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ANNUAL PROGRESS REPORT
TO
THE U. S. DEPARTMENT OF ENERGY

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FOR A WORK ENTITLED:

SCINTILLATING FIBER DETECTOR DEVELOPMENT FOR THE SSC

UNDER THE DIRECTION OF:

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During the past year, considerable effort has been applied to the development of scintillating fiber detectors in several areas:

1. New scintillation liquids and studies of their fluorescence properties.
2. New fluorescent dyes based on non-intramolecular proton transfer.
3. New dyes based on intramolecular proton transfer.
4. Incorporation of these new dyes in plastic (polystyrene) and liquid scintillation solutions.
5. Development of small cross section glass capillaries for the containment of liquid scintillators.
6. Studies of waveguide characteristics.
7. Studies of image intensifier phosphor screen characteristics.
8. Initial steps to form a collaboration to study the characteristics and develop appropriate new properties of the Solid State Photomultiplier.
9. Construction of a new laboratory at Notre Dame to enhance our capabilities for further measurements and studies.
10. Organization of and execution of a Workshop on Scintillating Fiber Detector Development for the SSC, held at Fermilab, November 14-16, 1988.

We now briefly examine each of these items.

Preprints removed

1. NEW SCINTILLATION LIQUIDS AND STUDIES OF THEIR FLUORESCENCE PROPERTIES.

We have been concerned about the properties of high quantum efficiency, rapid fluorescence decay, radiation resistance, and replaceability of scintillation materials in an SSC environment. Liquid scintillators are a natural choice to meet these objectives whether for calorimetry or tracking. We are studying scintillation liquid solvents which have high refractive index (making them suitable candidates for core materials of scintillation waveguides) and which lead to efficient scintillators. Several liquids have been tested. Of these, the most efficient scintillators have been produced from 1methylnaphthalene and 1phenylnaphthalene - see Table I. The scintillators based on 1phenylnaphthalene have fluorescence yields which exceed 80% of anthracene, and there are a number of such candidates. Hence these materials are more efficient than most other organic scintillators and their fluorescence decay is fast (typically 3-5nsec).

A paper has been published on the initial measurements in IEEE Transactions on Nuclear Science. A preprint is appended here as Appendix I. Further discussion of this work has also presented at the Scintillating Fiber Workshop held at Fermilab, November, 1988 and a paper has been submitted to those proceedings (see Appendix II).

More recently we have developed, in collaboration with J. Kauffman of Philadelphia College of Pharmacy and Medicine, a new synthesis for 1phenylnaphthalene which has led to the production of this material as a water-white liquid of high purity - and thus a reliable scintillation solvent from which additional scintillation studies can proceed.

TABLE I

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.

2. NEW FLUORESCENT DYES BASED ON NON-INTRAMOLECULAR PROTON TRANSFER.

The development of efficient fluorescent dyes depends upon the energy level structure of the molecules of the dye (or dyes) and the solvent material (for example polystyrene). Important here is overlap of the relevant energy levels both for initial energy transfer which is non-radiative (Forster Transfer) and for subsequent radiative transfers between dye molecules.

For tracking applications, the suppression of non-radiative transfers is essential for fibers of small cross section to maintain high effective quantum efficiency while simultaneously minimizing crosstalk. Hence dyes must have large Stoke's Shifts and minimal self-absorption. Among the important materials with these capabilities are PMP, a dye cited as interesting in our original proposal to DOE two years ago, and several new dyes developed in this program based on the structure of POPOP, but with greater solubility and improved energy level matching characteristics. These dyes are designated MOPOM and di-t-butyl-MOPOM. Papers on these materials will be presented at the IEEE Nuclear Science Symposium in San Francisco, in Fall 1989. Summaries of the material properties are included here in Appendices III and IV.

The MOPOM material could replace the combination PBD/POPOP and this development program will be continued further to produce secondary dyes which will shift the MOPOM fluorescence into the yellow, a spectral range where radiation damage effects are much less severe.

Additionally, we are pursuing vigorously the measurement of the properties of a large number of laser dyes incorporated in various binary and ternary solutions. Solvents have included polystyrene, benzyl alcohol, 1methylnaphthalene, 1phenylnaphthalene, and several pyridines (see Appendix I or Table I for measurements of binary solutions). Many of these lead to efficient liquid scintillators, with fluorescence maxima $\lambda_{max} > 400$nm. These potentially useful for scintillation calorimetry.

3. NEW DYES INCORPORATING INTRAMOLECULAR PROTON TRANSFER (IPT).

Dyes which involve intramolecular proton transfer (IPT) between ground and excited states have the potential to provide enormous Stokes' Shifts. Among the most successful of these materials are 3-HF (3-hydroxyflavone) and its derivatives. In this program, we have successfully developed a commercial synthesis for a new dye - one with reasonably high quantum efficiency (at least that of 3-HF) - named 3,3'- bipyridine - 2,2'- diol . [We have labeled it BPD for short.] This material appears to be soluble in polystyrene and in 1phenylnaphthalene and other solvents and is a relatively stable molecular configuration. We are currently attempting further developments based upon this structure. Preliminary measurements have made of the fluorescence properties of this material and are reported in Appendices I, II, and III.

4. INCORPORATION OF NEW DYES IN PLASTIC (POLYSTYRENE) AND LIQUID SCINTILLATION SOLUTIONS.

To be at all useful for experiments, the newly developed dyes must be soluble in plastic and liquid solvents - solvents which are suitable for scintillation "cocktails". The developments include attention to this important aspect. In fact the dye MOPOM has also been synthesized in a more soluble form di-t-butyl-MOPOM and a di-t-amil form is also being considered.

Polar dyes will probably only be useful in solution with benzyl alcohol (or other alcohols). Many salts fall into this category. However the parameter space of possibilities is vast and we are examining as many useful (and potentially fruitful) combinations as we can.

Currently the most promising results have been obtained with:

BPD in polystyrene
BPD in 1phenylnaphthalene
PMP in polystyrene
MOPOM in polystyrene
di-t-butyl-MOPOM in polystyrene
Coumarin 522, 490 and 540 in 1phenylnaphthalene

Additional listings may be found the appendices.

5. DEVELOPMENT OF SMALL CROSS SECTION GLASS CAPILLARIES FOR THE CONTAINMENT OF LIQUID SCINTILLATORS.

Through Collimated Holes, Inc, Campbell, CA, we have had fabricated borosilicate glass capillaries of various cross sections: 25μm, 50μm, 75μm, 100μm, and 1mm. Some of these capillaries were produced with and without extramural absorber (EMA) to help prevent crosstalk between neighboring guides. Attenuation length measurements are currently in progress with liquid scintillation solutions contained in the capillaries. As the refractive index of the glass walls of the capillaries is n = 1.49, it is essential that the liquid within the capillaries have a refractive index substantially greater than this. The most promising material we have found in this regard in 1phenylnaphthalene for which n = 1.66. We have developed a new synthesis for this material through the Philadelphia College of Pharmacy and Science (J. Kauffman), which lowers the cost and provides material of high purity. Studies of the liquid capillaries for tracking and calorimetric applications are being further pursued - in parallel with developments for detectors using plastic (polystyrene) waveguides.

6. STUDIES OF WAVEGUIDE CHARACTERISTICS.

We are studying (currently through Monte Carlo simulation) the dependence upon the cross-sectional profile of a given fiber-optic structure for light transmission in step-index waveguides. We have been modelling square, rectangular, circular, and hexagonal profiles. It appears that, over short distances and for guides with good reflection coefficients between core an cladding, fibers of circular cross section are superior to fibers of square or rectangular crosssection. However for realisitic fiber lengths (~1m for 1mm diameter fibers) and sensible optical attenuation lengths in material - such as a mix of 1% by weight PMP in polystyrene, the light collection is essentially independent of cross sectional profile. These studies are being completed and will be submitted for journal publication shortly.

Among additional aspects under study in this program are effects of cladding thickness on light transmission. These have been delayed in favor of other parts of the program and are about to get underway.

7. STUDIES OF IMAGE INTENSIFIER PHOSPHOR SCREEN CHARACTERISTICS.

We have been studying (via Monte Carlo simulation) the properties of phosphor screens with exponential and power law decay characteristics to try to understand the behavior of cascaded image intensifier stages. A number of screens have been modelled including P47, P46, P24, P15, and P11 screens. We observe a signal rise time which is proportional to the fluorescence decay constant of a given screen and a signal fall time which is a convolution of the number of screens used in cascade.

Varo, Inc. is currently making measurements of screen persistance for slow screens, such as P-20. To study the behavior of fast screens ($\tau < 100$ns) measurements are planned this summer at Notre Dame. Several test screens of P46 and a similar fast screen X3 have been prepared by VARO, Inc. and have been sent to us at Notre Dame for testing. These screens are moderately fast (100ns time constants) making them unlikely candidates for SSC detectors, but we are examining them to see if we can establish a test arrangement for measuring the properties of these screens. Properties of faster screens will then be studied subsequently.

To date only a few candidate materials have been developed which have a chance to be fast enough for SSC applications. These include: BaFBr, BaFCl, and CdS. These materials, particularly the latter, are supposed to provide fast response. Studies are being initiated on these, but we believe that the prospects are unlikely of finding simultaneously the properties of high speed and high efficiency.

8. INITIAL STEPS TO FORM A COLLABORATION TO STUDY THE CHARACTERISTICS AND DEVELOP APPROPRIATE NEW PROPERTIES OF THE SOLID STATE PHOTOMULTIPLIER.

Our current experience suggests that it is unlikely that one will be able to fabricate an image intensifier system which combines the following desirable qualities: high photocathode quantum efficiency for long wavelengths ($\lambda > 500$nm), high speed of response (few nanoseconds), high gain sufficient for single photon counting, and high spatial resolution. Hence we have been actively seeking alternatives to the vacuum image intensification structure. The best prospect to satisfy all of the above criteria is the solid state photomultiplier (SSPM) developed by Rockwell International Science Center. M. Atac of Fermilab/UCLA has developed contacts with Rockwell, and we are participating in discussions directed at forming a multi-institutional collaboration to incorporate the SSPM devices with scintillating fibers. Considerable effort is underway to generate a proposal to DOE to seek funds for this developmental program.

The fundamental advantages of the SSPM are: ultra-high quantum efficiency (80%) for light at visible wavelengths; speed (rise time of 5 nsec possible with appropriate impedance matching); high gain (2×10^4); and high resolution (the device can be fabricated like an areal CCD or linear CCD with conventional pixels. The device must be operated at 7° K in order to achieve appropriate operation and hence must be situated in a cryostat.

We hope to obtain operational, hands on skills with discrete forms of the SSPM by the end of June, 1989 and to initiate tests of scintillation materials and fibers with these SSPM structures.

9. CONSTRUCTION OF A NEW LABORATORY AT NOTRE DAME TO ENHANCE OUR CAPABILITIES FOR FURTHER MEASUREMENTS AND STUDIES.

The University of Notre Dame has completely rebuilt our SSC Detector Development Laboratory during the spring of this year. The work has taken approximately 15 weeks to complete. Final installation of hoods and laminar flow benches is in progress. This investment should pay great dividends in providing first-rate laboratory space for the further R & D work on scintillation materials, fiber detectors, and image amplification structures which we have planned. Approximately $60,000 was contributed by the University to the renovation and upgrade.

10. Organization of and execution of a Workshop on Scintillating Fiber Detector Development for the SSC, held at Fermilab, November 14-16, 1988.

The principal investigator of this contract was the principal organizer and chairman of a workshop on scintillating fiber detector development for the SSC held at Fermilab in November of 1988. Approximately 200 individuals representing U.S. and foreign universities and national laboratories as well as representatives of industry, both national and international, convened for three days of discussion and presentations on the latest research and development on the properties of scintillation materials - plastics, liquids, glasses, and inorganic materials. The status of scintillating fiber technology and the status of scintillation amplification and imaging systems were reviewed. In addition, reviews of physics issues and summaries of current experiments incorporating scintillating fiber devices were also included in the program. Finally, substantial time was included for discussion of radiation resistance of these materials and the prospects for improvements and further developments in this area.

The proceedings of the workshop have been submitted to the U.S. Government Printing Office. The proofs are expected by early June, 1989 with publication of the two volume set (over 1100 pages in all) in early July. The proceedings of this important meeting will be distributed world wide.

SUMMARY REMARKS

It has been an extremely busy year for the Notre Dame group, given the many aspects of our program as indicated above, and it should be noted that several graduate students (C. Kennedy and D. Puseljic) and several undergraduate students (A. Bose and T. Ditmire) have made substantial contributions to the program as part of their research duties. We are looking forward with enthusiasm and optimism with hopes of a very rewarding and successful year to come.

Respectfully submitted,

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