ liter mole}^{-1}\text{cm}^{-1}$ for 3-HF in the range of the solvent emission spectra one can calculate together with the above quoted molar dye concentrations absorption lengths of $L_s = 1/(\epsilon \cdot c \cdot \ln 10)$, i.e. 6 μm and 7 μm for NE 209A and NE 209B, respectively. In case of the 3-HF doped scintillator this value has been confirmed experimentally by UV- transmission measurements (340 nm) with 20 μm and 40 μm thin films of liquid. The light yield in this range of very high dye content is concentration independent, as could be shown in separate measurements with MN/PMP and IBP/3HF (fig.11).

At the high dye concentrations involved, it is expected that the dominating mechanism of energy transfer from solvent to solute will be non-radiative, i.e. via dipole-dipole interactions known as Foerster-transfer [16]; the range is of typical intermolecular distances. Therefore the determined absorption length from UV-light transmission can be considered as an upper limit for the locality of solvent-solute.

8. Conclusions

In view of our design goal, i.e. the construction of a massive high resolution tau-neutrino vertex detector, a target based on capillaries filled with liquid

scintillator constitutes a very promising technique. In particular we could show, that

- glass capillaries can be produced with appropriate inner diameters down to 20 μm .
- the glass scintillator interface can be prepared with reflection losses smaller than 1 part in 10^5 , which in turn ensures excellent light transmission in 1 m long light guides with diameters as small as several tens of microns.
- a well established production technology for rigid coherent capillary bundles exists, which allows also the introduction of extramural absorber material for cross-talk suppression.
- suitable liquid scintillators are available with high refractive index and large Stokes shift.
- some of these liquid scintillators can be produced already with sufficient purity and good enough light yield to be operated as an active core medium in thin capillaries.

Investigations with targets of coherent capillary bundles are presently carried out in a pion test beam at CERN. The results will be described in a forthcoming paper.

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Figure Captions

- Figure 1** Spectral transmission of Schott glass 8250 for 1 mm and 8 mm thick samples. The data have still to be corrected for Fresnel losses of about 7.7%.
- Figure 2** View of the endface of a coherent capillary bundle. The inner diameter of individual capillaries is 20 μm , the outer diameter is 27.5 μm . The pore area is 58% of the total and includes the wedges.
- Figure 3** Definition of geometrical quantities needed to describe light propagation in a cylindrical step index fiber. ρ is the distance of the light emission point P from the fiber axis in units of the core diameter, φ is the azimuthal angle of the direction of light emission in the plane orthogonal to the fiber axis and ϑ is the polar angle with respect to the fiber axis.
- Figure 4** Number of reflections n_{ref} of trapped light rays in a cylindrical fiber as obtained by Monte Carlo simulation. n_{ref} is given per unit of length along the fiber axis. The unit of length is defined as the fiber diameter. Only light rays are considered, which do not undergo total reflection at the exit window.
- Figure 5** Light transmission in cylindrical fibers as a function of reflection losses. A is the surface loss coefficient per reflection. The capillary length is expressed in units of the capillary diameter, e.g. $\ell/d = 5 \cdot 10^4$ corresponds to a 1 m long capillary of 20 μm diameter.
- Figure 6** Transmission of liquid filled capillaries as function of the extinction of the wall glass material. For the core material we assume $n = 1.58$ and perfect transparence. The cladding material is Schott 8250 glass and the corresponding extinction is indicated for various wavelengths. Parameter is ℓ/d , where ℓ is the length of the capillary and d the diameter. The calculation has been done in the meridional ray approximation.
- Figure 7** Wavelength dependent attenuation lengths recorded following UV excitation of capillaries of various inner diameters. The capillaries were filled with Isopropyl biphenyl and a small 3HF dye concentration to assure homogeneous light injection. The figure shows for each fiber diameter one typical measurement. Results of individual measurements are affected by bundle preparation, cleanliness of inner surfaces, etc. The averaged values for a set of measurements are given in Table 2.

- Figure 8** Absorption and emission spectra for two experimental liquid scintillators based on 1 Methylnaphtalene (1MN) as solvent. The scintillators are binary compositions a) is loaded with PMP (0.1 mole/litre, b) is a commercial product from Bicron Corp. ("Bicron B") with unspecified dye. The absorption is given for an optical path of 1 cm traversed in the respective scintillator.
- Figure 9** Absorption and emission spectra for two experimental liquid scintillators based on Isopropyl biphenyl (IBP) as solvent and a) with BBQ (0.06 mole/litre), and b) 3HF (0.08 mole/litre) as fluorescent dyes.
- Figure 10** Wavelength dependent absorption for three pure solvents. 1MN(a) has been specially purified, whereas 1MN(b) and 1 Phenyl naphtalene (1PN) are industry grade products. The absorption is quoted for an optical path of 1 cm traversed in the respective liquids.
- Figure 11** Dependence of scintillator light yield on fluorescent dye concentration.

Table 1

Physical properties of the capillary glass
Schott 8250 under investigation.

density	2.28 g/cm ³
radiation length	12.4 cm
refractive index	1.487
thermal expansion	5.10 ⁻⁶ K ⁻¹
transformation temperature	492°C
softening point	715°C

Table 2

Attenuation length L as a function of capillary
diameter and wavelength of the transported
light. The indicated values are averaged over
several measurements using different capillary
samples.

diameter	L(600nm)	L(540nm)	L(510nm)
49µm	215 ± 37cm	141 ± 10cm	115 ± 10cm
900µm	283 ± 19cm	171 ± 10cm	114 ± 6µm

Table 3

Properties of various liquid scintillators
described in the text.

Solvent	Ref. index	Solute	Concentr. [mole/l]	Lightyield [N _γ /keV]	Atten. length [m]
1 MN(a)	1.62	PMP	0.1	9.8	0.40
1 MN(b)	1.62	PMP	0.1	6.5	0.25
1 PN	1.66	PMP	0.1	7.2	0.11
IBP	1.58	3HF	0.08	6.8	0.80
IBP	1.58	BBQ	0.06	7.0	0.50
Bicron B	1.62	X	X	8.7	1.10

fig.1

fig.2

fig.4

fig.3

fig.5

fig.6

fig.7

fig.8

fig.9

fig.10

fig.11