# Exploring Organic Scintillator Directionality: Theory and Application

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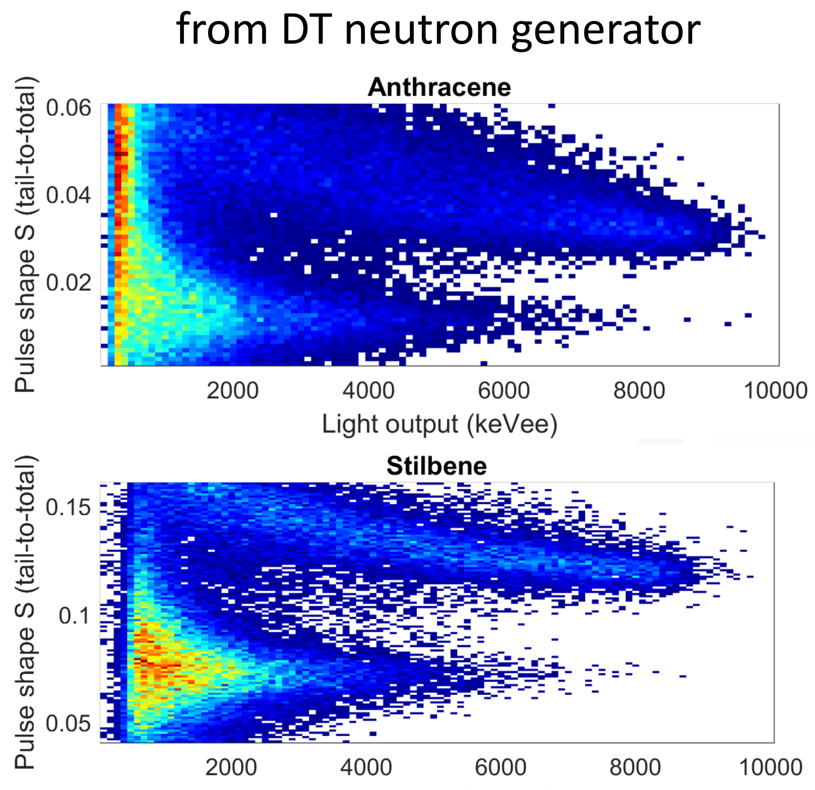
## Introduction and Motivation:

Organic scintillators serve as valuable neutron detection materials for nuclear nonproliferation, treaty verification, international safeguards, and many other areas. Organic scintillator materials offer simultaneous detection of fast neutrons and gamma rays and the ability to discriminate between them. Recent developments in growth methods for crystalline stilbene have produced stilbene crystals with superior neutron-gamma pulse shape discrimination.

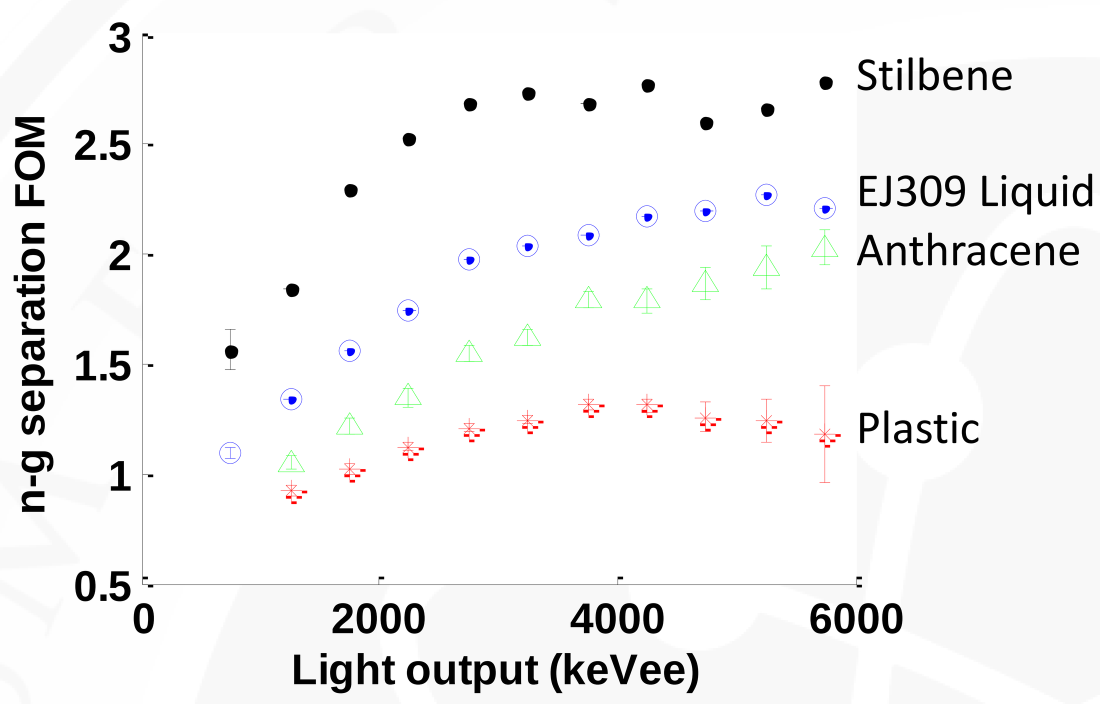
Crystal scintillators experience a directionally-dependent response to heavy charged particles (e.g. proton recoils produced by neutron interactions). During my dissertation work at the University of California, Berkeley, I performed detailed studies of the directional dependence that demonstrated that the effect is complex and varies in magnitude and behavior across materials. This effect is an interesting signature of the internal energy transfer processes that may unveil new information about poorly characterized physics.

## Significance of New Solution-Grown Stilbene

Pulse shape distribution measured from DT neutron generator

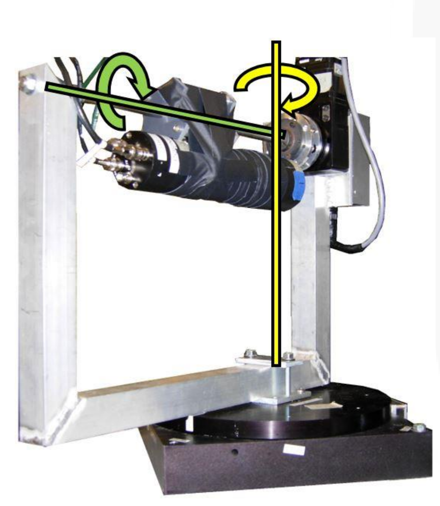



Pulse shape discrimination performance for DT neutron generator measurements




## Characterizing the Directional Dependence of Proton Recoil Events

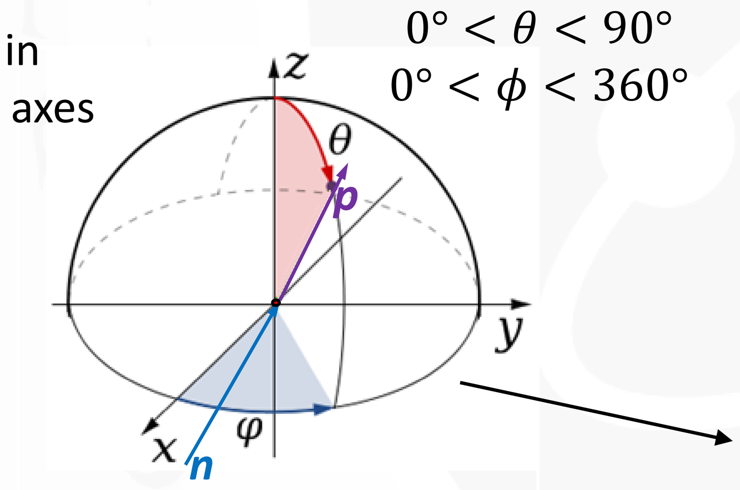
Measured 14 MeV and 2.5 MeV proton recoil events generated by DT and DD neutron generators



Rotational stage positions four crystals at all possible $(\phi, \theta)$ orientations

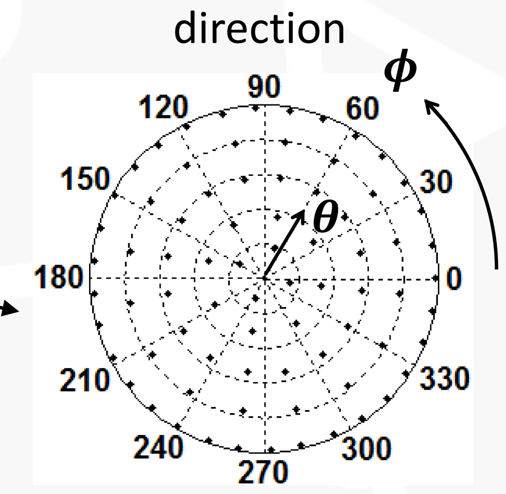
$(\theta, \phi)$ in crystal axes

Top hemisphere:
$0° < \theta < 90°$
$0° < \phi < 360°$

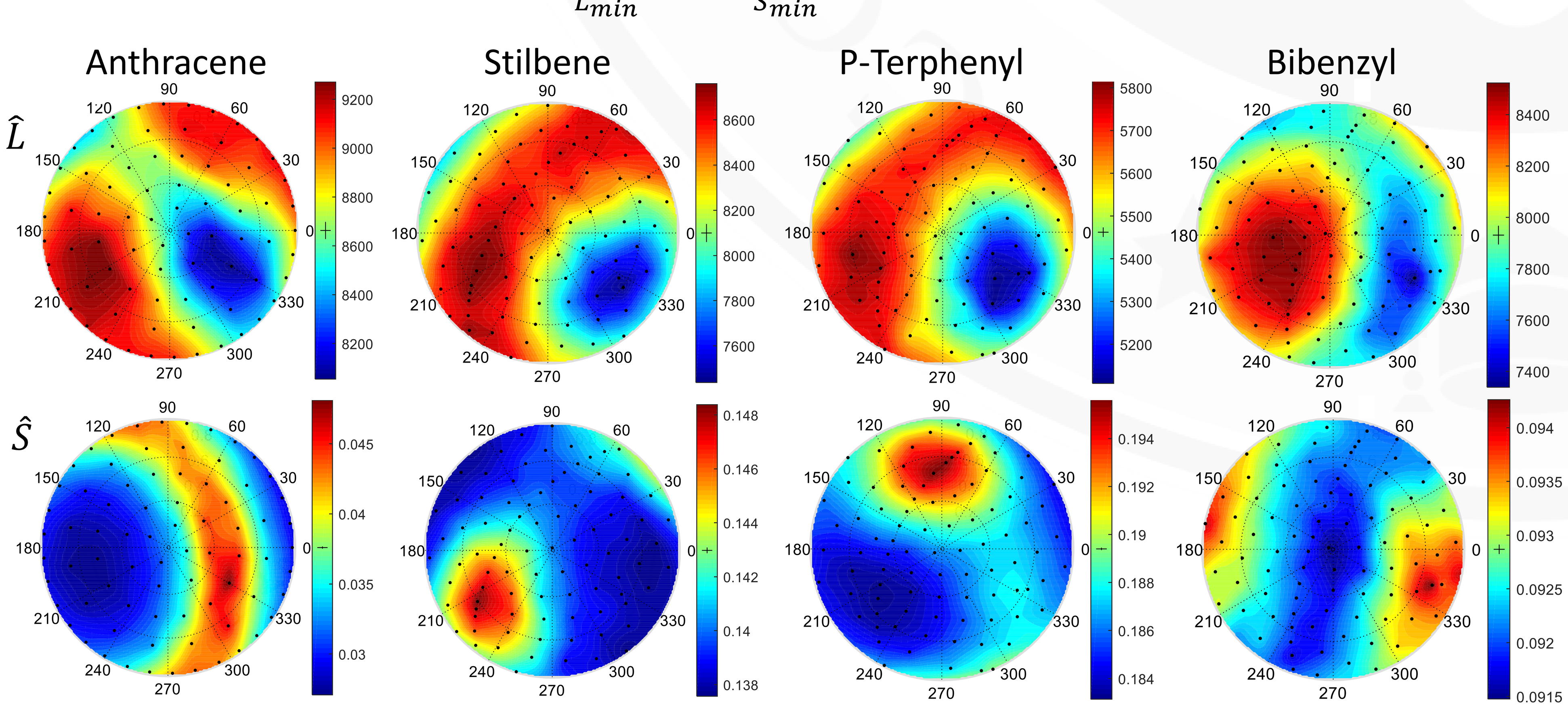



Represent directions in 2-D

Use full energy event from $n$ generator
↓
control $p$ energy, direction




Measure expected light output $\hat{L}$ and pulse shape $\hat{S}$ for 14 MeV proton recoil vs. $p$ recoil direction. Quantify effect as $A_L = \frac{L_{max}}{L_{min}}$, $A_S = \frac{S_{max}}{S_{min}}$.

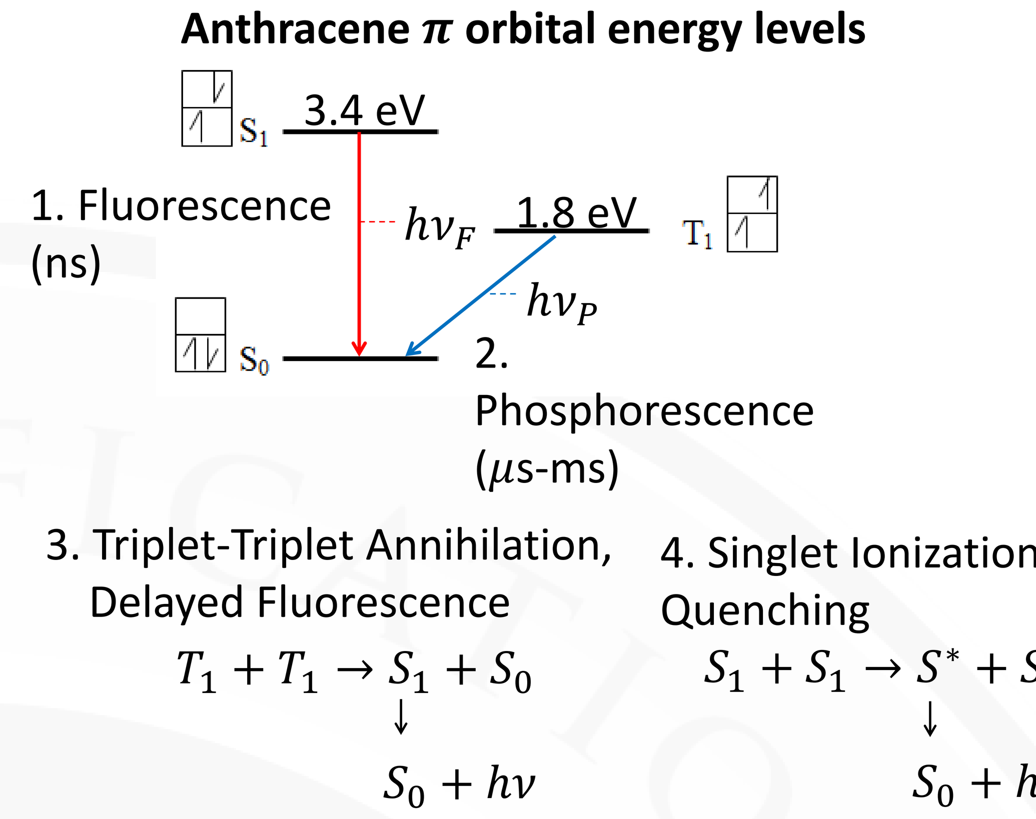



| Anthracene | Stilbene | P-Terphenyl | Bibenzyl |
|---|---|---|---|
| Min, Max out of sync; Saddle in sync | All in sync | All out of sync | Even more out of sync |
| $A_{\hat{L}} = 1.155 \pm 0.006$ | $A_{\hat{L}} = 1.182 \pm 0.006$ | $A_{\hat{L}} = 1.141 \pm 0.003$ | $A_{\hat{L}} = 1.161 \pm 0.008$ |
| $A_{\hat{S}} = 1.798 \pm 0.006$ | $A_{\hat{S}} = 1.081 \pm 0.001$ | $A_{\hat{S}} = 1.070 \pm 0.001$ | $A_{\hat{S}} = 1.031 \pm 0.001$ |

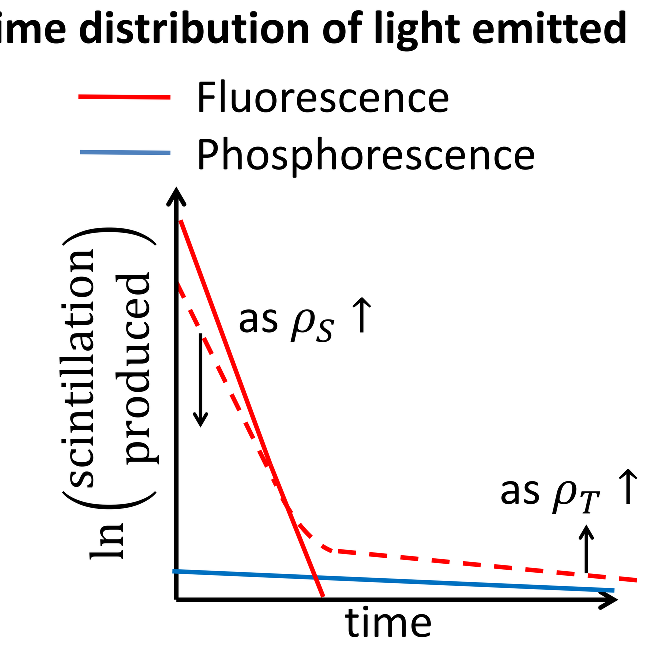
## Reframing Scintillators: Considering Individual Excitations

In order to understand why the directional dependence exists, it is helpful to think of the light production process on the level of individual excitations. These excitations are often considered as particles and called *excitons*. The following diagrams demonstrate several kinetic processes that are important for light production in organic scintillator materials:

**Anthracene $\pi$ orbital energy levels**



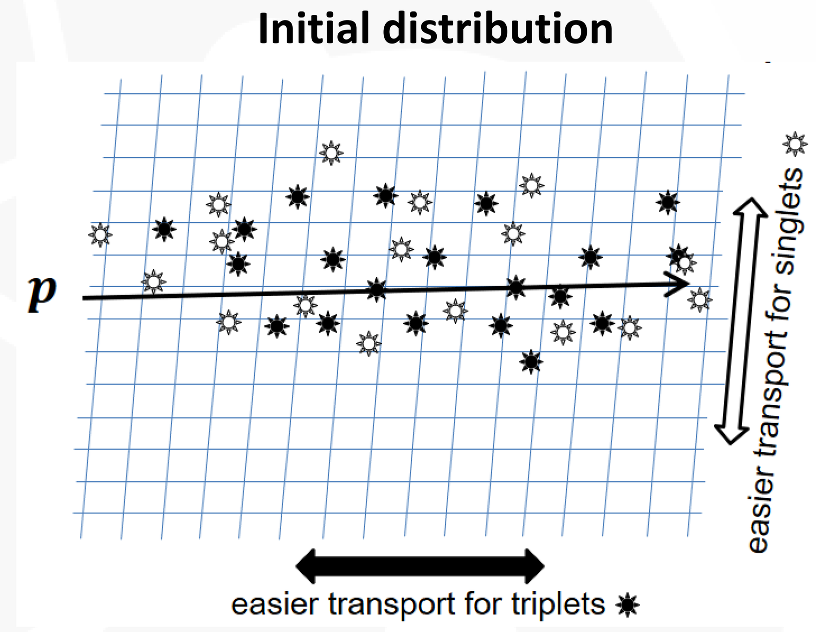

**Time distribution of light emitted**



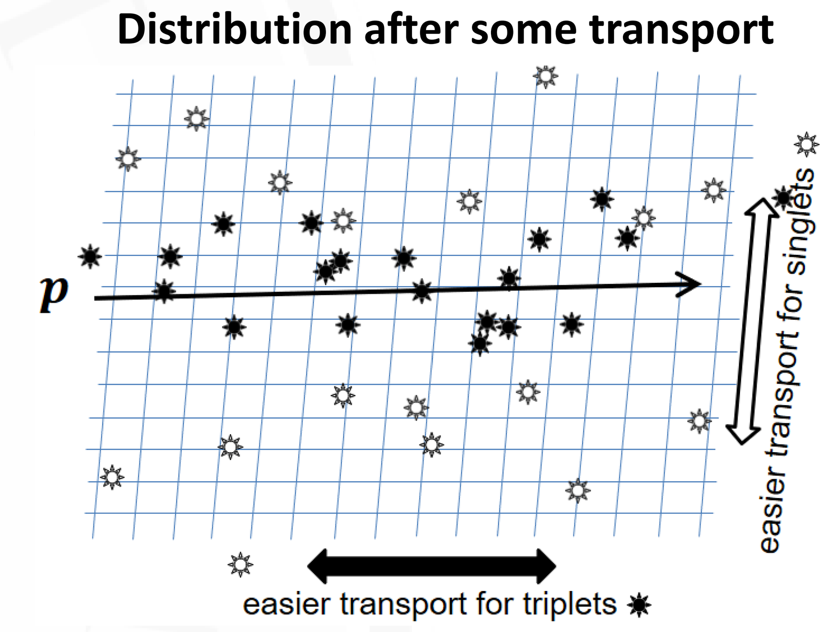

Why is there a directional dependence? Why do the behavior and magnitude of the anisotropy vary by material?

- There exist preferred directions of excitation transport.
- Those directions may be the same or different for singlet and triplet excitations.
- The relative difference in transport rate is different across materials.

**Initial distribution**




**Distribution after some transport**




## Impact, Applications, and New Theory

Impact: Degrades energy resolution, widens pulse shape distribution
- May be possible for correct for the effect when proton recoil direction is known
- Control measurement orientation for best PSD, light output

Applications: Use the effect in a directional modality
- Employ as compact directional detector with high efficiency
- Dark matter detection

New theory: Understand poorly characterized physics
- What physical properties dictate the anisotropy?
- How do quenching processes proceed?
- May contribute new understanding to other fields: OLEDs, OPVs

New development: Produce new materials
- Eliminate or enhance the directional dependence
- Increase light output, improve n-$\gamma$ PSD performance

## Conclusion:

The anisotropic scintillation response in organic crystal scintillators is a significant effect that results from directionally-dependent kinetic processes, including preferred directions of exciton transport within a crystal. An extensive characterization demonstrated that the magnitude and behavior of the effect vary across materials. One can visualize the basic physical mechanisms responsible for the effect by considering interactive and transport processes of individual excitons. This effect offers a signature of the internal energy processes that could be used as a directional detection modality or studied further to learn more about poorly characterized physics.

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