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DEVELOPMENT OF NEW SCINTILLATING FIBER DETECTORS FOR HIGH ENERGY PHYSICS APPLICATIONS

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SUMMARY

We have been developing new scintillating fiber detectors for colliding beam and fixed target applications. In this paper, we present initial results from a developmental study of high refractive index, liquid scintillators, and the incorporation of these liquids into glass capillaries. Advantages of liquid-in-capillary fiber detectors include: high efficiency and fast decay; the potential for high-resolution tracking as light emission is expected to be local to the deposited ionization in liquids containing single solutes; the potential for good radiation resistance; and replaceability.

INTRODUCTION

Scintillating fiber detectors are being actively developed and utilized for tracking and calorimetric applications. The conventional materials utilized for tracking devices have included coherent plates of scintillating glass fibers [1, 2], coherent plates of polystyrene scintillating fibers [1, 3], and single strand fibers of polystryene based scintillators [4]. In this paper, we present initial results on the development of liquid scintillators which, when contained in glass capillaries, offer the prospect of yielding high resolution and high efficiency scintillating fiber detectors [5].

The requirements that scintillation liquids must satisfy to be suitable media for high resolution tracking are:

1. The refractive index of the liquid should be as high as possible, so that light trapping by total internal reflection will be as efficient as possible.

2. The scintillation liquid should contain only a single solute (dye) and preferrably one with a large Stokes' Shift, to minimize self absorption effects in the material.[6]

3. The scintillation liquid should have high quantum effiency and fast decay.

4. The material should be radiation resistant.

HIGH REFRACTIVE INDEX LIQUIDS

In order to make a fiber-optic waveguide, one must have a guide structure in which the core material has higher refractive index than the cladding material. The refractive indices of borosilicate glasses used for cladding are typically in the range 1.47 - 1.49. For purposes of our present study, glass capillaries have been used which have $n = 1.49$.[7] Hence the refractive index of a scintillating liquid core material must exceed this value. This immediately rules out the use of such standard scintillation solvents as: benzene, xylene, and toluene, each of which has a refractive index near $n = 1.50$; alcohols such as ethanol and methanol, for which $n < 1.4$; and mineral oil with $n = 1.47$.

We have therefore attempted to identify potentially interesting, high refractive index liquids which could serve as scintillator solvents. A partial listing of candidates is given in Table I.

TABLE I
HIGH REFRACTIVE INDEX LIQUIDS

MATERIAL	INDEX
benzonitrile	1.527
benzyl alcohol	1.545
3phenylpyridine	1.616
1methylnaphthalene	1.617
2-(p-Tolyl)pyridine	1.617
2phenylpyridine	1.623
1phenylnaphthalene	1.664

Of these materials, the high refractive index of 1phenylnaphthalene offers the greatest light trapping capability. [For comparison, the refractive index of polystyrene is 1.59.] As we show below, in addition to its desirable high refractive index, the 1phenylnaphthalene has also yielded very efficient scintillation solutions as well.

SCINTILLATION EFFICIENCY AND FLUORESCENCE PROPERTIES

Our ultimate goal has been to create efficient liquid scintillation "cocktails" which are binary in construction. These incorporate single dyes with a given solvent. This choice is motivated by the desire to create efficient fiber detectors with small cross section (25μm-50μm) while maintaining good optical attenuation length properties (meter or greater lengths). This requirement is not satisfied by conventional multi-dye scintillators which incorporate wave shifting to achieve simultaneously good efficiency and good attenuation length.

To select suitable dye candidates, we have required the following properties: the quantum efficiency of the dye should be high; the spectral characteristics of the dye should be appropriately matched to those of the solvent as suggested by Forster transfer [8], and the molar extinction coefficient of the dye should be high in the overlap region between solvent emission and dye absorption; the Stokes' shift for the dye should be as large as possible, so that potential reabsorption of the dye fluorescence by dye and solvent molecules is kept to a minimum.

Of the liquid solvents listed above, we report here initial measurements with benzyl alcohol (BA), 1methylnaphthalene (1MN), 3 phenylpyridine (3PP), and 1phenylnaphthalene (1PN) . Studies of benzonitrile have been deferred because of its low refractive index. 2phenylpyridine and 2-(p-Tolyl)pyridine were brownish-colored liquids as received from the manufacturer and hence further purification of these materials is essential before useful studies can proceed. For purposes of initial measurements, the solvents (BA, 1MN, 3PP, and 1PN) were used as directly received from the manufacturer without additional purification and without concern for oxygenation.[9] More sophisticated handling and control procedures will be utilized in upcoming measurements.

In Figure 1, we show fluorescence excitation and emission spectra for 1MN and 1PN, as obtained from thin film measurements at 90^{o} using a SLM spectrophotometer. In Figure 2 are shown the excitation and emission spectra for one of the dyes, Coumarin 522, in saturated solutions of 1MN and 1PN (dye concentration is less than or equal to 1% by weight). Again fluorescence spectra are determined from thin film measurements at 90^{o} using an SLM spectrophotometer. Dyes were selected which provided good spectral overlap with the solvents, substantial Stokes' Shift, and good fluorescence quantum efficiency.

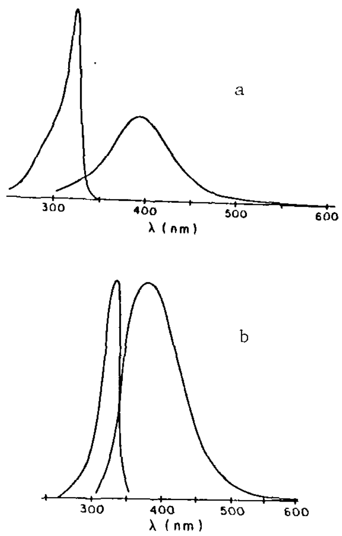

Figure 1: Excitation and emission spectra for:
(a) 1methylnaphthalene; (b) 1phenylnaphthalene.

In Table II are listed the spectral characteristics of saturated solutions of single fluorescent dyes in the solvents discussed above. The last column of the table indicates the scintillation efficiency of the solutions, normalized to Bicron 501 [10]. Scintillation efficiencies were measured using a ^{90}Sr source, which was used to excite liquid samples of approximately 2cc volume contained in quartz cuvettes. The cuvettes were placed in optical contact with a Hamamatsu R1104 PMT using Corning Q2-3067 optical couplant.. [The relative quantum efficiency measurements have not been corrected for S20 cathode response of the photomultiplier.] Excellent scintillation efficiency is observed for numerous dyes in the 1phenylnaphthalene - even dyes with large Stokes' Shifts such as PMP [11], BPD [12].

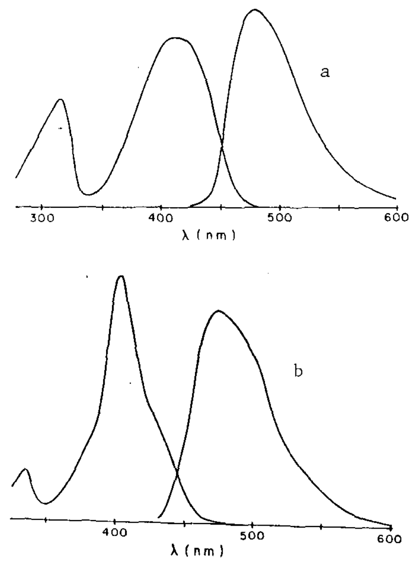

Figure 2: Excitation and emission spectra of saturated solutions of Coumarin 522 in (a) 1methylnaphthalene and (b) 1phenylnaphthalene.

In Table III are listed fluorescence decay times for selected materials. The measurements were performed using a YAG laser spectrometer, and decay times measured at the peak of fluorescence emission for a given solution (refer to Table II). The decay times are in the few nanosecond range, and are consistent with single exponentials. During these measurements, we did not observe obvious slow components; additional measurements will be performed to determine whether or not such components are present at a low level.

OPTICAL ATTENUATION LENGTH

Initial measurements of optical attenuation length are underway using 1mm diameter, liquid-filled, glass capillaries. Again light is detected with a R1104 PMT with S20 photocathode. Excitation of the scintillator is by ^{90}Sr source. For a saturated solution of Coumarin 522 in 1phenylnaphthalene, we observe an attenuation length of approximately 75cm. We expect that this value should improve with care to remove oxygen from the liquid and perhaps with refinements in the fabrication of the capillaries themselves.

DISCUSSION AND CONCLUSIONS

Liquid scintillators hold great promise as fast, efficient, radiation-hard, and replaceable media for tracking and calorimetric detectors. Fluorescence efficiency is competitive with the best plastic scintillation materials, and the solutions are easily prepared. Solutions of very high refractive index are possible, making them attractive candidates for the core materials in capillaries.

TABLE II

PROPERTIES OF LIQUID SCINTILLATION MIXTURES

SOLVENT	SOLUTE	n_{solv}*	λ_{ABS}(max)	λ_{EM}(max)	REL.EFF.
1PN	C522	1.664	400nm	470nm	1.0
1PN	C485	1.664	400nm	460nm	1.0
1PN	C540A	1.664	420nm	480nm	1.0
1PN	TPB	1.664	380nm	450nm	.85
1PN	DPH	1.664	360nm	430nm	1.0
1PN	3-HF	1.664	370nm	530nm	.73
1PN	2,2HBT	1.664	360nm	520nm	.47
1PN	2,2H5MBT	1.664	360nm	525nm	.43
1PN	2,2HBO	1.664			.55
1PN	2,2H5MBO	1.664			.55
1PN	DMANS	1.664	460nm	590nm	.77
1PN	DCM	1.664	460nm	575nm	.52
1PN	PMP	1.664	360nm	430nm	1.09
1PN	DPA	1.664			1.09
1PN	BPD	1.664	365nm	500nm	.82
BICRON 501 (for comparison)				425nm	.98
1MN	C522	1.616	415nm	480nm	.75
1MN	C485	1.616	400nm	470nm	.78
1MN	C540A	1.616	410nm	480nm	.70
1MN	TPB	1.616	375nm	450nm	.52
1MN	DPH	1.616	390nm	430nm	.80
1MN	3-HF	1.616	360nm	530nm	.60
1MN	2,2HBT	1.616	350nm	520nm	.32
1MN	2,2H5MBT	1.616	460nm	530nm	.34
1MN	2,2HBO	1.616	330nm	480nm	.44
1MN	2,2H5MBO	1.616	320nm	500nm	.40
1MN	DMANS	1.616	470nm	620nm	.62
1MN	DCM	1.616	475nm	580nm	.41
1MN	PMP	1.616	325nm	430nm	.99
BA	C522	1.540	400nm	510nm	.60
BA	C485	1.540	390nm	510nm	.42
BA	C540A	1.540	460nm	530nm	.50
BA	TPB	1.540	360nm	440nm	.30
BA	DPH	1.540	360nm	430nm	.50
BA	B-PBD	1.540	330nm	360nm	.66
BA	3-HF	1.540	360nm	530nm	.36
BA	2,2HBT	1.540	390nm	450nm	.35
BA	2,2H5MBT	1.540			.24
BA	2,2,6DBT	1.540			
BA	2,2HBO	1.540	360nm	430nm	.26
BA	2,2H5MBO	1.540	380nm	440nm	.27
BA	DMANS	1.540	470nm	610nm	.22
BA	DCM	1.540	460nm	610nm	.29
BA	PMP	1.540	330nm	450nm	
3PP	C522	1.616	420nm	480nm	.38
3PP	C485	1.616	400nm	440nm	.39
3PP	C540A	1.616	420nm	500nm	.36
3PP	TPB	1.616	370nm	450nm	.31
3PP	DPH	1.616	370nm	430nm	.37
3PP	3-HF	1.616	370nm	550nm	.31
3PP	2,2HBT	1.616	360nm	520nm	.23
3PP	2,2HBO	1.616	380nm	480nm	.29
3PP	DMANS	1.616	470nm	620nm	.34
3PP	DCM	1.616	470nm	600nm	.26
3PP	B-PBD	1.616	320nm	380nm	.37

*Solvent refractive index measured at 580nm and quoted from Manufacturer catalog.

TABLE III

FLOURESCENCE LIFETIMES OF SELECTED LIQUID SCINTILLATOR SOLUTIONS

MATERIAL	LIFETIME (τ)
1PN/C522	6.52ns
1PN/C485	6.97ns
1PN/TPB	3.87ns
1PN/3-HF	5.13ns
1MN/C522	3.24ns
1MN/TPB	4.74ns
1MN/3-HF	3.88ns
BA/C522	6.25ns
BA/TPB	4.52ns
BA/3-HF	2.73ns
PS/TPB	4.71ns
PS/3-HF	5.73ns

1PN	1-phenylnapthalene
1MN	1-methylnapthalene
BA	benzyl alcohol
3PP	3-phenylpyridine
2PP	2-phenylpyridine
2pTP	2-(p-tolyl)pyridine
PS	polystyrene (polyvinylbenzene)
PVT	polyvinyltoluene
PMMA	poly(methyl methacrylate)
C522	Coumarin 522
C485	Coumarin 485
C540A	Coumarin 540A
TPB	1,1,4,4-tetraphenyl-1,3-butadiene
DPH	1,6-diphenylhexatriene
DPA	9,10-diphenylanthracene
B-PBD	butyl-PBD
DMANS	4-dimethylamino-4'nitrostilbene
DCM	4-(dicyanomethylene)-2-methyl-6-(p-dimethyl-aminostyryl)-4H-pyran
3-HF	3-hydroxyflavone
2,2HBT	2-(2'-hydroxyphenyl)-benzothiazole
2,2H5MBT	2-(2'-hydroxyphenyl-5'-methyl)-benzothiazole
2,2,6DBT	2-(2',6'-dihydroxyphenyl)-benzothiazole
2,2HBO	2-(2'-hydroxyphenyl)-benzoxazole
2,2H5MBO	2-(2'-hydroxyphenyl-5'-methyl)-benzoxazole
BPD	2,2'-bipyridyl-3,3'-diol
DMPOPOP	dimethyl-POPOP
PMP	1-phenyl-3-mesityl-pyrazoline

Our initial measurements have been performed with capillaries of 1mm diameter borosilicate glass . We now have 50μm and 25μm diameter capillaries in hand, which will allow us to extend our measurements of the characteristics of liquid-in-capillary detectors to strructures having very small cross sections.

Important extensions of this program include: the continued development of new scintillation mixtures; purification and oxygen-control procedures in scintillation liquid preparation and handling; systematic measurements of the behavior of these liquid materials when exposed to high levels of radiation; and the development of radiation-resistant glass cladding materials to replace the borosilicate glass cladding. On this latter point, we are exploring the use of Cerium glasses of low refractive index as radiation-hard capillary material. Previously, we have reported the use of Cerium glasses as scintillating fiber-optic plates (SFTs) for use in high-resolution charged particle tracking applications. [1,13] We are now seriously considering the use of these materials for their radiation resistance properties, rather than scintillation properties.

ACKNOWLEDGEMENTS

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4. R.E. Ansorge, et al, Nuclear Instruments and Methods, **A265**, (1988) 33-49, and J. Alitti, et al, "Performance of the Scintillating Fiber Detector in the Upgraded UA2 Detector, CERN-EP/88-126 (1988).
5. The suggestion and demonstration that liquid-in-capillary devices are useful for particle tracking is due to D. Potter. See the Proceedings of the Workshop on New Solid State Devices for High Energy Physics, Lawrence Berkeley Laboratory, October, 1985, LBL-22778, CONF-8510364, UC-25.
6. For large diameter (1mm) capillary detectors scintillation cocktails with multiple solutes are preferable. The single dye (binary) solution is only necessary for small diameter devices (below a few hundred microns).
7. In principle, capillaries could be formed from materials other than glass - for example plastics and Teflon.
8. An excellent review of the Forster Mechanism and relevant calculations may be found in I. B. Berlman, *Handbook of Fluorescence Spectra of Aromatic Molecules*, Academic Press (1971).
9. The presence of oxygen often leads to a reduction in fluorescence emission from liquid solutions and is usually controlled by bubbling N_2 through the liquid.
10. Bicron 501is a standard liquid scintillator with light output 80% that of anthracene. The decay time of the short component is 3.3 nsec for this material.
11. See H. Gusten and W. Seitz, "Novel Primary Solutes for Liquid Scintillation Counting", in *Liquid Scintillation Counting, Recent Applications and Development, Volume 1 Physical Aspects*, Peng, Horrocks, and Alpen, eds., Academic Press (1980). The use of PMP has also been advocated by the CERN/LAA collaboration (H. Leutz, et al) for use in polystyrene.
12. The dye BPD is a potentially interesting material with large Stokes' Shift and fluorescence emission near 500nm. See H. Langhals and S. Pust, Chem. Ber. **118**, (1985) 4674-4681.
13. See references in R. Ruchti, et al, IEEE Transactions on Nuclear Science, **NS-31**, (1984) 69-73.