Experiences Using TPB to Detect Scintillations in Liquid Helium

Paul Huffman
North Carolina State University
Oak Ridge National Laboratory
Triangle Universities Nuclear Laboratory
• Work presented in this talk was performed in support of a measurement of the neutron lifetime

• The TBP characterization work is primarily the thesis work of Dan McKinsey with help from Carlo Mattoni

• Current collaboration

  Kevin Coakley - NIST  
  Paul Huffman - NCSU  
  H. Pieter Mumm - NIST  
  Alan Thompson - NIST  
  Scott Dewey - NIST  
  Mike Huber - NIST  
  Patrick Hughes - NIST  
  Andrew Yue - U. Maryland  
  Karl Schelhammer - NCSU  
  Craig Huffer - NCSU  
  Postdoc  
  Student
Measurement of the Neutron Lifetime

\[ V_m = -\mu \cdot \vec{B} \]

Magnetic moment \( \mu = -1.91 \, \mu_N \)

\[ 1.6 \, T \sim 1 \times 10^{-7} \, \text{eV} \]

- Produce UCN by downscattering in He
- Confine UCN in magnetic trap no wall losses
- Observe scintillation light produced in He, fit decay curve
Magnetic Trap

3.1 T deep trap
~9 L volume

Radial Confinement

Axial Confinement
• 0.89 nm (12 K or 0.95 meV) neutrons can scatter in liquid helium to near rest by emission of a single phonon.

• Upscattering (by absorption of a 12 K phonon)
  ~ Population of 12 K phonons
  ~ $e^{-12 \text{ K/T}_{\text{bath}}}$
• Recoiling charged particle creates an ionization track in the helium.

• Helium ions form excited He$_2^*$ molecules (ns time scale) in both singlet and triplet states.

• He$_2^*$ singlet molecules decay, producing a large prompt (< 20 ns) emission of extreme ultraviolet (EUV) light.

• EUV light (80 nm) is converted to blue using the organic fluor TPB (tetraphenyl butadiene).
Experimental Method
Experimental Method

Turn on neutron beam
Experimental Method

Turn on neutron beam

Accumulate neutrons in trap
Experimental Method

Turn off neutron beam

Neutrons remain in trap until they decay
Experimental Method

Detect pulse of light from each decay event

Turn off neutron beam

Neutrons remain in trap until they decay
Background Subtraction

- Trapping runs:
  Magnet on during entire run
  \[ T(t) = n(t) + b(t) \]

- Background runs:
  Magnet off during load period
  \[ B(t) = b(t) \]

\[ \epsilon = \frac{\sigma_{\tau}}{\tau} \approx \frac{\sigma_S}{S} = \sqrt{\frac{\sigma_{T}^2 + \sigma_{B}^2}{S}} \approx \frac{\sqrt{2b}}{n} \]
Typical Data Event

A typical event
- 2 ns / index
- 12 bit GaGe cards

Digitized data
4 channels
(2 primary detectors, muon veto, LED pulser reference).
Data Analysis

- Live-time corrections (~15 %)
- Active cosmic veto
- PMT gain correction (~3 %)
- Pulse Shape Discrimination
Example Data

Live-time & gain corrected data for 20 run-pairs (~3-4 days)
Example Data

Live-time & gain corrected data for 20 run-pairs (~3-4 days)
Our primary goal was to develop a detection system optimized for the neutron lifetime measurement.

Primarily focused on scintillation studies and detector development.
Scintillation Process

• Ionizing radiation passing through liquid helium creates large numbers of excited atoms and molecules.

• The excited atoms and molecules are quickly quenched to their lowest energy singlet and triplet electronic states, yielding a population of $\text{He}_2(\Sigma_1^u)$ and $\text{He}_2^*(\sigma^3\Sigma_u^+)$ molecules and $\text{He}(2^1S)$ and $\text{He}^*(2^3S)$ atoms.
Scintillation Process

• The singlet \( \text{He}_2(\Sigma^1_u) \) molecules radiatively decay within 20 ns of the original event, releasing an intense pulse of EUV light.

• The excited atoms \( \text{He}(2^1S) \) and \( \text{He}^*(2^3S) \) react with the ground state helium atoms of the liquid, forming vibrationally excited \( \text{He}_2(\Sigma^1_u) \) and \( \text{He}^*_2(\Sigma^3_u) \) molecules. The \( \text{He}(2^1S) \) quenching reaction is apparently evident in the afterpulsing data, producing scintillation light on a 1.7 \( \mu \)s time scale.
• Triplet He\(_2^*(\alpha^3\Sigma_u^+\) molecules diffuse out of the ionization track, reacting with each other via Penning ionization, forming some products that immediately decay, emitting more EUV light. This reaction appears to be especially evident when an \(\alpha\) source is used, since the high excitation density in turn yields a high metastable density. The scintillation light created decays as \(1/t\).
• Triplet $\text{He}_2^*(a^3\Sigma_u^+)$ molecules that make it out of the track diffuse through the liquid helium. Eventually these molecules either radiatively decay or are quenched at the container walls. The lifetime of these molecules in liquid helium is $13 \pm 2$ s.
Radiative decay of the metastable He$_2$(a$^3\Sigma^+_u$) molecule in liquid helium

Department of Physics, Harvard University, Cambridge, Massachusetts 02138

R. Golub and K. Habicht
Hahn-Meitner Institut, Berlin-Wannsee, Germany
(Received 27 July 1998)

Time dependence of liquid-helium fluorescence

1Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA
2Hahn-Meitner Institut, Berlin-Wannsee, Germany
3National Institute of Standards and Technology, Gaithersburg, Maryland 20899, USA
4Los Alamos National Laboratory, Los Alamos, New Mexico 87544, USA
(Received 7 January 2003; published 26 June 2003)
Scintillation Spectrum

- Scintillation spectrum of electron-bombarded liquid helium

Fluor Development

• Performed fluorescent efficiency measurements of several scintillators with emission spectra in the visible wavelengths
  - tetraphenyl butadiene (TPB), 440 nm
  - p-terphenyl (TPH), 335 nm
  - diphenyl stilbene (DPS), 409 nm

• Studied in various forms
  - evaporated
  - sprayed
  - doped in polystyrene

• All measurements made relative to sodium salicylate, a known standard
EUV apparatus

- Helium, 99.999% purity, 58.4 nm
- Neon, 99.995% purity, 74.0 nm
Sprayed Films

- Scintillator dissolved in either methyl alcohol (sodium salicylate) or ethyl ether (TPB).
- Solution sprayed onto translucent diffusing nylon substrates 25 mm x 10 mm x 0.81 mm.
- Films were less uniform than other two methods.
- Sample thicknesses ranged from 80 µg/cm$^2$ to 3040 µg/cm$^2$ as determined by weight.
Sprayed Films

![Graph showing relative fluorescence efficiency versus coating thickness (mg cm\(^{-2}\)) for two different coatings: 58.4 nm TPB and 58.4 nm NaSal.](image)
Evaporated Films

- TPB, TPH, and DPS evaporated onto translucent diffusing nylon substrates 25 mm x 10 mm x 0.81 mm.
- Deposited using a standard evaporator in a $10^{-5}$ mbar vacuum.
- Sample thicknesses ranged from 49 $\mu$g/cm$^2$ to 2650 $\mu$g/cm$^2$ as determined by weight.
Evaporated Films

![Graph showing relative fluorescence efficiency vs. coating thickness](image-url)

- **Relative Fluorescence Efficiency**
- **Coating Thickness (mg cm$^{-2}$)**

Legend:
- • 58.4 nm, TPB
- ○ 74.0 nm, TPB
- ▲ 58.4 nm, TPH
- △ 74.0 nm, TPH
- ■ 58.4 nm, DPS
- □ 74.0 nm, DPS
## Evaporated Films

<table>
<thead>
<tr>
<th>Scintillator</th>
<th>Thickness (mg cm(^{-2}))</th>
<th>F (58.4 nm)</th>
<th>F (74.0 nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPB</td>
<td>0.2</td>
<td>3.9</td>
<td>3.7</td>
</tr>
<tr>
<td>TPH</td>
<td>0.1</td>
<td>3.4</td>
<td>3.0</td>
</tr>
<tr>
<td>DPS</td>
<td>0.2</td>
<td>3.4</td>
<td>3.3</td>
</tr>
</tbody>
</table>
Plastic Doped Films

• Prepared using the following techniques
  - dipping into the substrate
  - dripping solution onto the substrate
  - spinning

• Explored different plastics
  - polystyrene - MW 280,000
  - polyvinyltoluene (PVT)
  - poly(2,4-dimethylstyrene) (PDMS)
  - polymethylmethacrylate (PMMA)
  - nitrocellulose
  - long-chain polystyrene - MW 1,880,000
  - short-chain polystyrene - MW 2,727
  - dicarboxy terminated polystyrene
Plastic Doped Films

• Film thickness measured with a micrometer or profilometer.

• Sample thicknesses
  - Dipped: ~12 µm thick
  - Dripped: ~31 µm thick
  - Spinning: ranged from 1.6 µm to 40.1 µm thick
A small amount of POPOP (1,500 ppm) was added with the p-terphenyl to shift all light to the visible spectrum.
TPB-Doped Polystyrene

Relative Fluorescence Efficiency vs. TPB Concentration (% by weight)

- 58.4 nm, 12 μm
- 58.4 nm, 31 μm
- 74.0 nm, 12 μm
Fluorescence efficiencies of thin scintillating films in the extreme ultraviolet spectral region

D.N. McKinsey a,*, C.R. Brome a, J.S. Butterworth a, R. Golub b, K. Habicht b, P.R. Huffman a, S.K. Lamoreaux c, C.E.H. Mattoni a, J.M. Doyle a

a Department of Physics, Harvard University, Cambridge, MA 02138, USA
b Hahn-Meitner Institut, Berlin-Wannsee, Germany
c Los Alamos National Laboratory, Los Alamos, NM 87545, USA

Received 6 March 1997; revised form received 20 May 1997
Detectors

• Examined several detector geometries
  - 2-conversion geometry using scintillating fibers
  - plastic-coated tubular geometry
  - evaporated tubular geometry
Fiber-based Design

- TPB evaporated onto Gore-tex
- Blue → Green wavelength shifting fibers
Estimated a detection efficiency corresponding to 6.7 photoelectrons on average for a 250 keV beta. (Note - 11,000 EUV photons produced for a 250 keV beta $\rightarrow 6 \times 10^{-2}$ % efficiency.)
• PMMA tube coated with TPB-polystyrene mixture on inner surface (fluorescence efficiency = 40 %).

1.8 % of the EUV light exits the end of the tube (3.8 % if the beam dump is removed).
Detecting ionizing radiation in liquid helium using wavelength shifting light collection

D.N. McKinsey\textsuperscript{a,\ast,1}, C.R. Brome\textsuperscript{a,2}, J.S. Butterworth\textsuperscript{a,3},
S.N. Dzhosyuk\textsuperscript{a}, R. Golub\textsuperscript{b}, K. Habicht\textsuperscript{b}, P.R. Huffman\textsuperscript{a,c},
C.E.H. Mattoni\textsuperscript{a}, L. Yang\textsuperscript{a}, J.M. Doyle\textsuperscript{a}

\textsuperscript{a}Department of Physics, Harvard University, Cambridge, MA 02138, USA
\textsuperscript{b}Hahn-Meitner Institut, Berlin-Wannsee, Germany
\textsuperscript{c}National Institute of Standards and Technology, Gaithersburg, MD 20899, USA

Received 16 January 2003; received in revised form 31 July 2003; accepted 16 August 2003
Gore-tex Cells

- TPB evaporated onto Gore-tex
- Relies on the reflectivity of Gore-tex
Reflectance factor of Gore-tex with evaporated TPB for 430 nm light normalized to an ideal Lambertian surface illuminated and viewed in the same manner.
In Situ Detector Calibration

PMT pulse height spectrum

\[ ^{113} \text{Sn source, } E_\beta = 364 \text{keV} \]

\[ \sim 5.5 \text{ p.e. (} L = 15 \text{ cm)} \]

Calibration Run w/\(^{113}\text{Sn}\)
Optics Optimization

Estimate neutron detection efficiency in new apparatus to be 56%
Spectrum of Neutrons in Trap

Average P.E./event = 11.9
Spectrum of Neutrons in Trap

Counts (Subtracted)

Counts (Raw)

Photo Electrons per Event

Nontrapping
○ Subtracted

200x10^3

150

100

50

0

4000

3000

2000

1000

0

0

50

100

150

200
Summary

• Using TPB as part of our detection system for a neutron lifetime experiment.

• Studied scintillation process in helium

• Studied the fluorescence efficiencies relative to other scintillators.

• Measured the reflective properties of TPB-coated Gore-tex.