Neutron Spectrometer for Improved SNM Search

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Abstract

With the exception of large laboratory devices with very low sensitivities, a neutron spectrometer have not been built for fission neutrons such as those emitted by special nuclear materials (SNM). The goal of this work was to use a technique known as Capture Gated Neutron Spectrometry to develop a solid-state device with this functionality. This required modifications to trans-stilbene, a known solid-state scintillator. To provide a neutron capture signal we added lithium to this material. This unique triggering signal allowed identification of neutrons that lose all of their energy in the detector, eliminating uncertainties that arise due to partial energy depositions. We successfully implemented a capture gated neutron spectrometer and were able to distinguish an SNM like fission spectrum from a spectrum stemming from a benign neutron source.

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1. Overview

The goal of this project is to build a new type of neutron spectrometer for the detection of Special Nuclear Materials (SNM), utilizing a lithium-loaded organic scintillator.

Why have neutrons not been studied as intensively for the search for nuclear materials? Until very recently, the only available single instrument neutron detectors were neutron counters[1]: detectors that can sense neutrons but cannot determine their energy distribution. Without the ability to determine the energy of the neutrons, it can be shown that neutron counters—while useful—have a very limited ability to detect SNM before its signal becomes indistinguishable from the background. Also, neutron counters are sensitive to benign non-fission neutron sources that are capable of creating false alarms. Figure 1 shows a fission spectrum, a fingerprint of SNM, compared to the neutron background and an example of a benign source, an americium-beryllium (AmBe) neutron source.
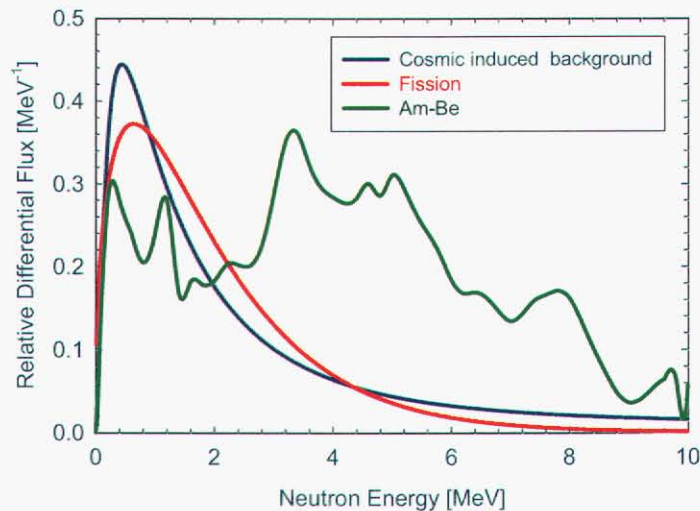

Figure 1: Comparison of different neutron spectra. Fission and americium-beryllium are calculated, while the background is estimated from experiments in the literature.

In contrast to neutron detectors, practical gamma-ray spectrometers have been around for more than 50 years (since the invention of the NaI (Tl) scintillation spectrometer by Hofstadter in 1948) and have been extensively studied in their use for SNM search. It is not an exaggeration to state that the situation with neutron detectors today is analogous to gamma-ray detectors in the late 1940's. Only two practical methods for measuring neutron spectra are currently under development: neutron scatter cameras and capture gated spectrometers, described here. Neutron scatter cameras look very promising because they simultaneously measure the angle of incidence of incoming neutrons. However neutron scatter cameras—like their analogs with gamma rays, Compton cameras—are complex, inefficient, and are not likely to be used in field applications without further development. On the other hand, the capture gated spectrometer under

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[1] Other spectrometer techniques are indirectly measuring spectra and not very practical for field use, i.e. a set of Bonner spheres can be used to gather neutron spectra. [Bramblett, R.L.; Ewing, R.I. and Bonner, T.W., NIM, Vol 9, P 1-12, 1960] [Gordon, M.S.; Goldhagen, P.; IEEE Trans. Vol 51, 2004 P 3427 – 3434]

investigation in this project promises to be the work horse of future neutron detectors for DHS applications, just as NaI detectors are to gamma-ray detection.

Thus, we think this project is truly transformative. This effort could lead to tools and techniques that will completely change (and dramatically improve) the way that neutrons are used to detect SNM.

To succeed in our goal of producing a high performance neutron spectrometer we had to overcome two major technical problems. First, we had to develop appropriate scintillator materials to detect both protons (from elastic neutron scattering) and the reaction products from a slowed neutron with ^{6}Li (or other capture agent). Second, we had to develop an optoelectronic readout system for the scintillator materials. This system consists of a fast light detector (photomultiplier tube or avalanche photodiode) and a high speed data acquisition and analysis system to process the signals.

Introduction

The physics approach of our spectrometer relies on the "capture gating" of slow neutrons, using the following ^{6}Li reaction:

$$_3^6\text{Li} + _0^1\text{n} \rightarrow _1^3\text{H} + _2^4\alpha + 4.78\,\text{MeV}$$
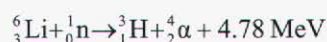
This reaction is used to tag neutrons that stop in the detector. Only neutrons that stop in the detector deposit their full energy. As a result, neutrons that scatter through the detector without depositing their full energy may be ignored, as they would not give a correct result for spectrometry. Figure 2 shows a schematic of a capture gated spectrometer. The escaping neutron is shown to the left, while the stopped neutron's path is shown on the right.
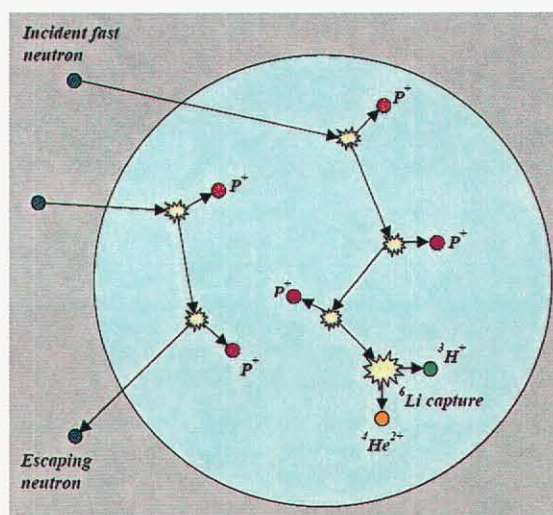
Figure 2: Schematic of a capture gated neutron spectrometer. Neutrons that are stopped in the detector are "tagged" with the ^{6}Li reaction, while other neutrons that just scatter and do not deposit full energy can be ignored. [2]

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[2] Adapted from: http://www.npl.co.uk/ionrad/training/nde/nde_2003_files/lgb_spectrometer_richard_mills.pdf

In our project the ^{6}Li was embedded in a solid organic scintillator. A solid was chosen to make the detector easier to field than liquid organic scintillators.

We also wanted to add a material property called pulse shape discrimination (PSD), which allows for superior gamma background rejection. When PSD is present in a material, the fluorescence of the scattered protons from neutron interactions has a longer decay time than the fluorescence of the scattered electrons from gamma interactions. Figure 3 shows a principle sketch of the resulting electronic signals—when the fluorescent light is captured and amplified with the use of a photomultiplier tube (PMT).
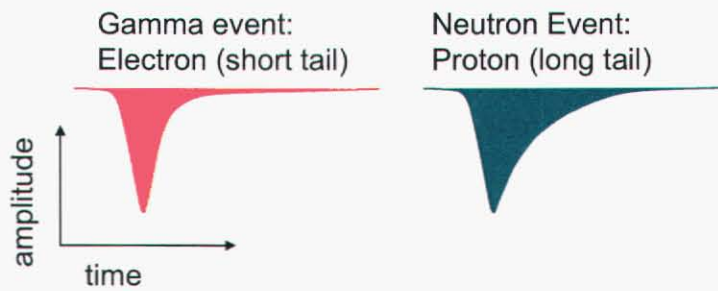
Figure 3: Principle sketch of electronic signals from a scintillator that exhibits pulse shape discrimination.

Our approach to the project was twofold. We focused on materials tasks while developing the necessary physics tools in parallel. The main tasks in the materials development were to develop a solid scintillator that exhibits PSD (for gamma background rejection) and then to dope this scintillator with ^{6}Li as a neutron capture agent. The main tasks in the physics part of the project were to implement a testing capability for new materials being developed along with building a test spectrometer and the related electronics with state-of-the-art materials.

Figure 4 shows a principle layout of our approaches in material development. The main material chosen was trans-stilbene, a solid organic. It was processed or combined with other materials in four different approaches.

Approaches to Lithiated PSD Scintillators			
Melt or Solution Crystallization	Pressed Disks	Polymer-bound	tSB in Silicone or Sol-Gel
Polycrystalline for Screening	PSD Demonstrated	Good Optical Clarity	Optical Clear Sol Gel
Challenge: ^{6}Li incorporation	Challenge: Optical Clarity	Challenge: No PSD (up to 25% tSB)	Challenge: Weak Sol Gel Matrix and Uneven Blending in Silicone
Plans for Melt Furnace and / or Industry Collaboration	^{6}Li Addition in Progress Improve Dispersion & Mixing	^{6}Li-Addition Possible if PSD can be shown Polymers Ideal for Processing	Silicones May Allow in situ tSB Melting ^{6}Li Salts could be Added

Figure 4: Different approaches to lithiated scintillators that exhibit pulse shape discrimination.

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Having physics and material development capabilities under one roof allowed for fast prototyping. Over 250 samples were created and tested throughout the project.

2. Technical Progress Achieved against Goals

Development of an Optoelectronic Readout System

Our first major task was to implement a modular electronics system for testing the PSD characteristics of materials. The readout system to be implemented had to determine the difference between pulse shapes as they are shown in Figure 3. We opted for a short and long integration time to distinguish the shapes of the pulses. This was done with the system shown in Figure 5 in a principle plot.

We successfully demonstrated PSD in a liquid available in house (Bicron BC-501, 2-inch x 2-inch cylinder) and later on a 1"x 1" single crystal trans-stilbene cylinder. Figure 6 shows a typical plot derived from the apparatus. Neutron events (proton scatter) can be clearly distinguished from the gamma events. This apparatus was used to test for PSD in solids and materials that we developed. Its basic principle is also applicable and portable to the more complicated electronics of a gated spectrometer.

Diagram by Stan Mrowka
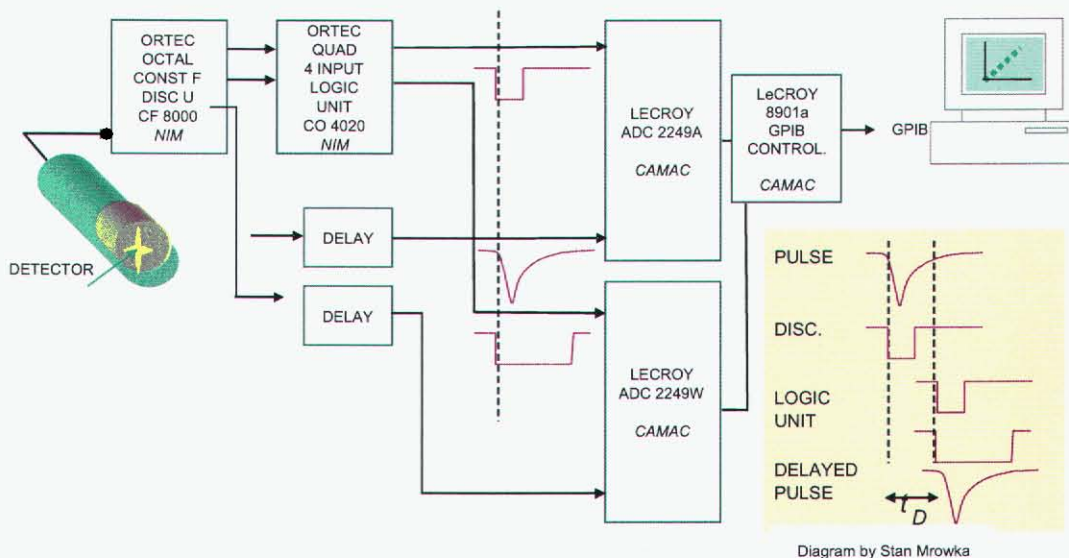
Figure 5: Block diagram for the PSD readout test electronics.
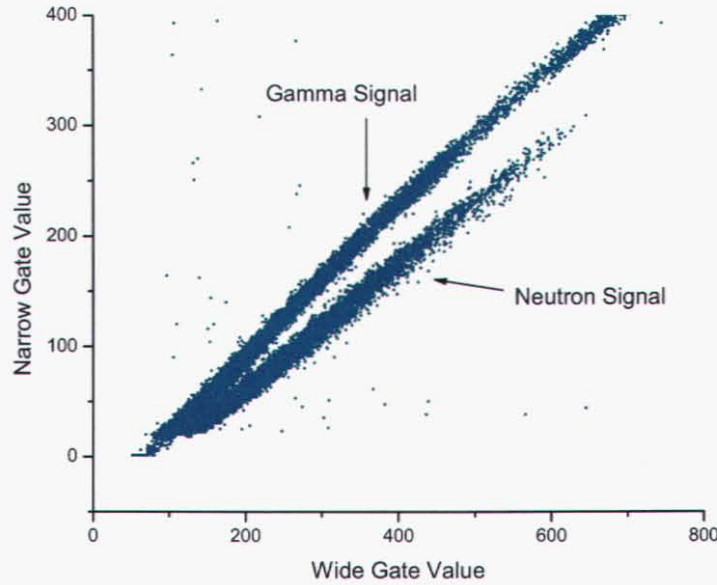
Figure 6: PSD signature from a liquid scintillator, showing clear separation of gamma and neutron events. The neutron source used for testing was a 241americum-berillium AmBe source.

It was imperative to develop the ability to quantify PSD. In principle there are two ways of doing so. A common figure of merit M used in scintillator research is defined as follows:

$$M = \frac{\text{peak separation}}{FWHM_\gamma + FWHM_n}$$

where the peak separation is between the neutron and gamma peaks and *FWHM* are the full width half maxima of the two distributions gammas (γ) and neutrons (n). We found that our apparatus with the 1″ trans-stilbene crystal achieved a figure of merit of M = 2.2 at 500 keV electron equivalent, which compares well with values reported in the literature for liquid scintillators using state-of-the-art read out electronics.[3]

Looking at gamma rejection ratio is the other method for quantifying PSD that corresponds to a homeland security scenario. This means that one looks at the distributions of gamma and neutron events and determines how many gamma events may be mistaken for a neutron event. We set the cut off between events in the center between neutron and gamma distributions and received a rejection ratio of $5 \cdot 10^9$, which is an excellent ratio. This gives us confidence in our apparatus and allows us to ensure that we will reliably detect PSD in experimental materials.

Development of a Capture Gated Spectrometer

The physics and electronics of a capture gated spectrometer were investigated and an actual spectrometer developed, to ready the apparatus as a "plug and play" application once a new

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[3] Wolski, NIM A 360 (1995) p. 584-592

material became available. We successfully implemented a first capture gated spectrometer using a lithium (^{6}Li) containing scintillator in combination with a 2″ x 2″ cylindrical single trans-stilbene crystal. Figure 7 shows the readout electronics schematics. This system relied on the separation of the capture agent from the rest of the scintillator, which acted as the main moderator. However, there is little change required to this configuration when using a scintillator with a homogeneously distributed capture agent.
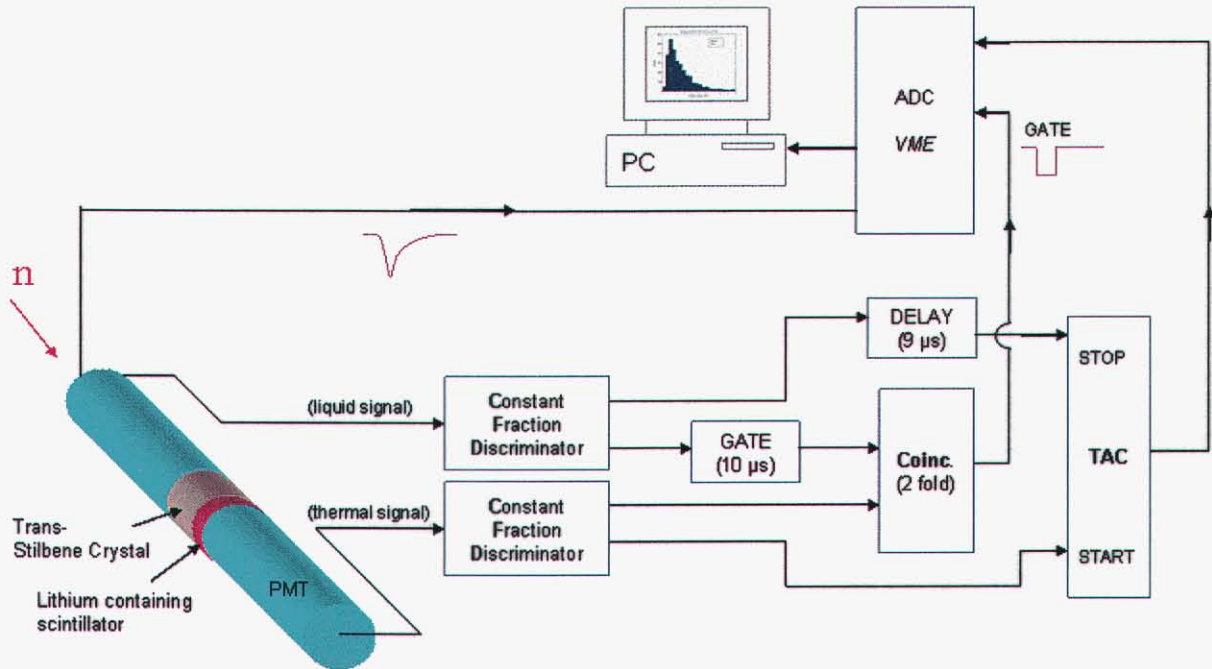
Figure 7: Schematic of the first capture gated spectrometer implementation.

Figure 8 shows the Californium (^{252}Cf) spectrum acquired with this new spectrometer. This spectrum is a raw spectrum, meaning that it is uncorrected for detector efficiency vs. energy. These results compare well to similar experiments reported in the literature [4] and give us good confidence that we established a state-of-the-art instrument in our laboratory.

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[4] Czirr, NIM A, (2002), p. 309-312
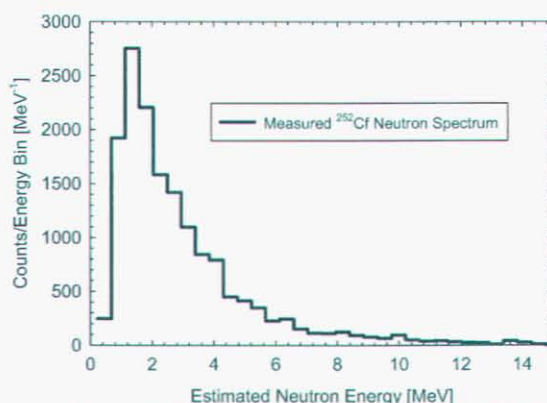
Figure 8: First spectrum measured for ^{252}Cf.

The time that it takes for a neutron to be captured is defined as the time between the first signal in the moderating scintillator where the neutron loses most its energy and the second signal—the capture from the ^{6}Li containing scintillator. This capture time was measured in our experiment. Figure 9 shows a schematic of the detector response of such an event. Comprehensiveness aside, capture time is important for applications in a high gamma field. When one does not take advantage of PSD capabilities, a high gamma field could lead to high coincidental rates that may not be tolerated by an instrument with very long capture times.

As shown in Figure 10, the measured capture times were mostly below 5 µs. The time distribution resulted in a nontrivial function. We believe that this is due to the layered geometry of the spectrometer (trans-stilbene crystal and ^{6}Li-containing scintillator). To validate this distribution, Monte Carlo calculations were employed.[5] Figure 10 shows the results from our calculations compared to the measured times, which match very well. These results give us confidence in both our experiment as well as modeling capabilities. When implementing other instrument geometries, i.e., scaling up our detector for the field, modeling will be a valuable tool to optimize detector configurations.

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[5] Software package used was MCNP5: T. Goorley, J.Bull, F.Brown, et. al., MCNP Monte Carlo Team, X-5, Release of MCNP5_RSICC_1.30, Los Alamos National Laboratory

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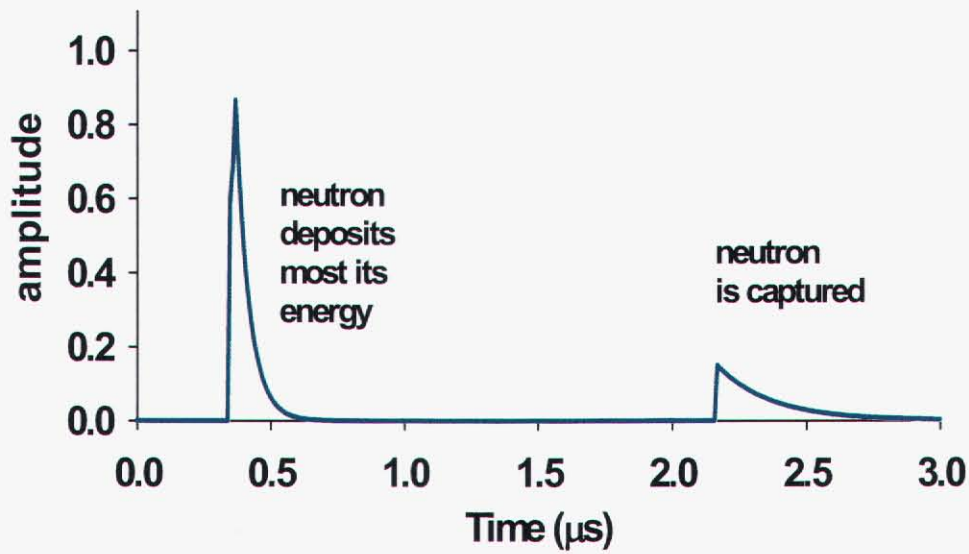
Figure 9: Schematic of a detector signal where the neutron is first slowed down to thermal energy and then captured in the lithium of the spectrometer. The time between the pulses is defined as the capture time of the neutron as measured in the experiment.
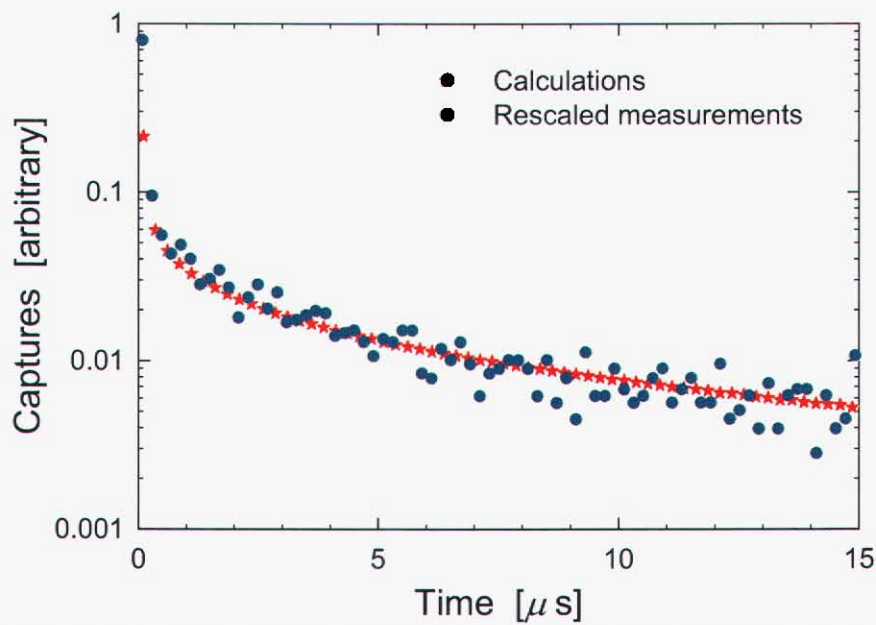
Figure 10: Measured capture times for neutrons in our spectrometer compared to Monte Carlo calculations.

In the next iteration of our spectrometer, we introduced PSD to the spectrometer readout electronics. As mentioned above, PSD is used to allow for gamma background rejection. We used an Ortec Model 552 Pulse-Shaping Analyzer, which uses a trailing-edge constant-fraction (CF) timing technique. The input to the module is the photomultiplier tube signal from the single crystal trans-stilbene. The timing output of the pulse shape analyzer module is sent to a time to amplitude converter (TAC), which then allows separation of neutron and gamma events by using an analog to digital converter and software. Figure 11 shows a schematic of the readout electronics, similar to the setup in Figure 5 except that the pulse shape is now recorded as well in an additional channel of the analog to digital converter.
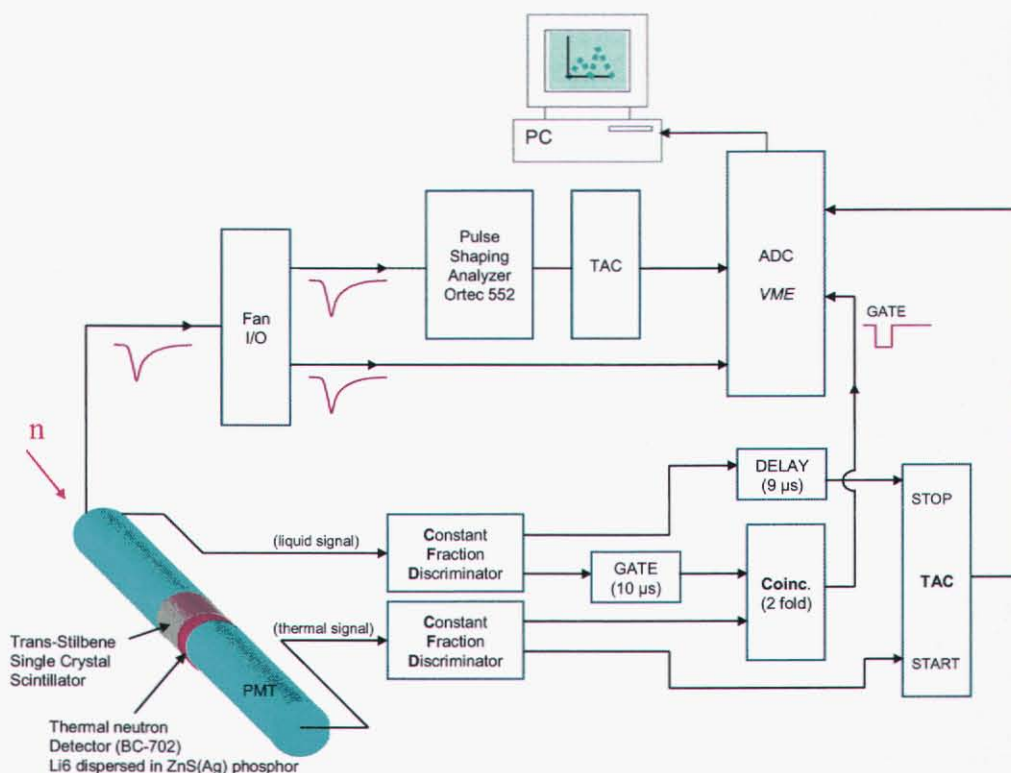
Figure 11: Readout electronics including pulse shape discrimination for gamma ray background rejection.

Figure 12 (left) shows an example of separation peaks from the time to amplitude converter for gamma and neutrons. The gamma signal is then "cut" from the data, as indicated in Figure 12 (right). This cut is performed on the list mode data and therefore is applied to all the line entries, including energies measured with the analog to digital converters and the measured capture times. The energy spectrum with gamma background included is shown in Figure 13 (left) and after removing the gamma events in Figure 13 (right). Figure 14 shows the corresponding capture time with (left) and without (right) gammas. It is obvious that gamma events are represented by a very short capture time, as they travel with the speed of light and leave signals in both the moderating scintillator and capture gate agent containing scintillator. Figure 14 is interesting, as it illustrates how this timing information could also be used to eliminate gamma ray background by preventing the counting of all of the very short capture times.
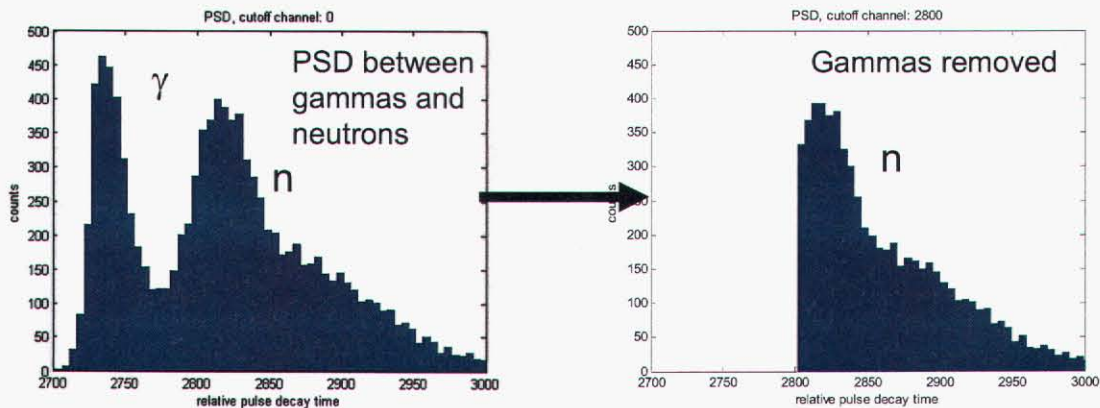
Figure 12: Pulse shape discrimination resulting from the experimental setup described in Figure 11. Gammas are represented by the distribution to the left, neutrons by the distribution to the right. When a "cut" is applied, most gammas are eliminated from the dataset.
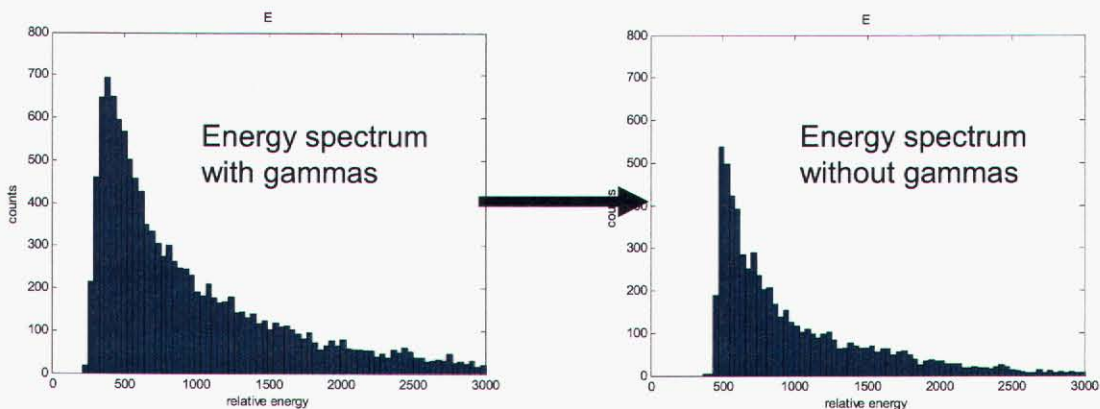
Figure 13: Energy spectra with and without gamma background removed.
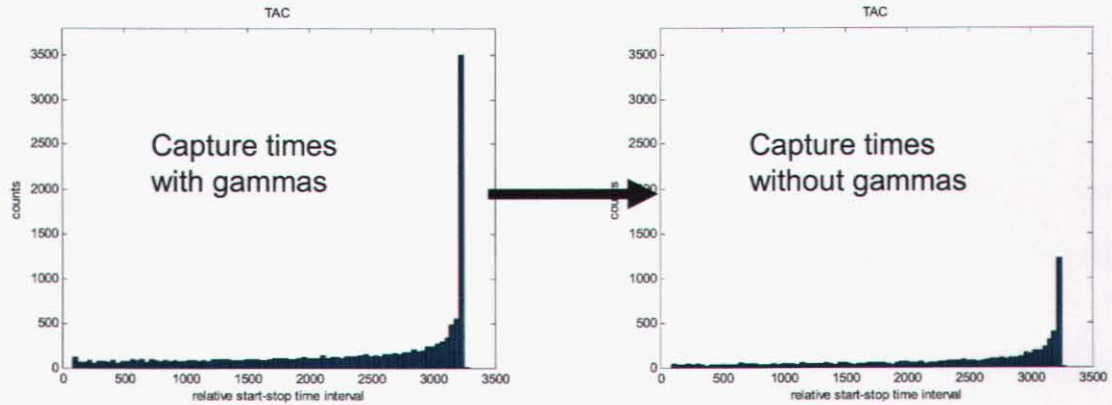
Figure 14: Capture times measured with the spectrometer. Gammas are cut in the right hand plot. It is obvious that gamma ray background leaves a signal immediately in both detectors, leading to a very short capture time measured.

Finally we demonstrated in the laboratory that we are in principle able to distinguish a fission source from a benign source by using our capture gated spectrometer prototype. Figure 15 shows two spectra taken. The top spectrum shows that of ^{252}Cf, a fission source, and the bottom spectrum shows the spectrum taken from AmB, a benign source. The spectra are significantly different from one another. While at first glance these spectra show similar shapes, the AmBe spectrum exhibits more high energy entries. These results are uncorrected for the detector efficiency versus energy, which results in a suppression of the higher energy entries. This explains why the spectra do not represent the same shapes as the calculated spectra we have shown in the overview section of this report (Figure 1). This spectrometer has only a small active volume of ca. 100 cm^3, which adds to the suppression of higher energy entries. A fielded detector would have a larger volume, combined with the correction for the varying detector efficiency and would make the difference between the spectra significantly more pronounced.
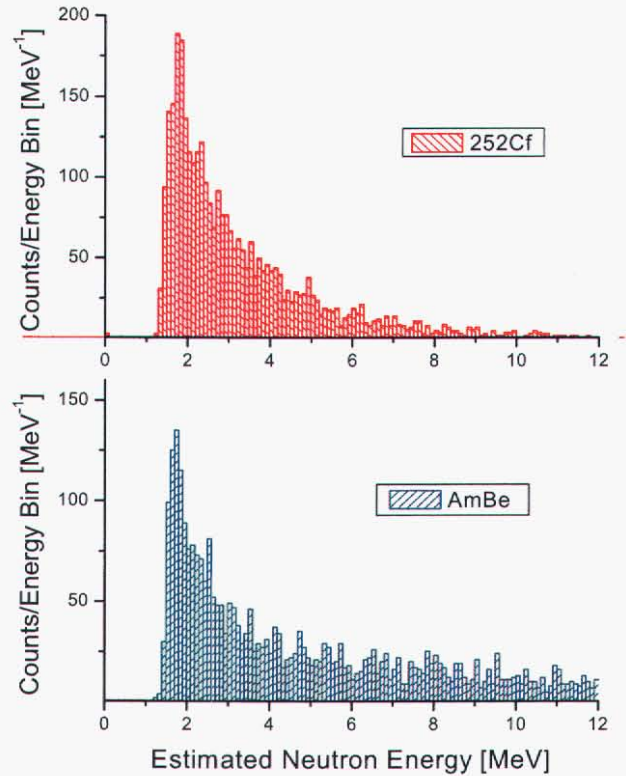
Figure 15: Spectra taken with our prototype spectrometer. From these measurements, we can successfully distinguish between a fission source (^{252}Cf) and a benign source (AmBe).

Development of Scintillator Materials for Capture Gated Spectrometry

To develop scintillation materials appropriate for capture gated spectrometry, we first identified solid state organic scintillation systems capable of PSD for gamma ray background rejection and then attempted to incorporate lithium into these materials. As mentioned in our proposal, the most promising scintillator system for incorporation of lithium is trans-stilbene because:

- Trans-stilbene is capable of PSD in the solid state.
- The physical and chemical properties of trans-stilbene look promising for the incorporation of lithium as a neutron capture agent.

The required ^{6}Li concentration in the material was calculated using Monte Carlo modeling. The results are shown in Figure 16. A concentration of 1-2% mass appears appropriate, as higher concentrations offer little added benefit due to a saturation effect. Capture efficiency is also a function of detector size and is small in this model, which is based on a volume of ca. 100 cm^3.
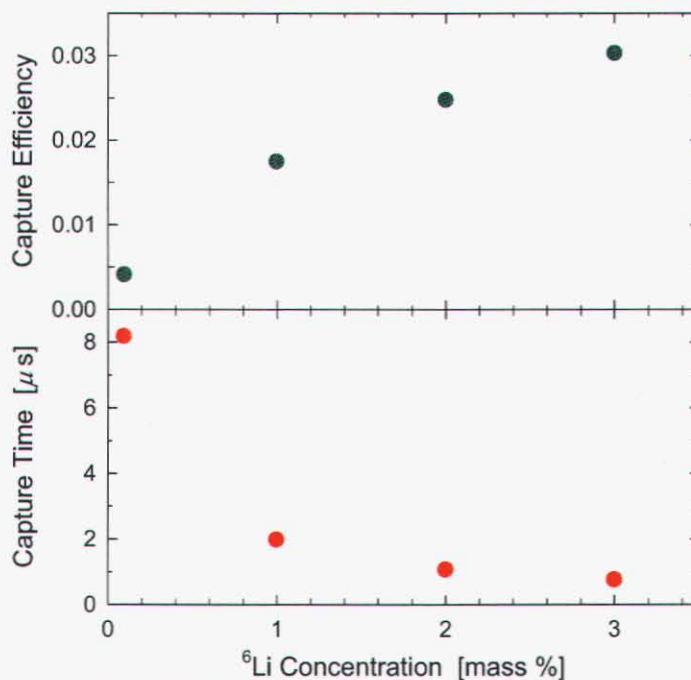
Figure 16: Calculated capture efficiency of a detector and capture time, depending on the concentration of ^{6}Li in the scintillator.

According to the above, our materials research effort focused on incorporating lithium and lithium compounds into various forms (single crystal and polycrystalline) of trans-stilbene and trans-stilbene-containing polymer matrices using these approaches:

Hot pressing trans-stilbene: Growing single crystals of highly purified trans-stilbene using the vertical Bridgman technique can take days to weeks. We therefore determined that a viable rapid screening method for doped trans-stilbene would be the production of non-single crystal trans-stilbene. Hot-pressing of trans-stilbene (microcrystalline or small crystals) led to semi-transparent disks that were tested for PSD and shown to be capable of discriminating between gamma and neutron radiation. Figure 17 shows an example of a 1.3 mm thick disk, photographed with backlighting. The disk is opaque exhibiting some transparency.

Figure 17: Pressed disk of trans-stilbene, 1.3 mm thick. This disk was opaque but showed some light transmission using backlighting.

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Figure 18 shows the corresponding scatter plot showing PSD. The figure of merit M at channel 500 in this sample is about M = 0.5 and the gamma rejection ratio would be $4 \cdot 10^4$. Energy (electron equivalent) was not determined here, as the energy resolution was poor due to the opaqueness of the sample. The figure of merit and the gamma rejection are not as good as that measured in an ideal sample earlier, but even this level of PSD may add a layer of protection from gamma ray background coincidence that is very beneficial. To the best of our knowledge, we are the first to report PSD in a polycrystalline sample of trans-stilbene.
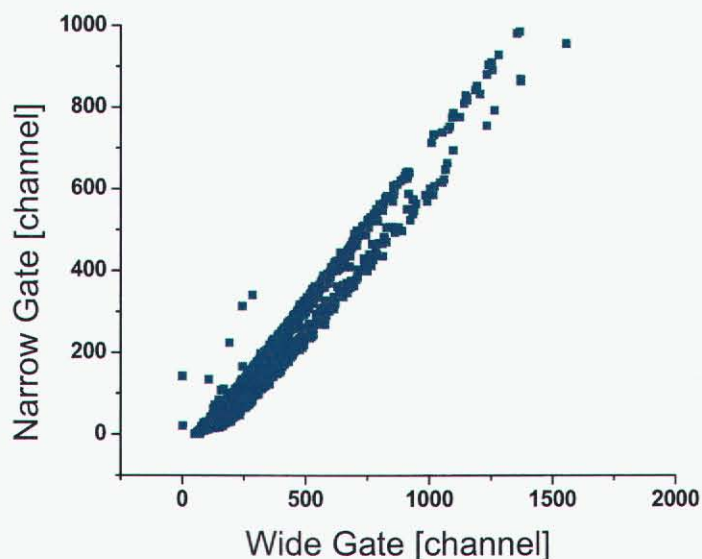
Figure 18: Pressed powder sample exhibiting pulse shape discrimination.

The transparency of the pressed disks could be improved by using a solution of recrystallized trans-stilbene as shown in Figure 20 (left). Also, higher preheat temperatures and higher pressures yielded better optical clarity. The light output from these samples was superior to the first samples of this kind produced without optimization. The annealing of disks showed some improvement, but the conditions need to be chosen carefully, as over-annealing leads to embrittlement of the material.

Doping of hot-pressed trans-stilbene: Trans-stilbene was blended first with natural-abundance lithium salts, such as lithium chloride, and disks were prepared by hot-pressing of the mixed solids. The addition of doping agents was shown to have no effect on the PSD capability of the trans-stilbene and a scatter plot taken from this series of samples would look identical to that in Figure 18.

Incorporation of trans-stilbene into polymer matrices: With reports in the literature that trans-stilbene in polystyrene produced scintillator materials, we evaluated trans-stilbene in polymer matrices to determine the feasibility of generating polymeric scintillators capable of PSD.[6]

Clear trans-stilbene-doped polystyrene (PS), polyvinyl toluene (PVT), and polymethyl methacrylate (PMMA) could be prepared by melt processing or in situ polymerization of

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[6] Koski, Phys. Rev. 1951, p. 230–232

monomers such as styrene. Figure 19 shows an example of an optically clear sample created in our laboratory. These materials had trans-stilbene concentrations approaching 30% and were acceptable scintillators but did not show PSD. Blending trans-stilbene with polymers followed by hot-pressing yielded disks that lacked the optical clarity of the melt and solution polymerized samples but did show PSD at trans-stilbene concentrations as low as 10%.
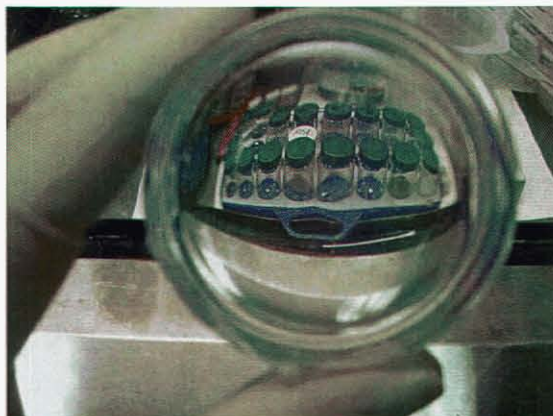
Figure 19: Optically clear sample of 10% trans-stilbene in polystyrene. The sample is a 25 mm thick cylinder. The distortion in the image results from the shape that is molded from the glass jar used for polymerization.

In summary, clear trans-stilbene-doped materials can be made with excellent optical properties, but they do not show PSD, while semi-transparent to opaque materials show PSD but lack the desired optical clarity. Resolving this issue would allow production of PSD-capable polymeric scintillators, which would greatly improve the ability to field large solid state neutron detectors with excellent gamma background rejection.

Incorporation of trans-stilbene into silicone and silica sol-gel matrices: These initially promising approaches later fell to lower priority due to the insolubility of trans-stilbene in silicone precursors and to the weak structure of the sol-gels, which did not permit their removal from the glass vessels in which they were formed. Still of interest is the possibility of suspending nanocrystalline or microcrystalline trans-stilbene in an optical silicone matrix. Various attempts have not yielded high quality materials. These attempts included mixing of a liquid solution of trans-stilbene with silicone precursors, which led to a cloudy silicone material; mixing powdered trans-stilbene directly with silicone part A or part B before curing of the silicone; and curing of trans-stilbene-doped silicone followed by heating of the material above the melting point of trans-stilbene to try to generate crystalline trans-stilbene within the silicone.

Melt processing of trans-stilbene: While not applying the time-consuming vertical Bridgman technique of single crystal growth, efforts to generate improved polycrystalline trans-stilbene have been pursued, and some promising results have been observed. Figure 20 (right) shows an example of a large polycrystalline sample produced with this method. Control of atmosphere and cooling rates are important, and we worked with various parameters for improved materials. This approach is of interest for exploring requirements for incorporation of [6]Li salts into crystalline trans-stilbene. By attempting to determine reasonable parameters for trans-stilbene melt-processing, we expect it to be possible to determine the best avenue for doping of [6]Li into the crystal.
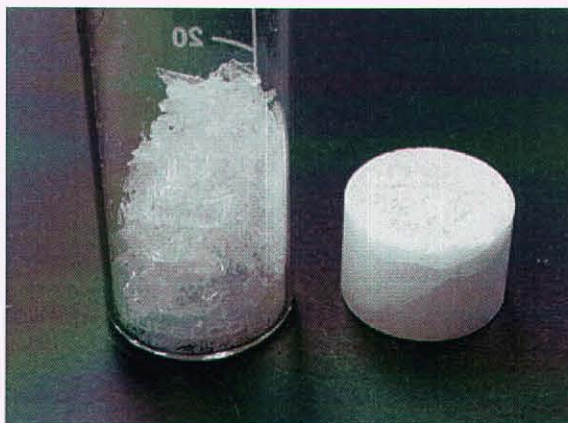
Figure 20: Solution grown trans-stilbene (left) and melt grown 1" diameter trans-stilbene cylinder.

Lithiation of scintillator materials: [6]Li for synthesis is readily available in the form of lithium hydroxide. From this starting material, it is possible to generate various [6]Li salts. We worked with lithium benzoate, lithium chloride, and lithium carbonate. Lithium benzoate was chosen for its potential compatibility with the aromatic moieties of trans-stilbene. Lithium chloride and lithium carbonate were chosen for their relatively high lithium content. Because many lithium salts are white, rather than clear crystalline materials, we faced the significant challenge of finding techniques that minimize the effect of the salt in the trans-stilbene. Such techniques may include solution processing or sonication to break up larger particles of the salts. Another challenge is that [6]Li salts have not yet been shown to dissolve in melted trans-stilbene. Ideally, for thorough and even dispersion of the lithium in the trans-stilbene crystal, the lithium salt should dissolve and not precipitate during the crystal growth.

Further exploration of [6]Li compounds: The commercially available form of [6]Li best suited to the preparation of lithium salts for incorporation into scintillators is lithium hydroxide. After obtaining [6]LiOH (enriched to 95% [6]Li), we used it to prepare lithium benzoate, lithium salicylate, and lithium carbonate. In addition, [6]Li fluoride was ordered from another vendor. Lithium carbonate and lithium fluoride are potentially advantageous due to their relatively high lithium content, which means that less overall mass is added to the scintillator to achieve 2% lithium loading. Lithium benzoate and lithium salicylate, with their aromatic moieties, may be more compatible with trans-stilbene. Lithium salicylate has been reported as an effective neutron capture agent in sol-gel films.[7]

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[7] S. Dai et al. Appl. Phys. Lett. 2004, 2448-2450

Polymer/trans-stilbene/⁶Li blending: Disks were prepared with ^{6}Li salts. The first two viable samples were disks containing PMMA, trans-stilbene, and either lithium benzoate or lithium carbonate. Initial neutron exposure experiments showed that PSD was retained, but a neutron capture signal was not detected. Efforts were focused on attempting to improve the clarity of the disks and the mixing of the lithium salts, which tend to show visible, non-uniform distribution in the trans-stilbene/PMMA matrix. Figure 21 shows a sample with such uneven blending present. Possibly the quenching of the signal in the organic is responsible for the capture signal not being present.
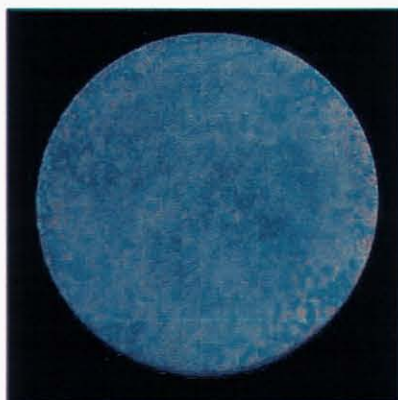
Figure 21: Trans-stilbene ^{6}Li-benzoate pressed disk under UV illumination to highlight the inhomogeneous blending of two components.

Revisited doping of optical silicone RTV 615: Trans-stilbene, lithium carbonate, and lithium benzoate were mixed in separate batches with RTV 615 resin and the samples cured. In all cases, the additives are insoluble in the silicone. However, the combination of silicone with organic scintillator and lithium salts was explored again due to the possibility of finding a method for blending these materials in a matrix capable of being heated above the melting point of trans-stilbene. It may be possible to use the silicone as a carrier for melt-blending of trans-stilbene with ^{6}Li salts. While it so far appears unlikely that this will lead to an optically clear material, the concept of blending trans-stilbene with the neutron capture agent in a polymer matrix remains worth investigating.

3. Difficulties Encountered and Recovery Actions

Procurement Risks

Lithiated liquid scintillators (Li as the capturing agent) are not available off the shelf. The two major suppliers both list such products in older sales literature but are unable to deliver. We mitigated this by ordering a boron loaded scintillator (Bicron BC-523-A), which gave us similar performance and allowed us to build our first set of test electronics.

Materials Risks

As we had stated in the statement of work, we are running the inherent risk of treading on new ground in attempting to combine the solid PSD scintillator with a capturing agent. To mitigate the risk, we aggressively pushed forward in different possible directions.

The pressed polycrystalline materials are not optically clear. Varying pressure and temperature when pressing samples led to an improvement in clarity, but not to a transparent material. Energy resolution and light output in these materials (for neutron spectroscopy) has therefore been shown to be poor. We attempted to mitigate this risk by mixing with a transparent material to improve clarity.

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4. Lessons Learned and Their Impact on Future R&D

We have successfully demonstrated that even at an early stage in our project, our neutron spectrometer is capable of distinguishing between a benign and fission neutron source (AmBe and ^{252}Cf, respectively). Our neutron spectrometer concept has the potential to transform SNM search and identification.

We have developed new scintillator materials that are solids, polycrystalline, and exhibit PSD. We are the first to report such materials. However, the lack of optical clarity remains an issue. The material side of this project is high risk and therefore would require more effort to be completed. It is obvious that there is a region between polycrystalline opaque materials and suspended clear materials that should give us the performance we are seeking. In the final stages of the project, we investigated organic ^{6}Li salts that may be capable of both PSD and neutron capture.[8] In future work, this would be one of the main avenues to pursue.

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[8] ^{6}Li salicylate reported as PSD material in: NIM, 1979, p. 129

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5. Overall Management

Cumulative Funding Profile
(*Planned as of June, 2006)

Cumulative Actual and Planned Expenditures
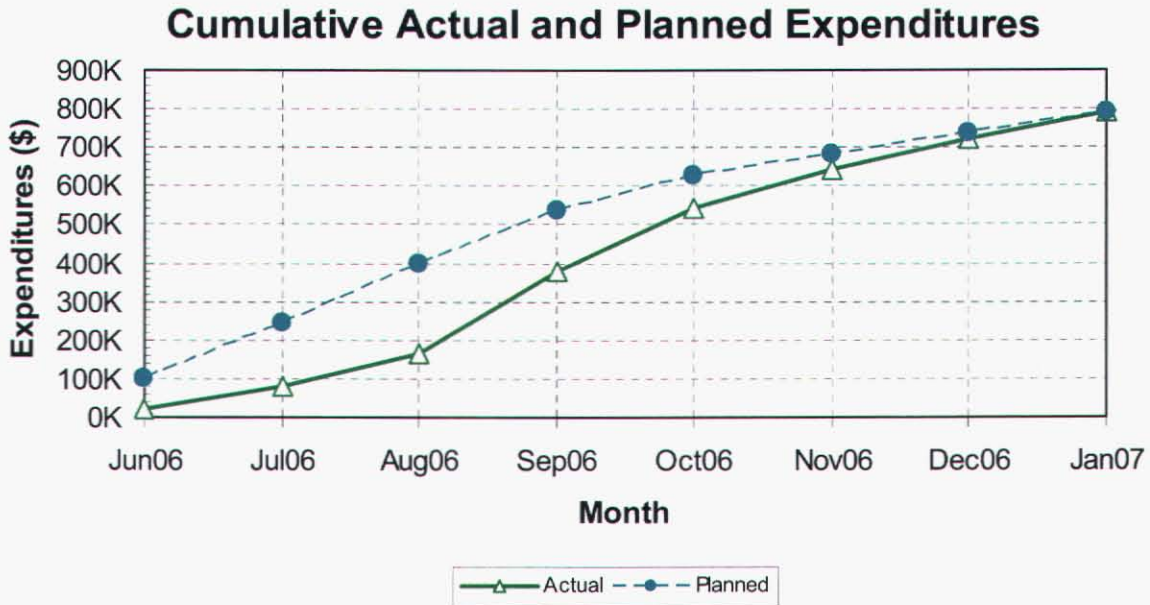
Note: Project has outstanding commitments of $9K for purchase orders for items received but not yet invoiced. These costs, when paid, will bring the cumulative project costs to the budgeted $800K.

Funding Summary- Actual Costs

Table 1. Cost Breakdown in Thousands of Dollars by Task and Phase as of *February 9, 2007*.

Task (Phase.task)	Labor	Matl's	Capital	Travel	Other	Indirect	Monthly Total	Cumulative Total	Plan Total	%
Monthly Total	59	4		8			71			
Cumulative Total	647	130		13				790		
Plan Total	667	125		8					800	

Monthly Travel	
Trip Destination & Dates	**Purpose of Trip**
Washington DC, Dec 15, 2006	DNDO TTRD TA01 Program Review (four participants)

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Contract Schedule Status

Task Name	Jun '06	Jul '06	Aug '06	Sep '06	Oct '06	Nov '06	Dec '06	Jan '07	Feb '07
Task 1: Incorporation of lithium compounds into pulse shape discrimination materials									
Selection and evaluation of capture agents (e.g. lithium compounds)									
Intercalation of capture agent into crystal matrix									
Evaluate doping of trans-stilbene through deposition and migration									
Optimize crystal growth and zone refinement									
Investigate feasibility of sol-gel to produce lithium-stilbene doped materials									
Develop lithium-doped liquid scintillator									
Deliverable: Feasibility Report							◆ 12/11		
Task 2: Capture gated neutron spectrometry readout electronics									
Investigate commercially available gated PSD liquid scintillators and procure adequate units									
Implement basic experiment using modular electronics and fast signal analyzers									
Software development for pulse shape analysis									
Port software to demonstrate Capture Gated Spectrometry technique									
Deliverable: Fully Functional Readout System					◆ 9/15				
Task 3: Characterization of lithiated trans-stilbene									
Measure Li distribution									
Fluorescence distribution of Li doped crystals									
Measure PSD properties of candidate materials									
If successful in subtasks above, test spectrometer using new crystal									
Deliverable: Identification of Materials and Possibly Prototype									◆ 1/31

Account of Funds Expended by Program, Project, and Tasks

Comparison of Expended Funds with Projections from Contract Start

FY06 Gantt Chart

ID	Task Name	Jun '06	Jul '06	Aug '06	Sep '06	Oct '06	Nov '06	Dec '06	Jan '07	Feb '07
1	Task 1: Incorporation of lithium compounds into pulse shape discrimination materials									
2	Selection and evaluation of capture agents (e.g. lithium compounds)									
3	Intercalation of capture agent into crystal matrix									
4	Evaluate doping of trans-stilbene through deposition and migration									
5	Optimize crystal growth and zone refinement									
6	Investigate feasibility of sol-gel to produce lithium-stilbene doped materials									
7	Develop lithium-doped liquid scintillator									
8	Deliverable: Feasibility Report							12/11		
9	Task 2: Capture gated neutron spectrometry readout electronics									
10	Investigate commercially available gated PSD liquid scintillators and procure adequate units									
11	Implement basic experiment using modular electronics and fast signal analyzers									
12	Software development for pulse shape analysis									
13	Port software to demonstrate Capture Gated Spectrometry technique									
14	Deliverable: Fully Functional Readout System				9/15					
15	Task 3: Characterization of lithiated trans-stilbene									
16	Measure Li distribution									
17	Fluorescence distribution of Li doped crystals									
18	Measure PSD properties of candidate materials									
19	If successful in subtasks above, test spectrometer using new crystal									
20	Deliverable: Identification of Materials and Possibly Prototype									1/31

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FY07 Gantt Chart

ID	Task Name	Jan '07	Feb '07	Mar '07	Apr '07	May '07	Jun '07	Jul '07	Aug '07	Sep '07	Oct '07	Nov '07	Dec '07
1	1 Optimize first year Materials												
2	PSD capable scintillators												
3	Li doping												
4	2 Develop Materials												
5	Modeling												
6	Synthesis of candidate materials												
7	Incorporation in scintillator matrix												
8	3 Improve performance												
9	Improve materials testing												
10	Refine test spectrometer												

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