Measurements to be made at KSU: scintillator response to protons and properties of ^{9}Li production events

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Two projects

- **Study of non-linear effects in scintillator's response** using 7-14 MeV protons. Includes measuring Birks' constant and pulse shape effects, and also some other interesting things.
- **Study of properties of ^{9}Li production events** using natural muons at shallow depths, with emphasis on getting some quantitative measurements to back up the "showering muon" idea I advanced at the Munich meeting last year. Hope to also study track position correlation.

Non-linearity: the issue

- Scintillator yield and pulse shape depend on linear energy transfer (dE/dx) and nature of the interactions of the parent particle.
- This can introduce some uncertainty in calibrating e+ using gamma sources.
- It definitely affects response to proton recoils, e.g., from fast n.
- Can also be beneficial: might make pulse shape discrimination (PSD) possible.

Non-linearity: the proposal

- Hit samples of liquid scintillator with protons from our accelerator.
- Use PMT to measure total light yield and pulse shape vs. incident proton energy.
- Use CCD camera to measure differential light yield dS/dx vs. distance along track, directly relate to calculated E(x), dE/dx.
- Information on spatial distribution of emitted light is also interesting.

Scintillator study goals

- Get Birks' constant for any given scintillator.
- Check for spatial effects in "slow component" amplitude and fluor reemission.
- Nail down the $\gamma \rightarrow e^{+}$ calibration issue.
- Calibrate the fast-n signal.
- Test possibility of PSD.

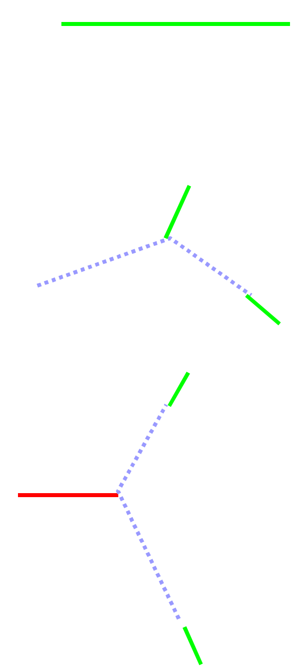
Yield dependence on dE/dx and particle type

Birks' law:

$$\frac{dS}{dx} = \frac{k\, dE/dx}{1 + kB\, dE/dx}$$

kB ≈ 0.015 cm/MeV in KamLAND
(see arXiV:physics/0404071)

Incident particle determines secondaries, changes calibration:



2.2 MeV e-

$\neq$

2.2 MeV γ

$\neq$

1.2 MeV K.E. e+
(2.2 MeV deposited)

"S(2.2) $\neq$ S(1.1)+S(1.1) $\neq$ S(1.2)+S(0.5)+S(0.5)"

The slow and fast scintillation components †

Fast component:

- Decays exponentially
- Time const. ~ few ns
- Has ionization quenching (Birks' law)
- Produced by fluorescence decay of excited singlet state: $^{1}M^{*} \rightarrow {}^{1}M$
- Occurs only in the track of the ionizing particle.

Slow component:

- Decays *non-exponentially*
- "Effective" time constants ~ hundreds of ns
- Little or no ionization quenching!
- Attributed to collisional interactions of pairs of molecules in an excited triplet state: $^{3}M^{*} + {}^{3}M^{*} \rightarrow {}^{1}M + {}^{1}M^{*}$
- Occurs over entire volume available to $^{3}M^{*}$.

† See Birks' 1964 book, or his 1973 review in "Proc. of Intl. Symp. on Liq. Scint. Counting", Sydney, Australia.

Pulse shape discrimination

Figures from Birks' classic book tell the story: because the fast part quenches and the slow part doesn't, the pulse shape can tell you something about <dE/dx>.

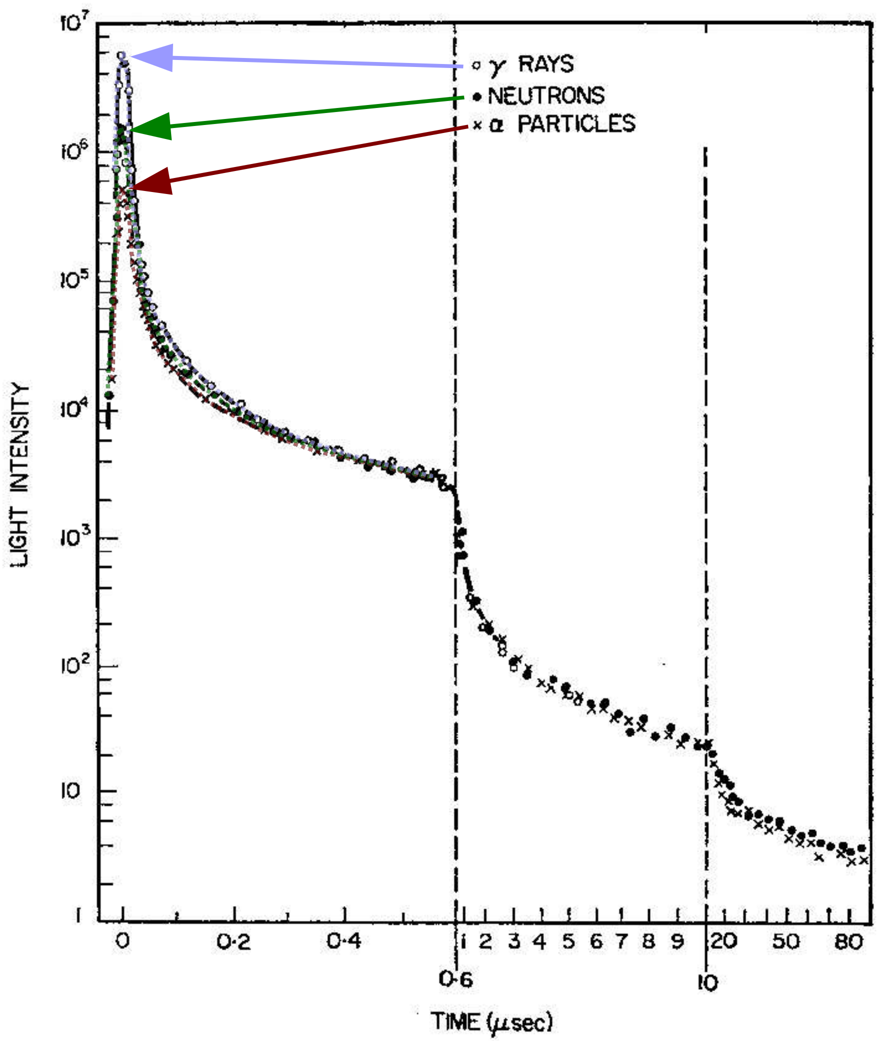


FIG. 6.19. *trans*-Stilbene crystal. Decay of scintillations excited by γ-rays, neutrons and α-particles. The intensities are normalized at time $t = 400$ nsec, to show the similar form of the slow decay component (Bollinger and Thomas, 1961).

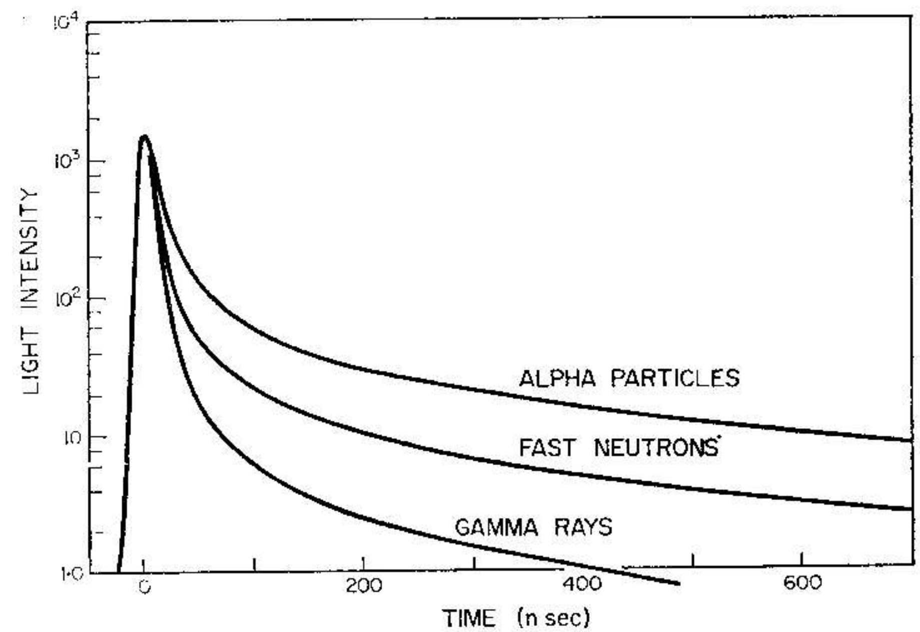


FIG. 6.20. *trans*-Stilbene crystal. Decay of scintillations excited by γ-rays, neutrons and α-particles. The intensities are normalized at the peak (time $t = 0$), to show the dependence of the scintillation pulse shape on the nature of the exciting radiation (Bollinger and Thomas, 1961).

Other effects

- Cerenkov light adds another non-linear contribution to output: $dN_c/dx = k_c(1-\beta^{-2}n^{-2})$

$$N_{\text{phot}}(E\,,\text{primary}) = \sum_{\text{secondaries}} \int_{\text{track}} \left[\left(\frac{k_{\text{fast}}}{1 + kB\,dE/dx} + k_{\text{slow}} \right) \frac{dE}{dx} + k_C \left(1 - \frac{1}{n^2(1 - m^2/E^2)} \right) \right] dx$$

- Spatial dependence of emission and reemission cause a non-exponential dependence of light collected vs. distance from source.

  $N_{pe}(x_{PMT}\,, x_{source}\,, E) = N_{phot}(E)\, f(x_{PMT}\,, x_{source})$,

  where $f(x_{PMT}\,, x_{source})$ is some nontrivial function,

  $f(x_{PMT}\,, x_{source}) \neq f(|x_{PMT} - x_{source}|)$.

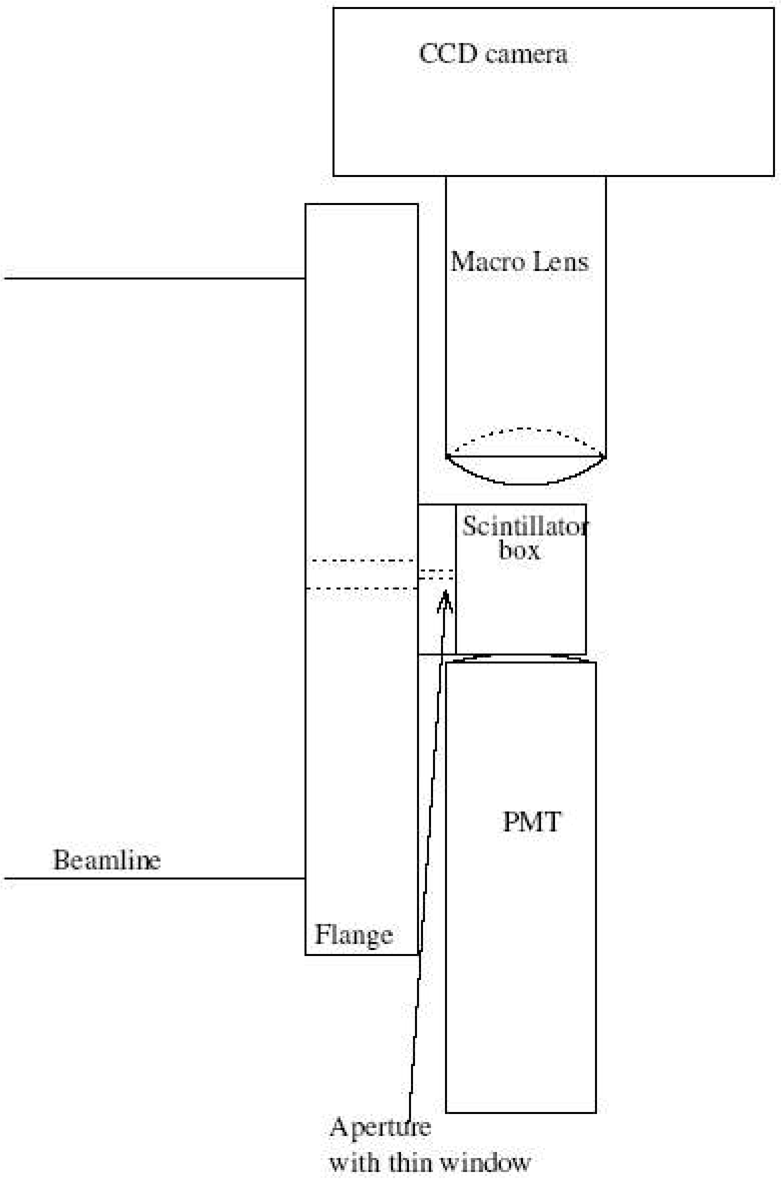
So what? Why should I care?

- If you want to do any shape analysis of the signal, then certainly you care a great deal about calibration issues.
- Even if you just want to do the "rate above physical threshold" measurement, you still care about the fast neutron backgrounds.
  - You want to be able to calculate the shape and normalization of the proton recoil spectrum.
  - You want to know if pulse shape discrimination is possible using a given scintillator formulation.

So what is KSU going to do about it?

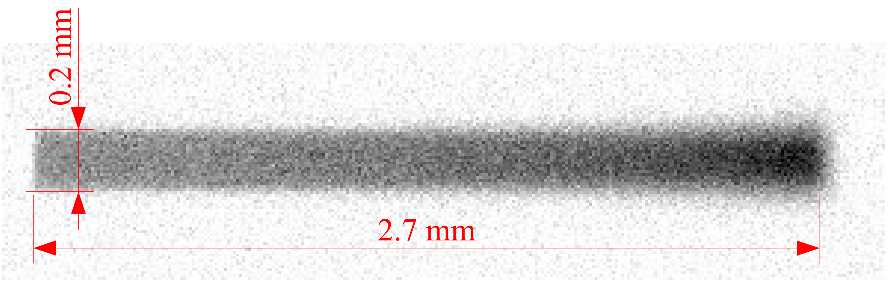
- Hit scintillator samples with 7 to 14 MeV protons from our accelerator.
- PMT can see light curve for each particle.
- Cooled CCD can see with good signal/noise sum of ~3000 protons.

"Good" defined as SNR>10 in each pixel, and there are a lot of pixels.



Camera vs. PMT

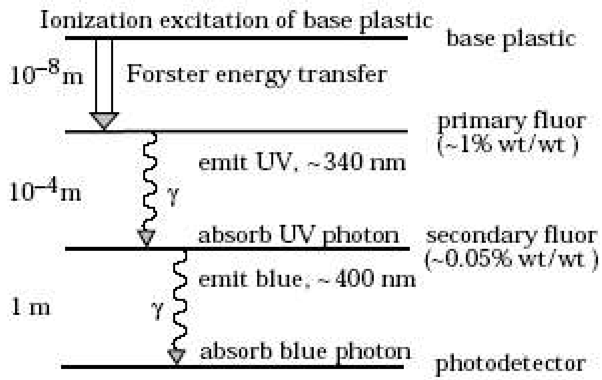
- With PMT, measure total light S as function of E, fit kB.
- With CCD, measure dS/dx at each x, fit kB. Less affected by edge effects.
- Also get to see light emitted away from track separately.



Portion of simulated image of 3000 14-MeV protons emerging into scintillator from a 0.2 mm × 0.2 mm square aperture. Proton beam is assumed to be tuned for a 2 cm (RMS) waist at a location 1 m upstream. Light collection is based on KamLAND scintillator being viewed by a 2-inch macro lens placed 3-inches from the track. The quantum efficiency, image resolution, magnification, and CCD readout noise specified for the SBIG ST-237 camera have been applied. 0.040 mm emission length of the scintillator is assumed, based on 2 g/L PPO and no tertiary fluor.

More about the camera idea

- Separation of the fast light from the track is determined by the absorption length of final fluor: L(λ) = 0.030 to 0.060 mm with PC primary and 2 g/L PPO secondary.
- A study like this was done at Indiana's cyclotron for miniBoone oil*, using much higher energy protons, but in that case the fluor absorption length had to be huge.
- If the camera sees emission over lengths > cell size, then our PMT measurement is skewed too.



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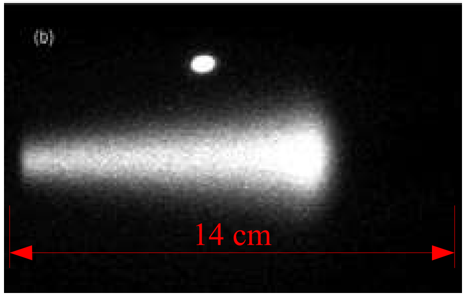

* von Przewoski, Tayloe, and Whitmore, CERN Courier 43N5, 13 (2003).
** From "Particle Detectors" chapter of Review of Particle Physics.

Scintillator experiment plan of study

- Get various scintillator samples, stick 'em in the beam, take data.
  - First try BC-517L (nuTeV oil – thanks, Janet!)
  - Next try KamLAND scintillator (also selling this to KamLAND as a calibration for supernova fast proton recoil signal as well as fast-n background)
  - Next apply to whatever y'all want to send us.
- General conclusions → general publication (e.g., Nucl.Instr.Meth.)
- Specific numbers → scintillator provider.

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^{9}Li: the issue

- Beta-neutron decay looks like inverse beta decay, half life is 178 ms.
- N(^{9}Li) / N(inverse beta) ~ 0.01 at far det.
- IMHO, the uncertainty in the ^{9}Li production rate at 450 m.w.e. is more than 50%.
- IMHO, no one actually knows enough about ^{9}Li production to be sure that our post-veto background uncertainty is less than 20%.

^{9}Li: the proposal

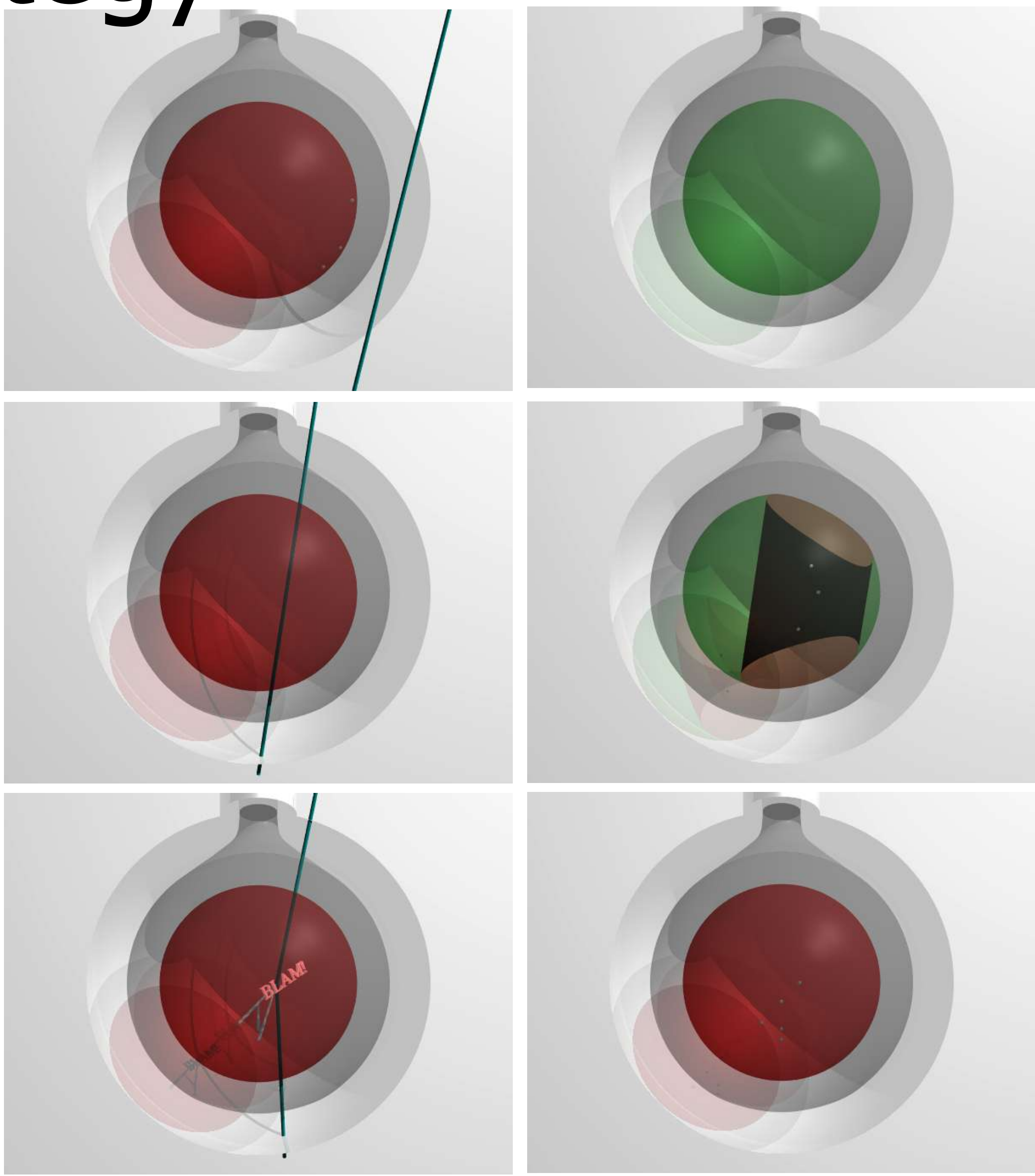
- Observe ^{9}Li production events at shallow depth in a specialized small detector:
  - record ^{9}Li candidates and all cosmic ray events in previous two seconds
  - look for incoming "shower" signature in energy deposit of prior cosmic rays
  - look for outgoing multi-track signature in energy deposit pattern of prior cosmic rays
  - get data point for rate at shallow depth(s)
- Upgrade later for position correlation study.

^{9}Li "cosmogenesis" study goals

- Identify best method of tagging ^{9}Li production events.
- Provide input to muon veto design goals: more important to track single muons well or catch showers? Small can or big umbrella?
  - N.B. Fast neutron background control may be more critical for veto design than ^{9}Li.
- Determine efficiency and purity of ^{9}Li production event tagging.

KamLAND “large and deep” strategy

- 2 ms cut of whole volume after any muon within 3 m of the target vol.
- 2 s, 3 m cut around good tracks.
- 2 s cut of whole volume after untrackable or “showering” muons

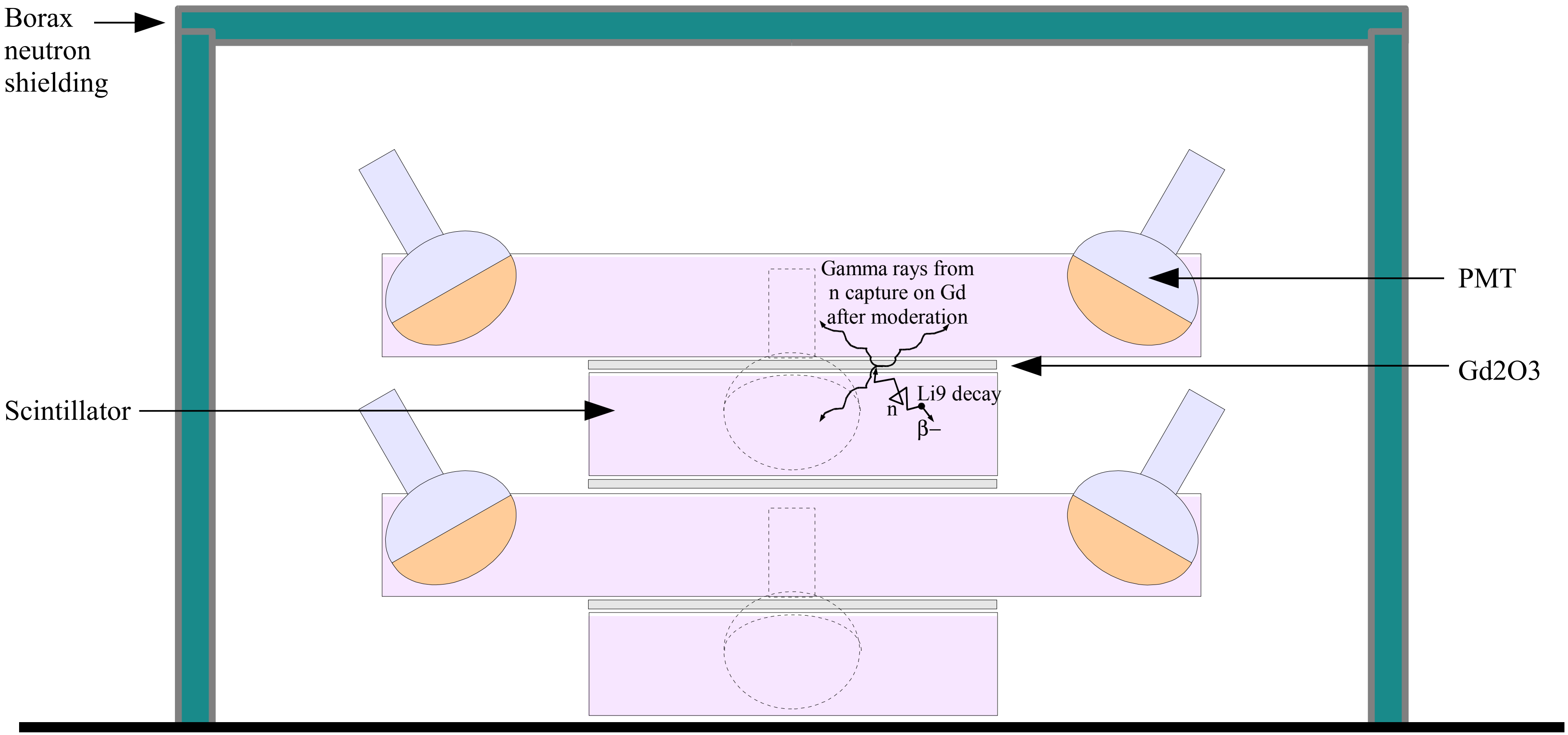


“Medium size, medium depth” strategies

- Strategy 1: Overwhelm the background with signal. *(Works best at near detector.)*
- Strategy 2: Track the muons more accurately, and apply a tighter cylinder cut. In order to keep dead-volume-time below 10%, need cylinder radius < 20 cm. *(Are most ^{9}Li events made so close to primary track?)*
- Strategy 3: Don't veto at all after muons that have very low probability of making ^{9}Li. *(Do most muons qualify? How do we tag them?)*

This is what I want to do about it...

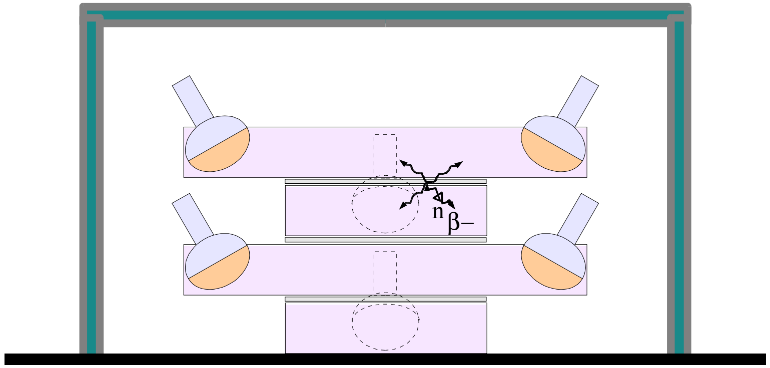
Experimental setup



Four layers of liquid scintillator in rectangular 120 cm×60 cm×15 cm boxes, alternately stacked, separated by three layers of dry Gd_2O_3 to capture neutrons, surrounded by a borax-paraffin shield to exclude external neutrons.

Signal

^{9}Li candidates consist of a prompt event with 4 to 12 MeV in *one* central layer (e-), followed within 0.2 ms by an event with 4 to 12 MeV in 2 adjacent layers (Gd(n,γ) "fireball").



Background rate at surface

- External thermal neutron flux controlled by > 8 attenuation lengths of boron-loaded shielding.
- Fast neutron recoils contribute less than 0.03 Hz in energy range.
- Accidentals controlled using E>4 MeV and applying different prompt & delayed event topology (one-layer vs. multiple-layer).
- Singles rate less than 0.05 Hz, total background less than 0.04/day.

Signal rate at surface

$$\begin{aligned}\Gamma_{\rm surface} &\approx \Gamma_{\rm KamLAND}\left(\frac{<E_{\mu,\rm surface}>}{<E_{\mu,\rm KamLAND}>}\right)^{\gamma}\left(\frac{I_{\mu,\rm surface}}{I_{\mu,\rm KamLAND}}\right)\\ &\approx (1.5\pm 0.5/{\rm day/kt})\left(\frac{4\ {\rm GeV}}{200\ {\rm GeV}}\right)^{0.73\pm0.10}\left(\frac{110\ {\rm m}^{-2}{\rm s}^{-1}}{1.6\times10^{-3}\ {\rm m}^{-2}{\rm s}^{-1}}\right)\\ &\approx 6\times 2^{0\pm1}/{\rm day/ton},\end{aligned}$$

==> **$0.5\times2^{0\pm1}$ ^{9}Li/day**

in the central 60 cm×60 cm×30 cm volume

(if you believe in ~$<E>^{0.73}$ scaling)

About 10 times the background, more or less.

^{9}Li "cosmogenesis" experiment plan of study

- Build in KSU "high bay", get ~100 days data.
  - Using 3.1 barrels of nuTeV oil – thanks, Janet!
- Could add more accurate muon tracking.
  - Use E-12 neutron counters / DONUT muon veto?
- Could try relocating – will it transport well?
- I'd like to try a cave or tunnel someplace:
  - 5 m.w.e enough to get rid of hadrons and first GeV of surface spectrum.
  - Kansas Underground Vaults and Storage, Jaegers Subsurface Paintball, Hutchinson Salt Museum...

Tentative schedule

- Scintillator studies this spring and summer.
- Timely start for ^{9}Li project is contingent on approval of my OJI proposal by (in the words of one of my colleagues) "those [people] in Washington."
  - Buy stuff in spring 2005.
  - Build and commission in summer and fall 2005.
  - Data-taking and analysis 2006 and 2007.

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