APPENDIX II

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physics department
university of notre dame

LIQUIDS-IN-CAPILLARIES

NEW FIBER DETECTORS FOR HIGH ENERGY PHYSICS APPLICATIONS*‡

B. Baumbaugh, A. Bose, T. Ditmire, C. Kennedy, D. Puseljic, R. Ruchti, and J. Ryan
Department of Physics, University of Notre Dame, Notre Dame, IN 46556

A. Baumbaugh and K. Knickerbocker
Fermi National Accelerator Laboratory, Batavia, IL 60510

J. Ellis, R. Mead, and D. Swanson
Collimated Holes, Inc., Campbell, CA 95008

Presented by R. Ruchti

ABSTRACT

We are developing scintillating-fiber detectors incorporating organic liquid scintillation cocktails in glass capillaries. The organic solvents have high refractive index, making them suitable as core materials for scintillation waveguides. Only one fluorescent dye at high concentration (1%) is utilized in the solution. This ensures that the dominant energy transfer between solvent and solute will be nonradiative, and that fluorescent emission from the dye will be local to the ionization deposition in the material. Hence such structures might be suitable for high resolution tracking devices. Liquid scintillation solutions may also provide advantages in radiation resistance and replaceability.

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INTRODUCTION

Scintillating fiber detectors are being actively developed and utilized for tracking and calorimetric applications in particle physics. 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 and ribbons of polystyrene-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].

We are particularly interested in tracking and micro-vertex applications. To be suitable media for such applications, scintillation liquids must satisfy the following criteria:

1. The refractive index of the liquid should be considerably greater than that of conventional borosilicate glasses. The greater the liquid index, the greater the percentage of light trapping by total internal reflection.

2. The scintillation liquid should contain only a single solute (dye) in large concentration (of order 1%) so that energy transfer between solvent and dye will be non-radiative [6]. The dye should have large Stokes' Shift, so that self-absorption effects in the scintillation medium are minimized over the emission spectrum of the dye.

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

4. The liquid scintillator should be radiation resistant.

SCINTILLATION MATERIALS

In order to make a useful fiber-optic waveguide, one must have a guide structure in which the core material has a higher refractive index than the cladding material. Table I indicates the range of refractive indices available in currently used scintillation materials. As can be seen from the table, liquids should have $n > 1.52$ to be of any use as core materials.

TABLE I
SCINTILLATION WAVE GUIDE MATERIALS

GLASS SCINTILLATORS	GS1/2 CORE	n = 1.56
	CLAD: GLASS	n = 1.467 - 1.49
PLASTIC SCINTILLATORS	POLYSTYRENE	n = 1.59
	CLAD: PMMA or VINYL ACETATE	n = 1.46 - 1.49
GLASS SCINTILLATORS	CORE LIQUID	n (core) > n (clad)
	CLAD: GLASS	n = 1.49 - 1.52

As Table II indicates, conventional solvents for liquid scintillation cocktails have refractive indices which are too low to be useful as core materials for waveguides.

TABLE II
REFRACTIVE INDICES OF CONVENTIONAL LIQUIDS

MATERIAL	REFRACTIVE INDEX*
Benzene	< 1.50
Toluene	< 1.50
Xylene	< 1.50
Ethanol	< 1.40
Methanol	< 1.40
Mineral Oil	1.47

*catalogue values

Therefore we have attempted to identify potentially interesting, high-refractive-index liquids which could serve simultaneously as suitable scintillator solvents and suitable core materials for liquid-in-capillary devices. Table III indicates a partial listing of such solutions.

TABLE III
HIGH REFRACTIVE INDEX LIQUIDS

MATERIAL	REFRACTIVE 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

*catalogue values

Of these materials, the high refractive index of the 1phenylnaphthalene affords the greatest light trapping capability. As will be shown below, this compound has also yielded the highest efficiency scintillation solutions that we have prepared and tested.

SCINTILLATION EFFICIENCY AND FLUORESCENCE PROPERTIES

Our objective has been to create efficient, liquid scintillation "cocktails" which are binary solutions, incorporating a single dye with a given solvent. This choice is motivated by the desire to create efficient fiber detectors with small cross section (25-50 microns) while maintaining good optical attenuation length properties (meter or longer lengths). This requirement is not satisfied by conventional ternary scintillators which incorporate wave-shifting from primary to secondary dyes to achieve simultaneously high efficiency and long attenuation length.

Of the liquid solvents listed in Table III above, we report here initial measurements with benzyl alcohol (BA), 1methylnaphthalene (1MN), 3phenylpyridine (3PP), and 1phenylnaphthalene (1PN). Studies of benzonitirile have been deferred because of its relatively low refractive index. The 2-(p-Tolyl)pyridine and 2phenylpyridine were brownish-colored liquids as received from the manufacturer - and could not be studied without further, signficant purification. For purposes of the initial measurements reported here, the solvents (BA, 1MN, 3PP, and 1PN) were used as directly received from the manufacturer - without additional purification and without concern for oxygenation [7]. More sophisticated handling and control procedures will be utilized in upcoming measurements.

In Table IV are shown a list of solvents and fluorescent dyes which have been used in our fluorescence measurements, plus acronyms which we have employed to label the scintillation solutions listed in Tables V and VI.

TABLE IV
ACRONYMS FOR SOLVENTS AND DYES

1PN	1-phenylnaphthalene
1MN	1-methylnaphthalene
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

In Table V are listed the spectral characteristics of saturated solutions of binary liquid scintillators. The last column of the table indicates the scintillation efficiency of the solutions relative to Bicron 501, which is a ternary scintillator with light output 80% that of Anthracene. The 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 quantum efficiency measurements have not be corrected for the S20 cathode response of the photomultiplier. Excellent scintillation efficiency is obtained for numerous dyes in the naphthalene solutions, and in particular, the 1PN solutions. Even dyes with large Stokes' shifts such as PMP and BPD produce excellent results.

TABLE V
PROPERTIES OF BINARY LIQUID SCINTILLATORS

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	2,2HSMBT	1.664	360nm	525nm	.43
1PN	2,2HBO	1.664			.55
1PN	2,2HSMBO	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	2,2HSMBT	1.616	460nm	530nm	.34
1MN	2,2HBO	1.615	330nm	480nm	.44
1MN	2,2HSMBO	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-PBO	1.540	330nm	360nm	.66
BA	3-HF	1.540	360nm	530nm	.36
BA	2.2HBT	1.540	390nm	450nm	.35
BA	2.2HSMBT	1.540			.24
BA	2.2.6DBT	1.540			
BA	2.2HBO	1.540	360nm	430nm	.26
BA	2.2HSMBO	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-PBO	1.616	320nm	380nm	.37

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

In Table VI are listed fluorescence decay times for selected materials. The measurements were performed using a YAG laser spectrometer, and decay times were measured at the peak of the fluorescence emission for a given solution (refer to Table V for appropriate wavelengths). 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.

TABLE VI
FLUORESCENCE DECAY TIMES OF SELECTED LIQUID AND PLASTIC SCINTILLATORS

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

OPTICAL ATTENUATION LENGTH

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, and the scintillator is excited using a ^{90}Sr source. For a saturated solution of Coumarin 522 in 1PN, we observe an attenuation length of approximately 75cm. We now have capillaries on hand with diameters in the 25-50 micron range, which will allow us to extend our measurements of the characteristics of liquid-in-capillary detectors to structures of very small cross section.

DISCUSSION AND CONCLUSIONS

Liquid scintillators hold great promise as fast, radiation-hard, replaceable media for tracking a calorimetric detectors. Because of the efficiency and optical transparency of binary liquid solutions, they also may serve as microtracking devices when contained in fiber capillaries of very small cross section. The fluorescence efficiency is competitive or better than the best plastic scintillation materials, and the solutions are easily prepared. Solutions of very high refractive index are possible, allowing for efficient trapping and transport of scintillation light within capillary waveguides.

Important extensions of this program include:

1. The continued development of scintillation solutions.
2. Improved purification and oxygen-control procedures during solution preparation and handling.
3. Systematic measurements of radiation damage.
4. Development of radiation resistant cladding materials.

On the 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 radiation-hard scintillation detectors [8]. We are now seriously considering the use of these materials for their radiation resistance properties, rather than scintillation properties.

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6. For a review of non-radiative transfer and the Forster mechanism, see I. B. Berlman, *Handbook of Fluorescence Spectra of Aromatic Molecules,* Academic Press (1971).

7. The presence of oxygen often leads to a reduction in fluorescence emission from liquid solutions and is usually controlled by bubbling N_2 gas through the liquid.

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