Semiconductor-Based Neutron Detectors

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Semiconductor neutron detectors can be divided into two classes:

- Thin-film coated or “foil” coated detectors

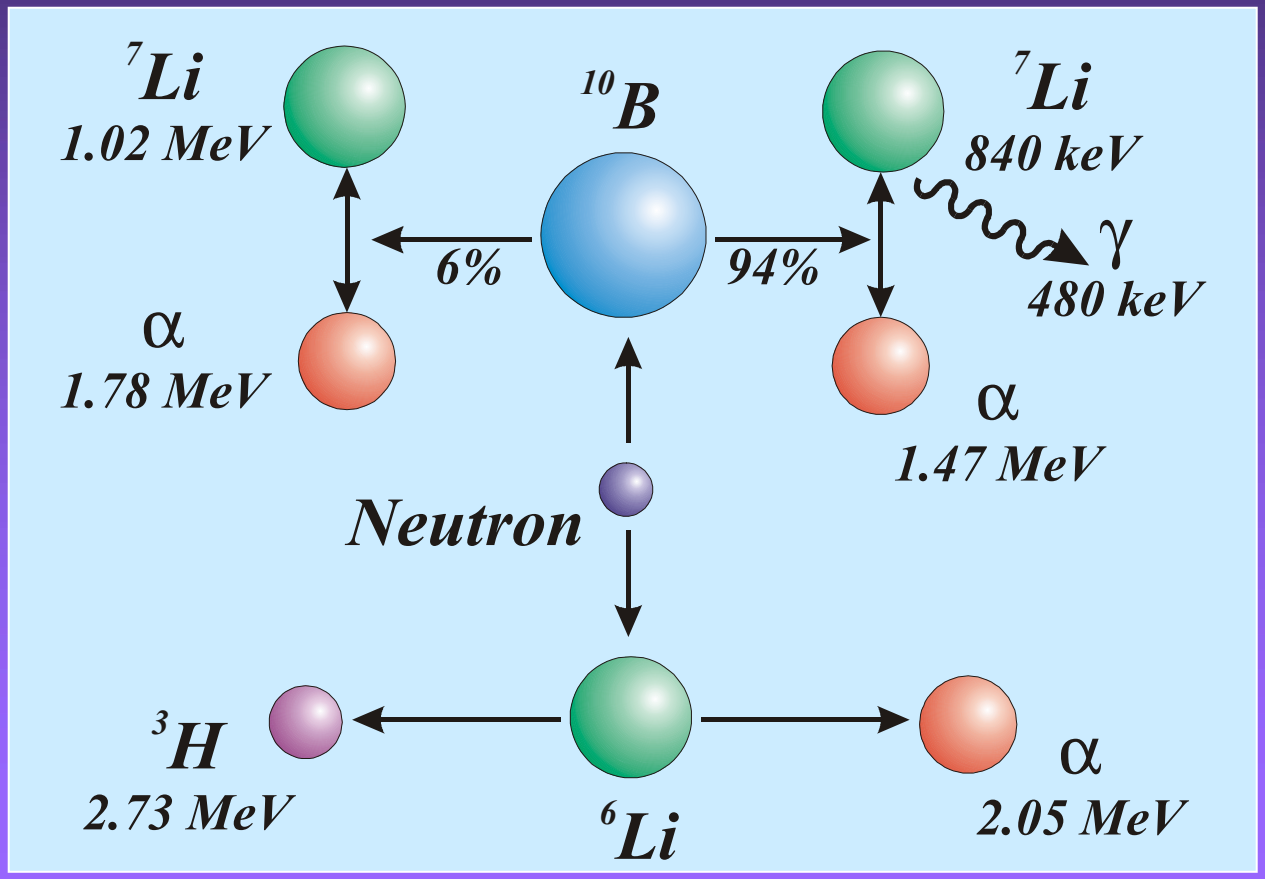
  Thin-film detectors refer to diodes that have an overcoat of neutron reactive materials.

- Solid form detectors

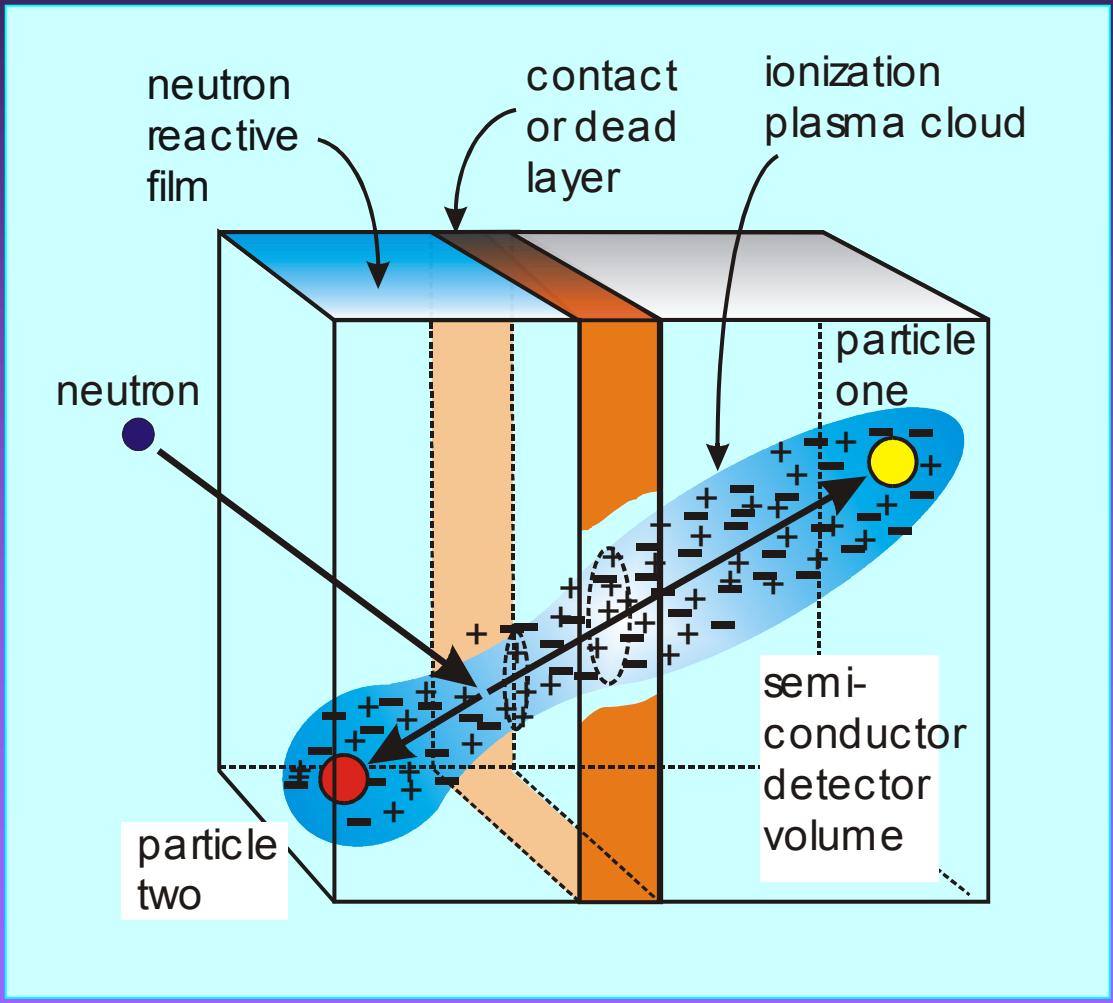
  Solid form detectors refer to diodes or devices in which the diode material is a neutron reactive substance.

Compact Semiconductor Neutron Detectors

Two very popular neutron reactions for thermal neutron detection are the $^{10}B(n,\alpha)^{7}Li$ reaction and the $^{6}Li(n,\alpha)^{3}H$ reaction.

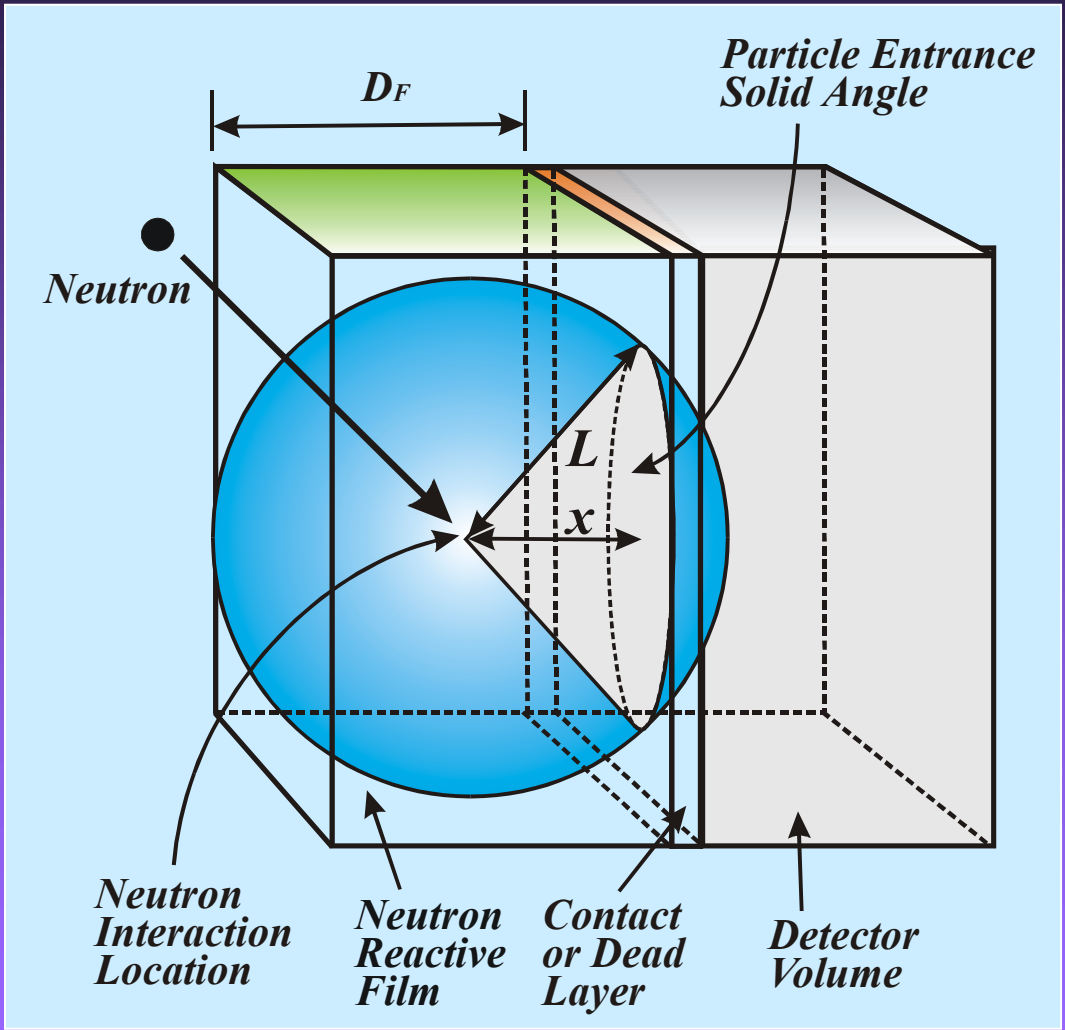


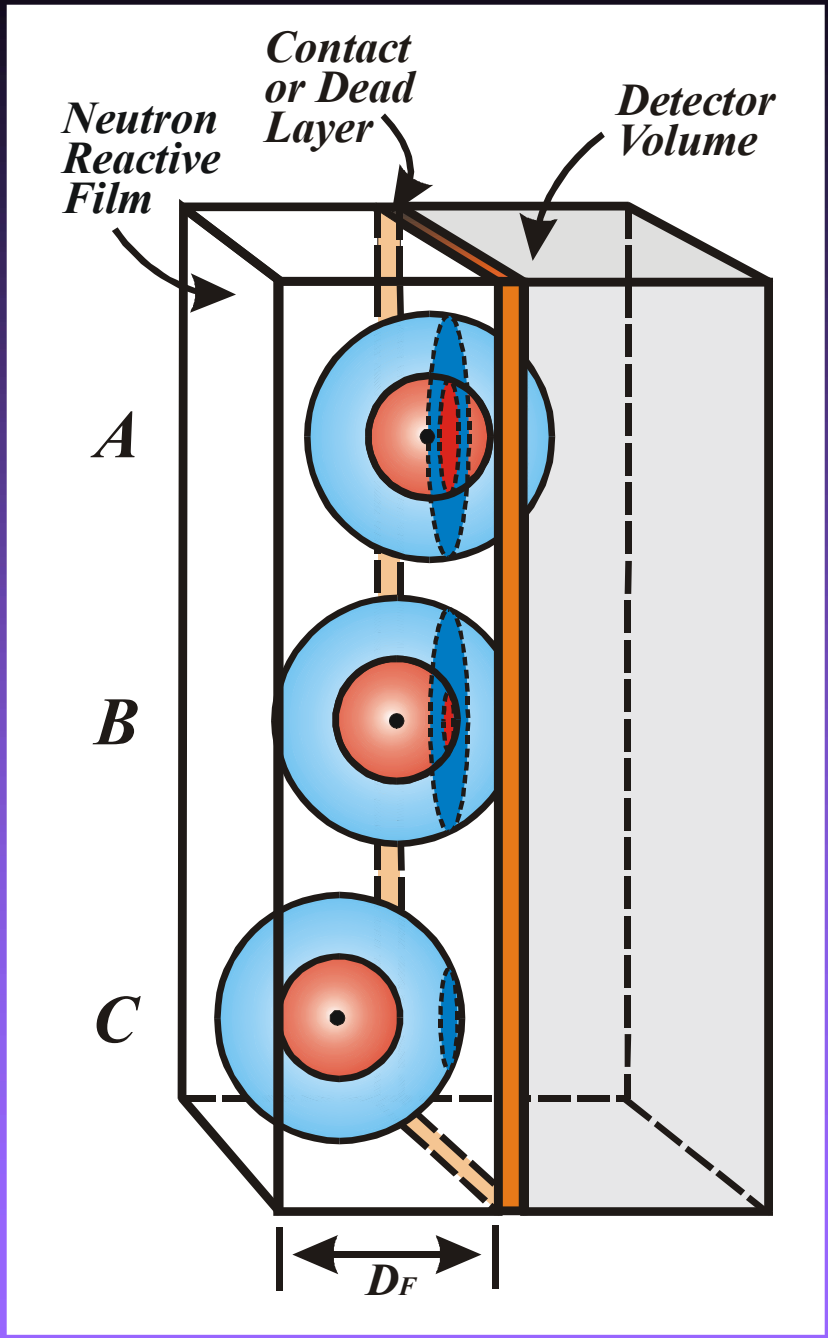
Basic configuration for thin-film coated detectors



Theoretical Considerations

The effective range and the solid angle determine the probability of a reaction product entering the detector.

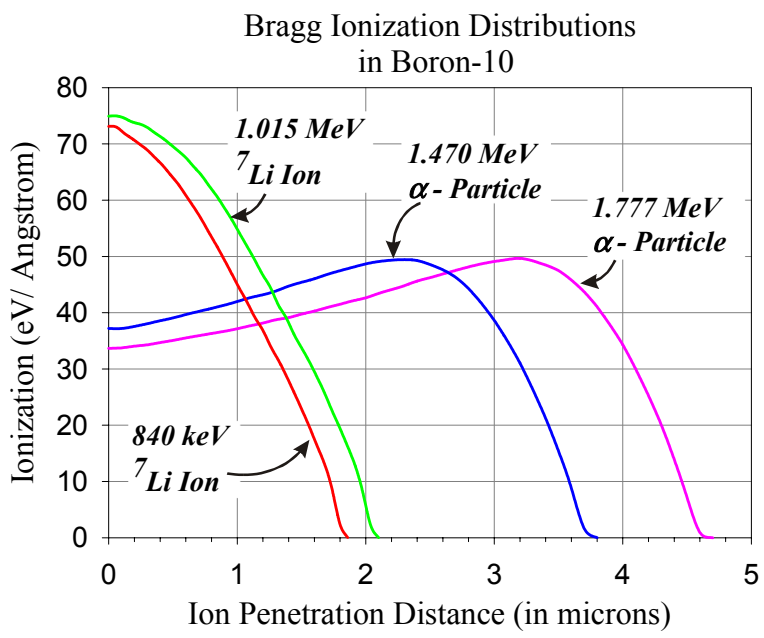


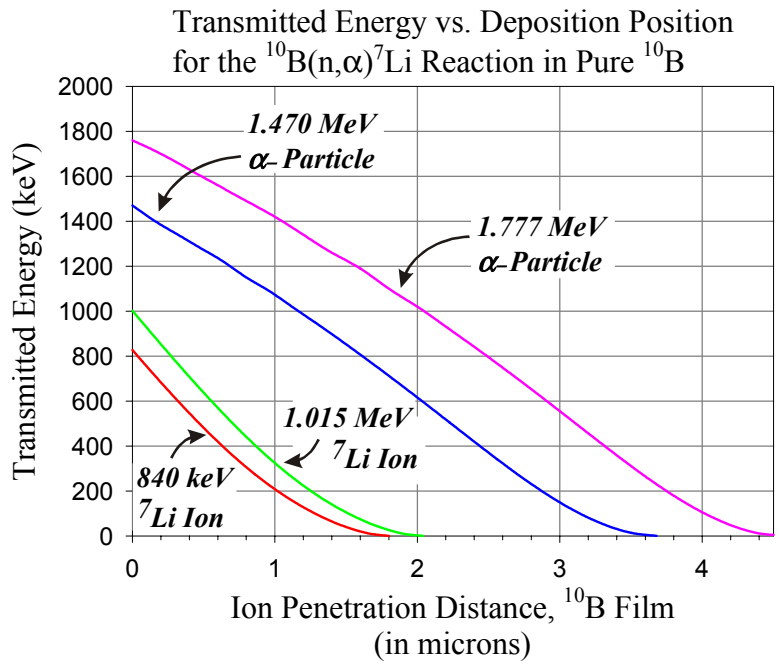


The solid angle subtending the detector decreases with distance from the device interface.

Reaction product ranges in pure boron

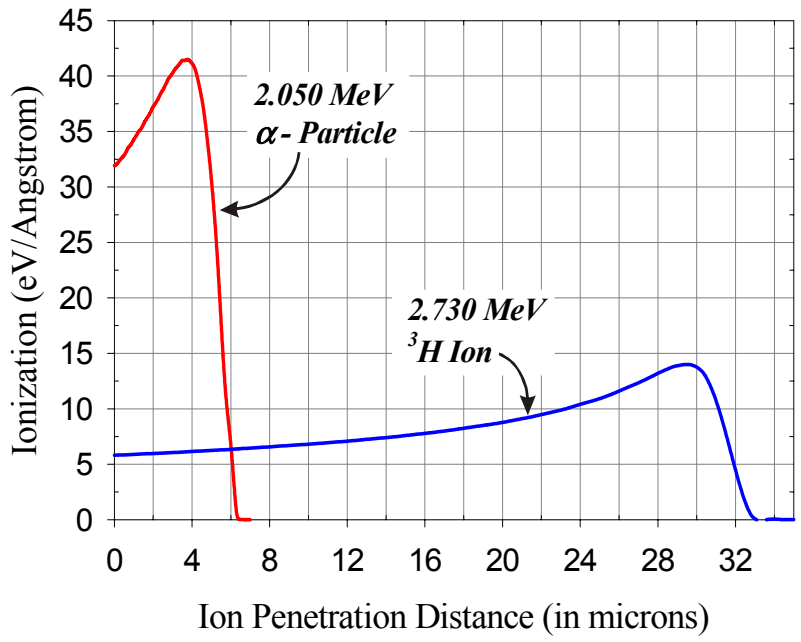
Below: Bragg energy loss distribution in B for the $^{10}B(n,\alpha)^{7}Li$ reaction.

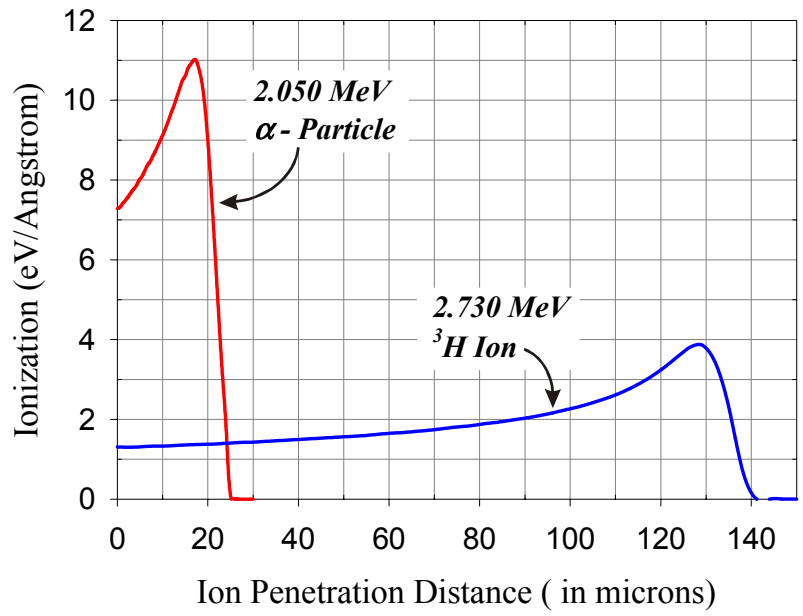




Above: Transit energy after attenuation through the reactive film.

Reaction product ranges in LiF and Li

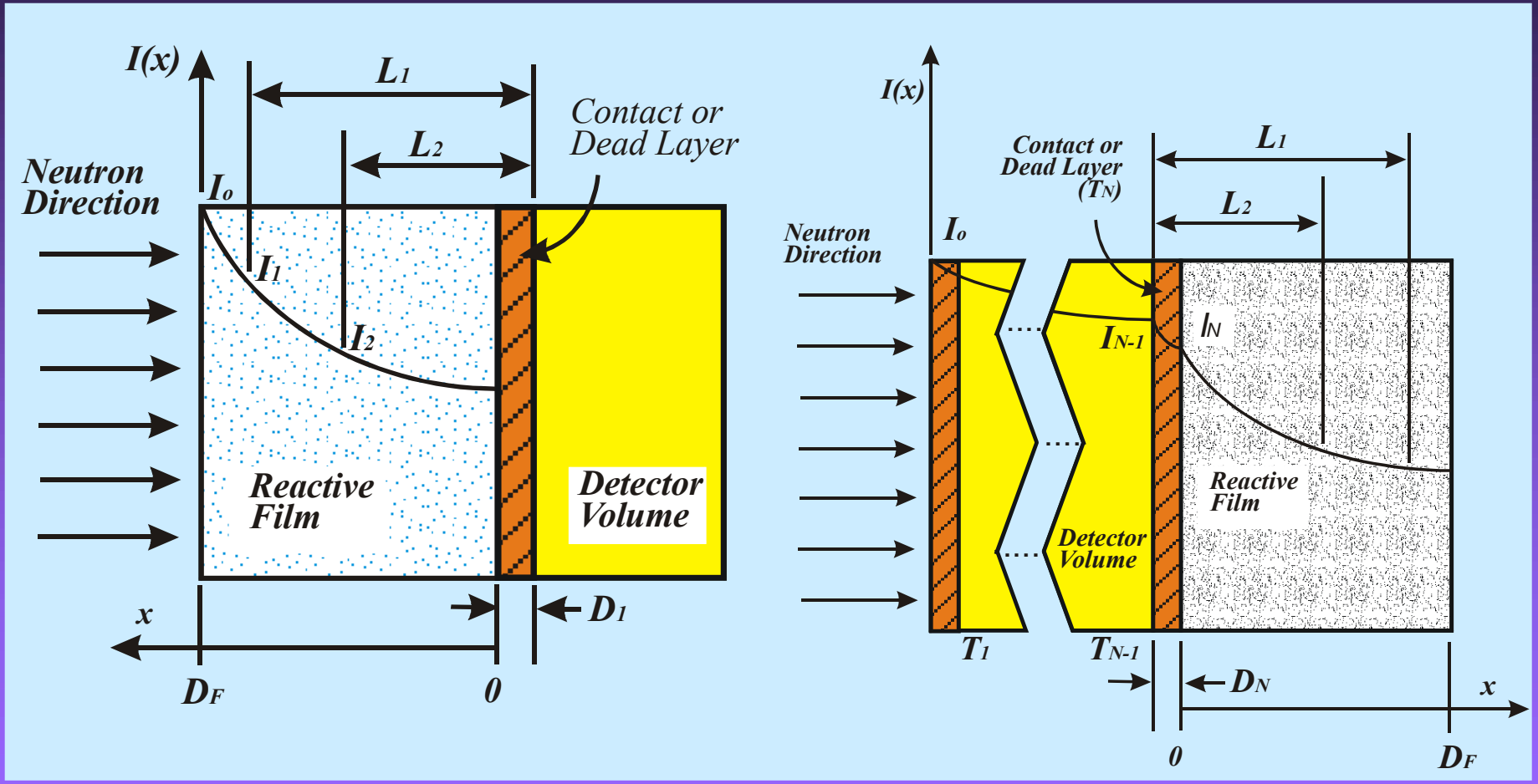




Bragg energy loss distribution in LiF for the $^{6}Li(n,\alpha)^{3}H$ reaction.

Bragg energy loss distribution in Li for the $^{6}Li(n,\alpha)^{3}H$ reaction.

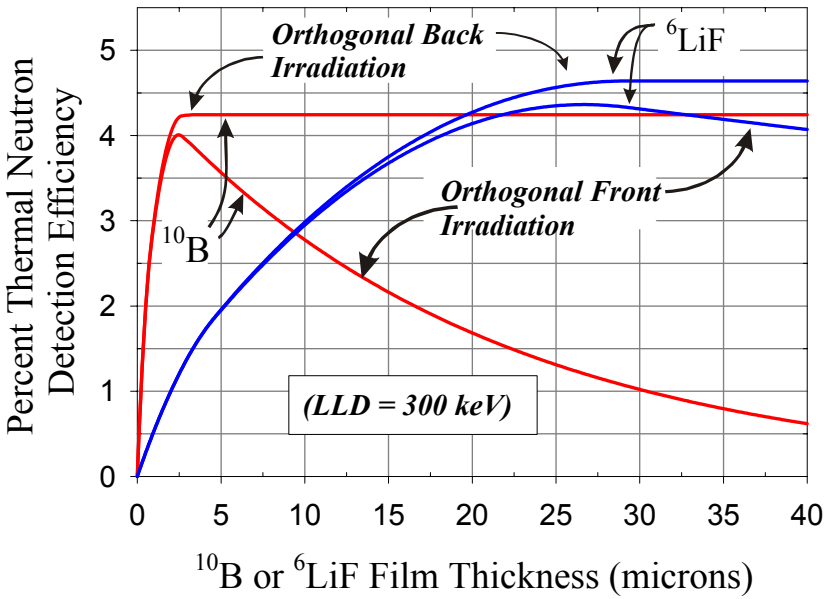
Front and back irradiation make difference

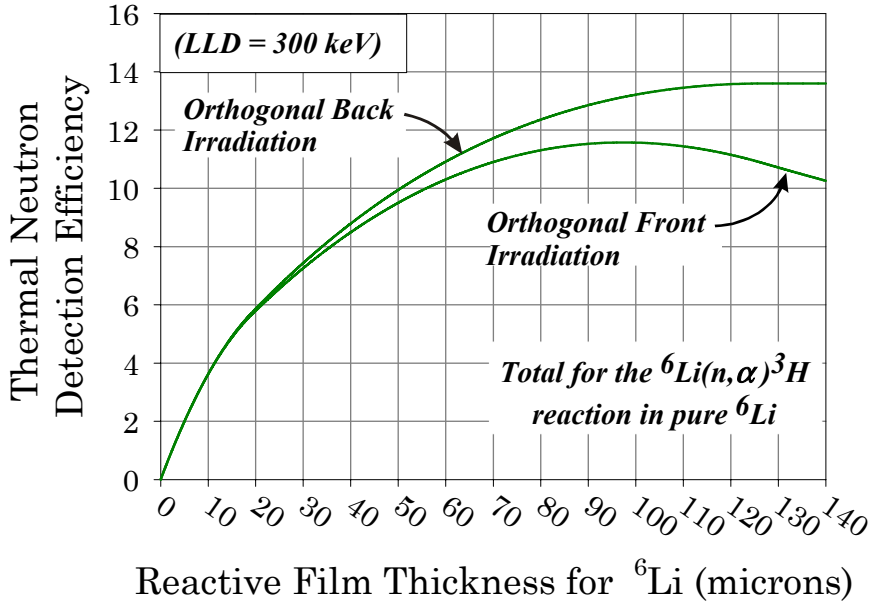


Front Irradiation

Back Irradiation

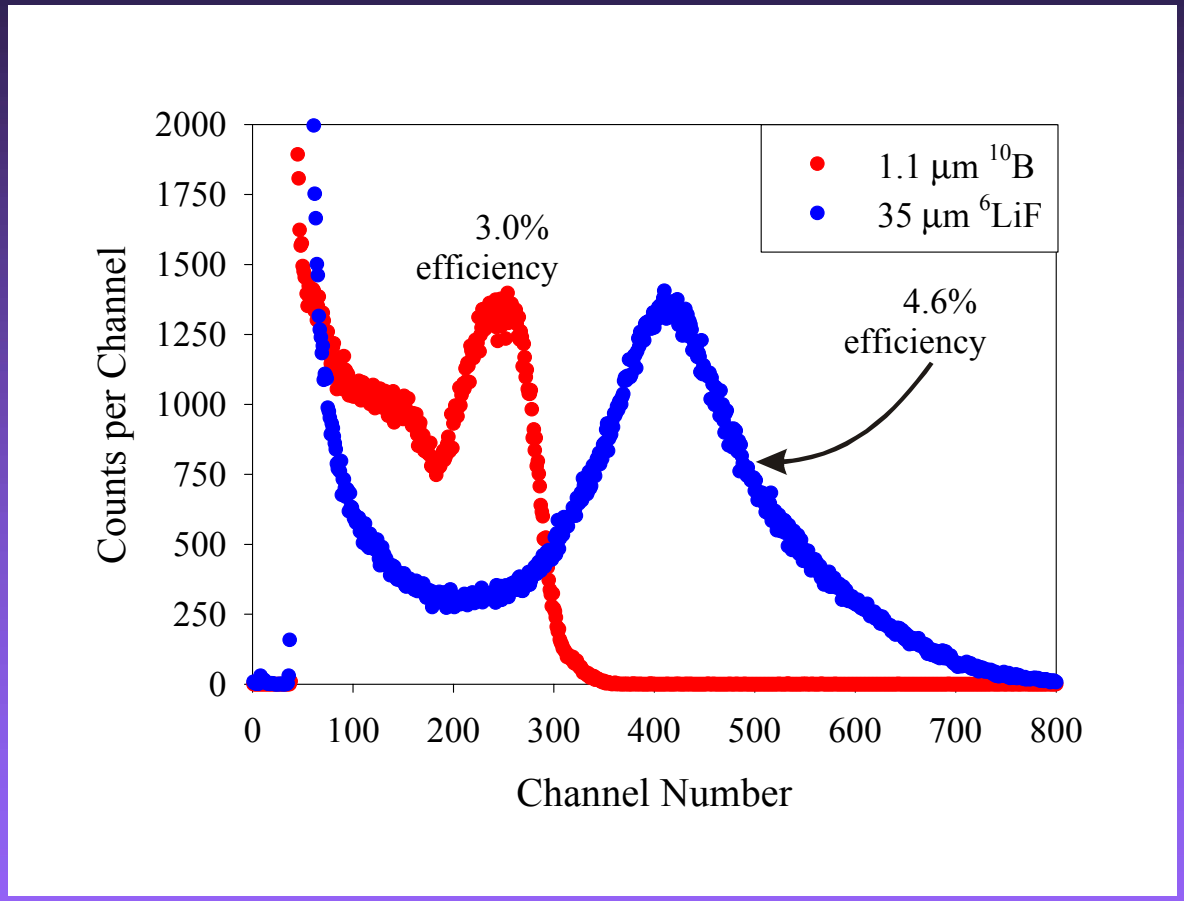
Optimum Thermal Neutron Detection Efficiency





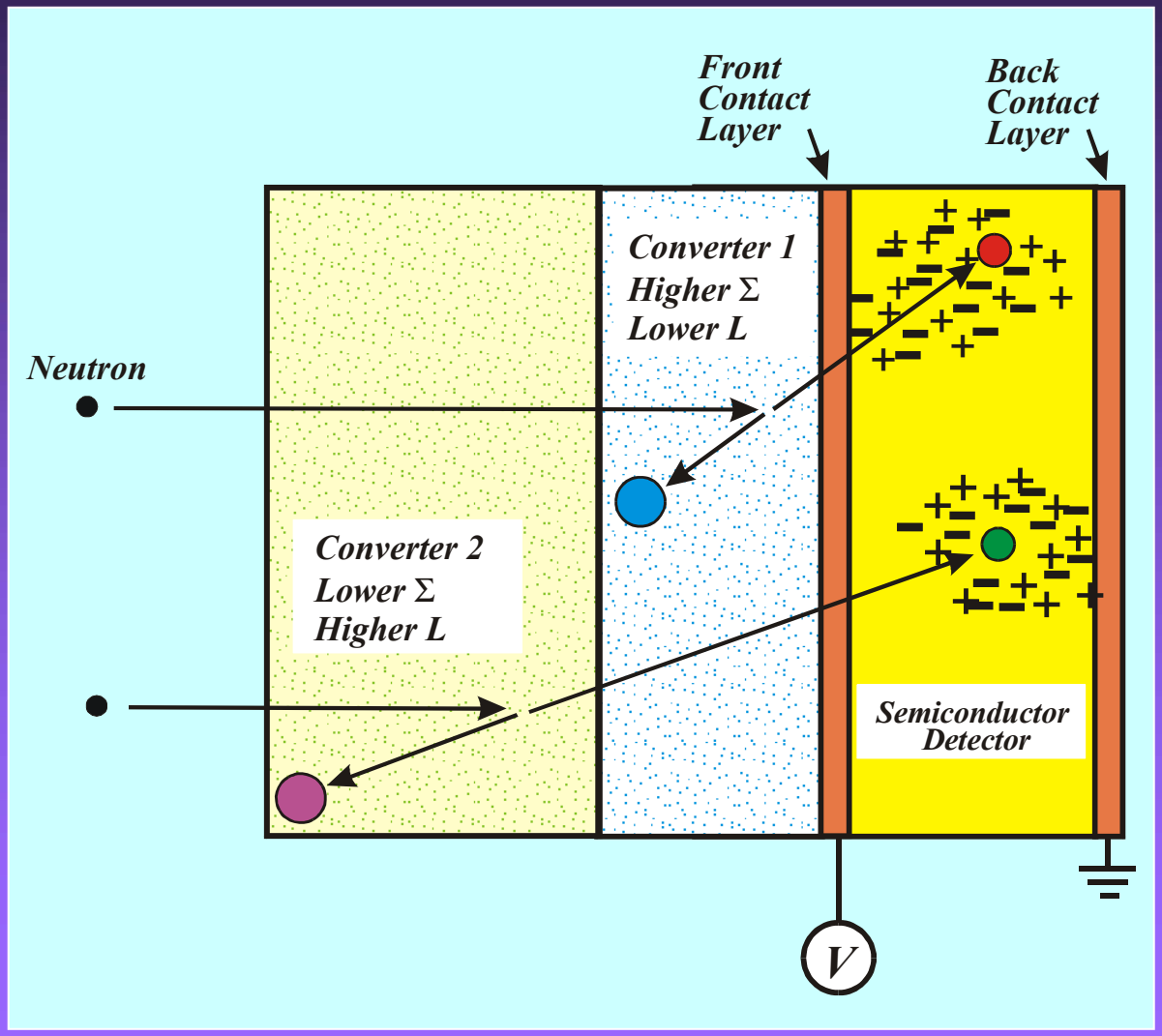
With the *LLD* set at 300 keV equivalent, maximum efficiencies range from 4% up to 12.8% depending on the <u>film</u> and the <u>irradiation direction</u>.

Comparison Spectra of ^{6}LiF and ^{10}B-Coated Devices



^{10}B-coated devices require less material while ^{6}LiF-coated devices have improved gamma ray discrimination.

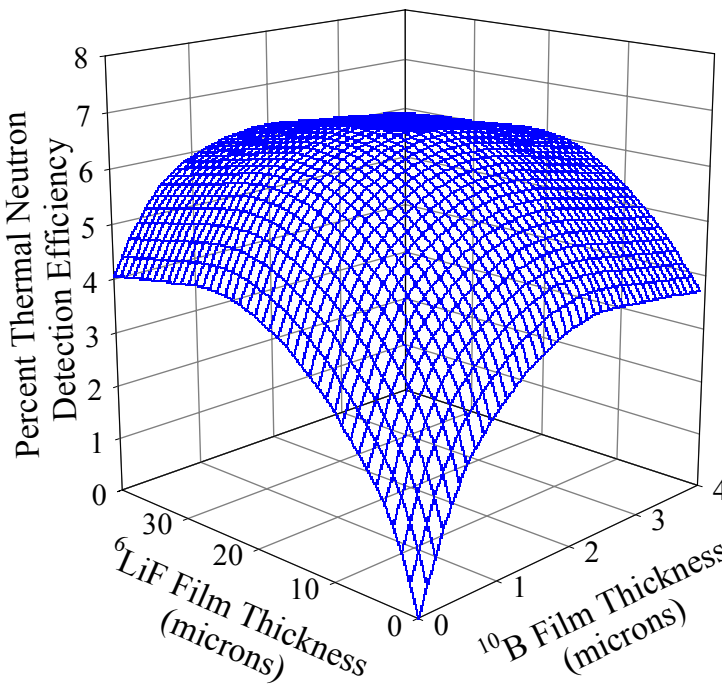
Double-Coated Design

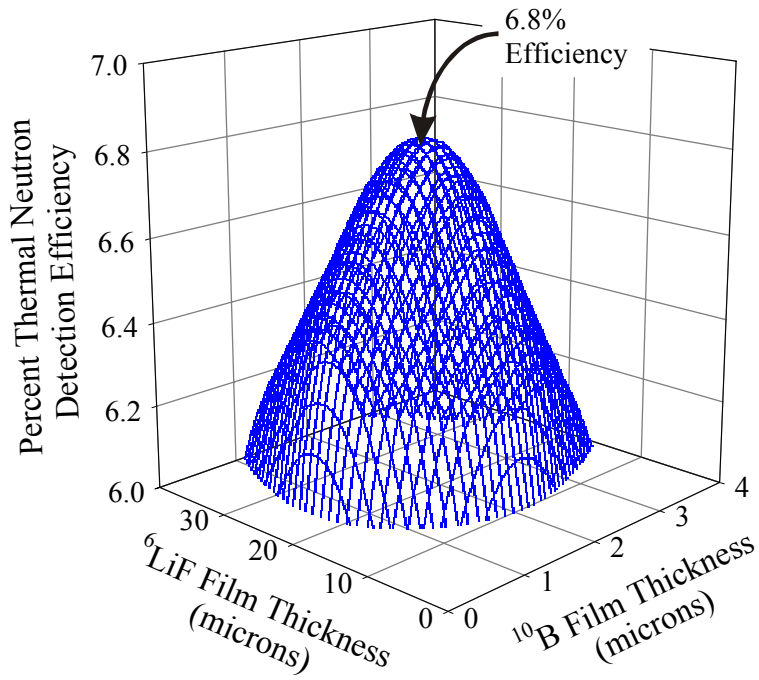


First Coat:
High Σ, Low L

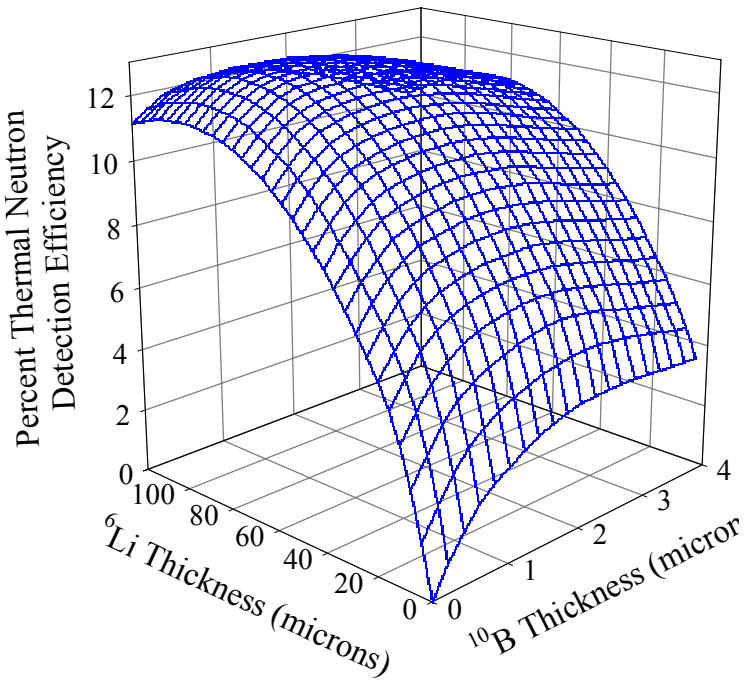
Second Coat:
Low Σ, High L

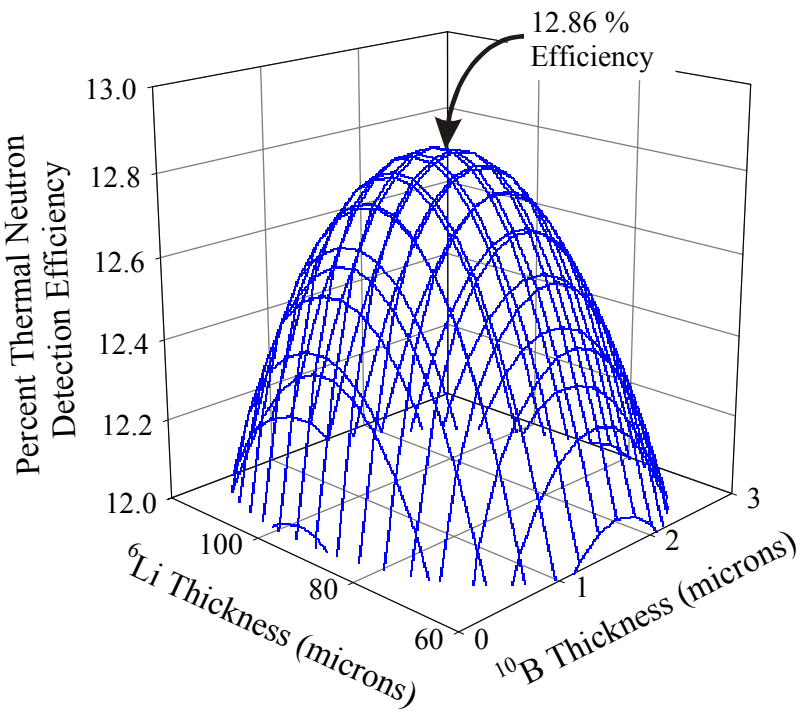
$^{6}LiF/^{10}B$ System



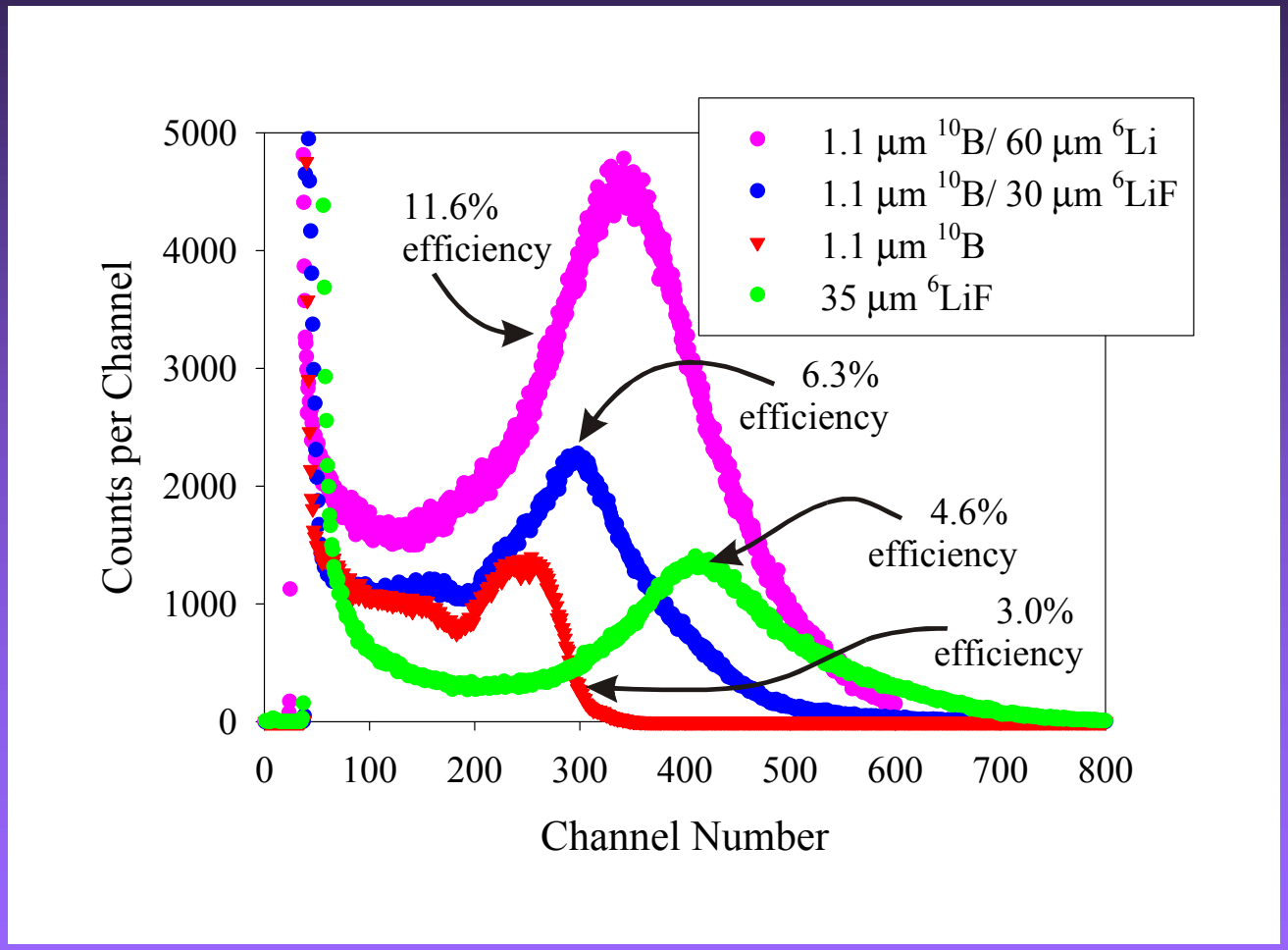


$^{6}Li/^{10}B$ System

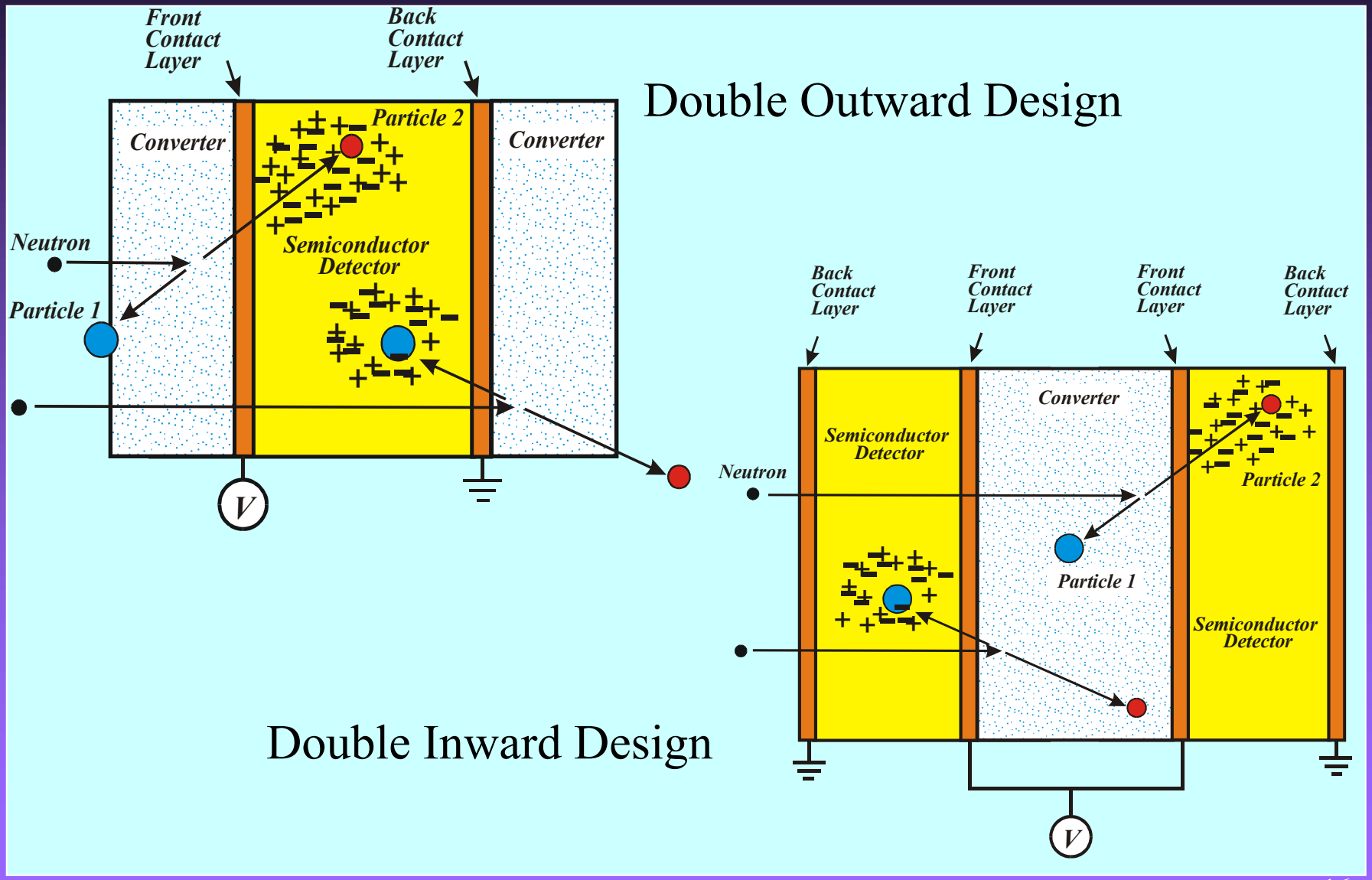




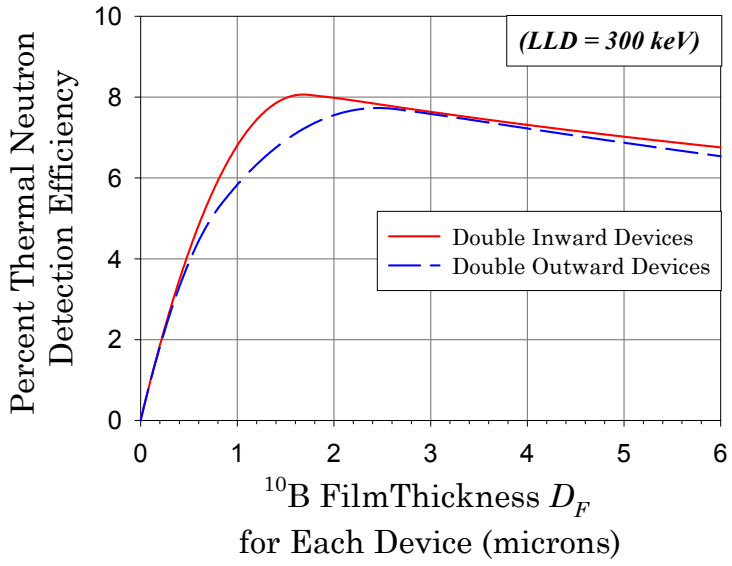
Comparison Spectra of Single-Coated and Double-Coated Devices

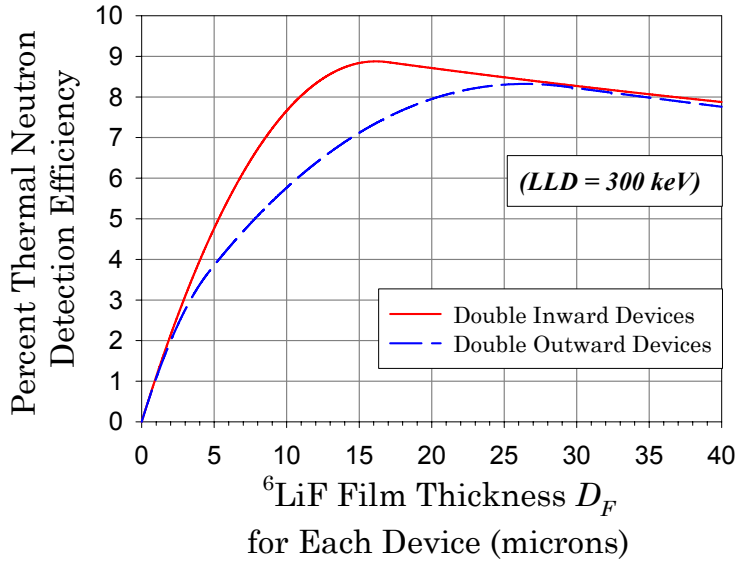


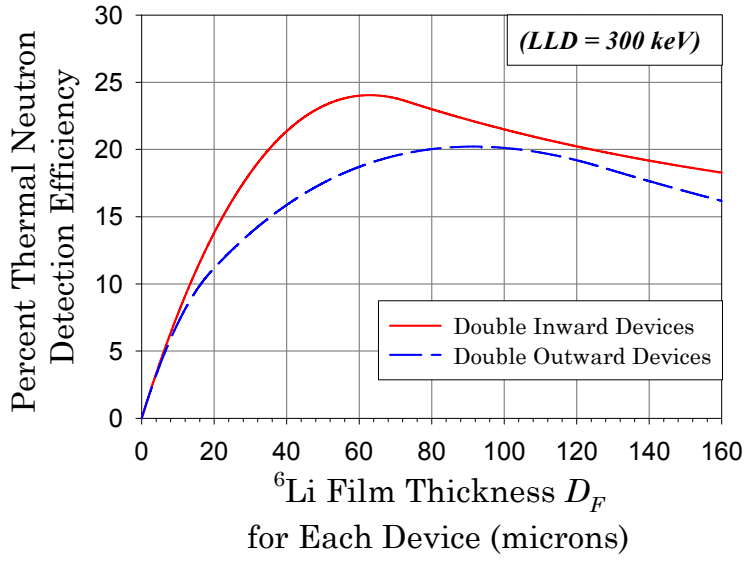
"Sandwich" Designs



"Sandwich" Designs

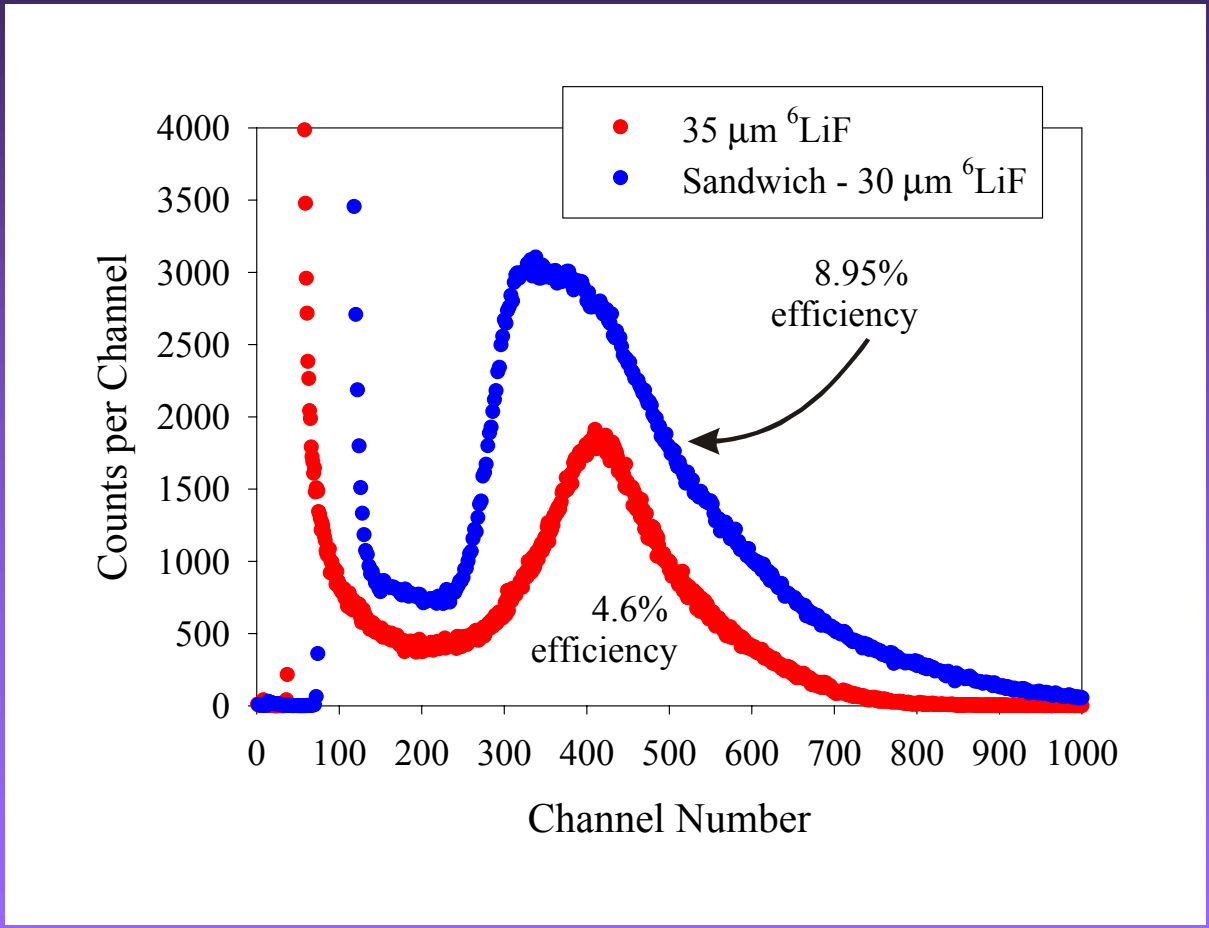




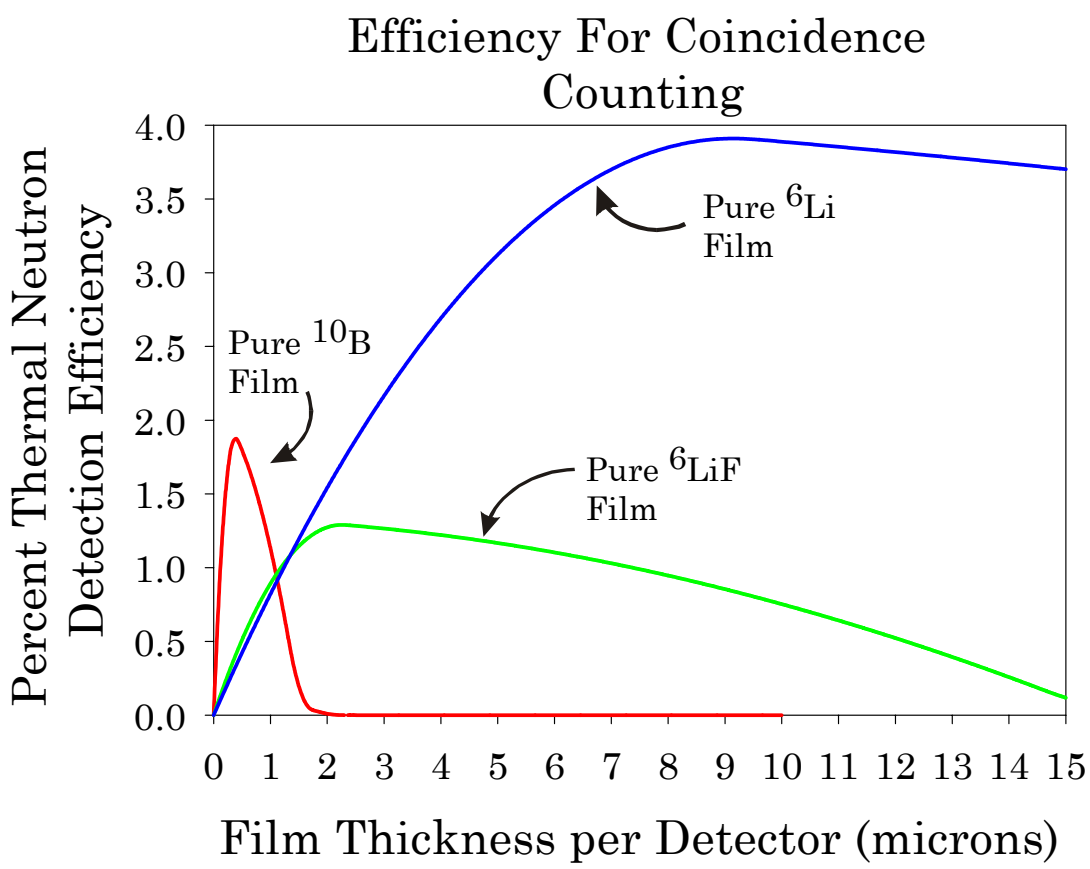


Double-inward design has highest efficiency.

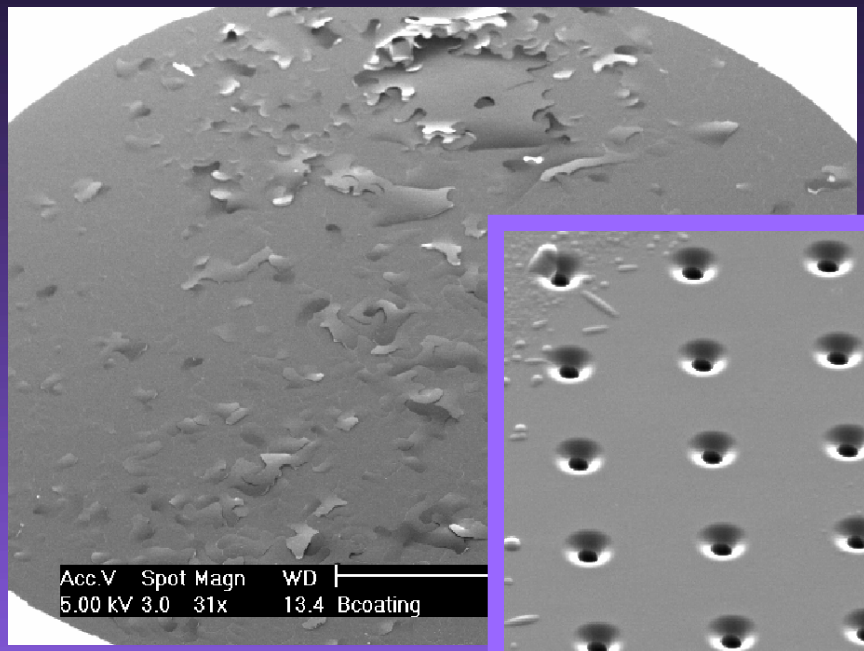
Comparison Spectra of Single and Double-Inward ^{6}LiF-Coated Devices



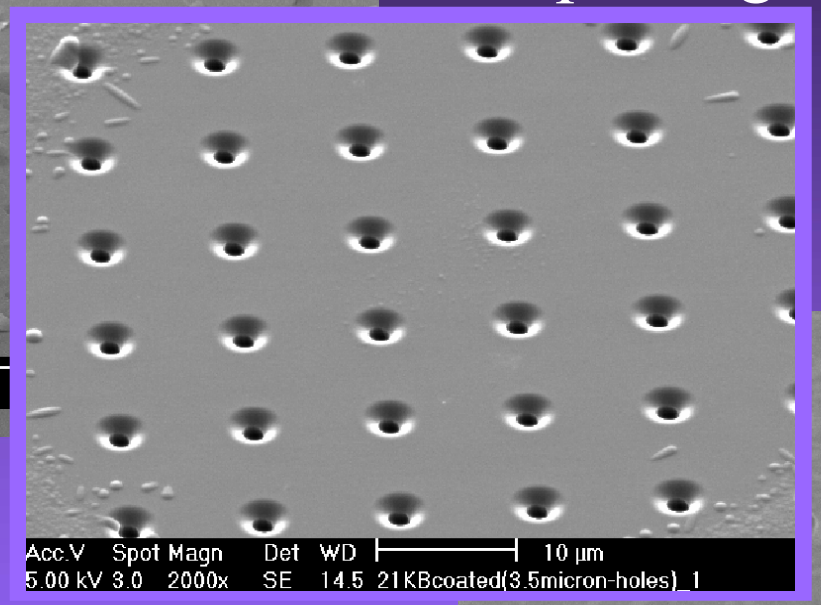
Gamma ray discrimination through coincidence counting of "sandwich" devices



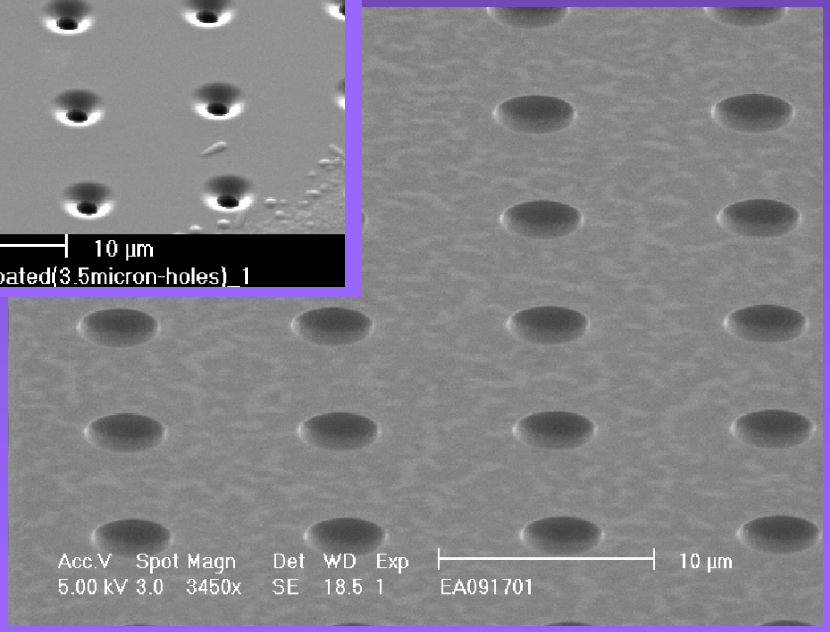
Dimpled Devices



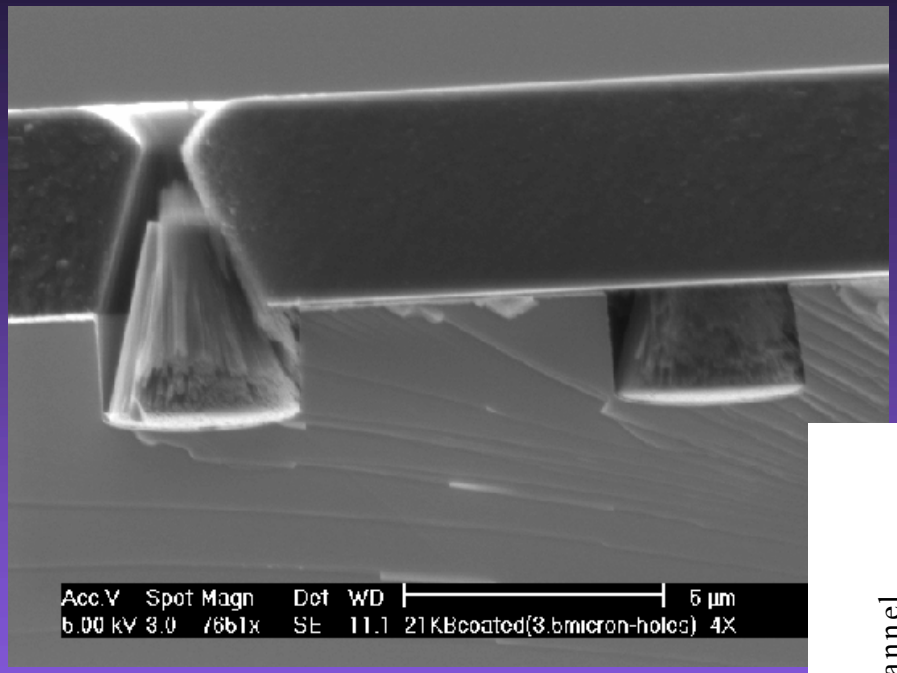
Problems with cracking and peeling of boron films



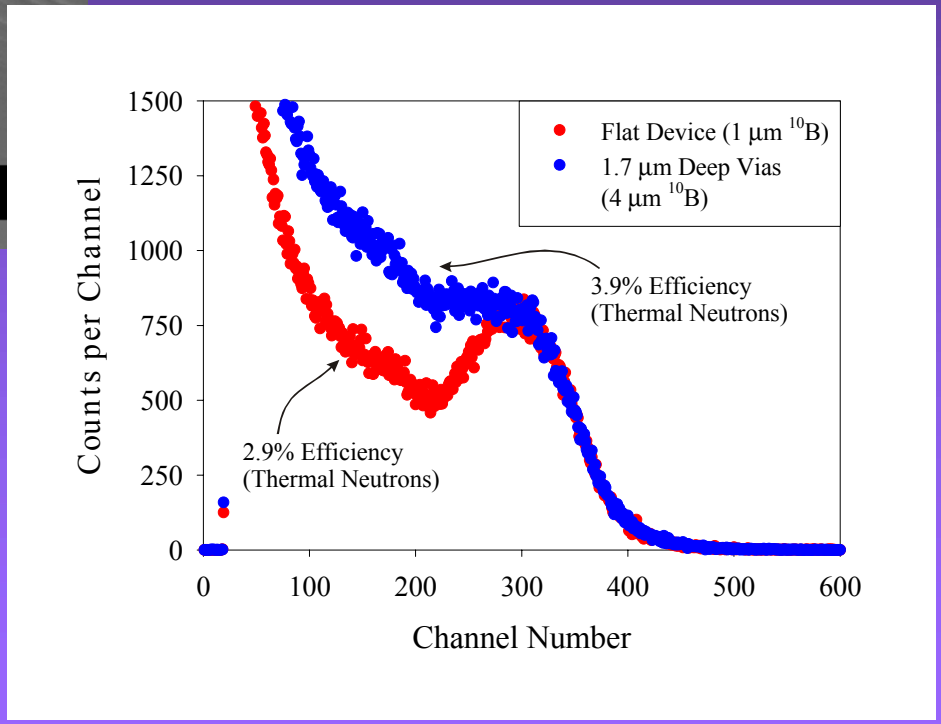
are eliminated by dry etching tiny holes into the substrate before the coatings are applied.



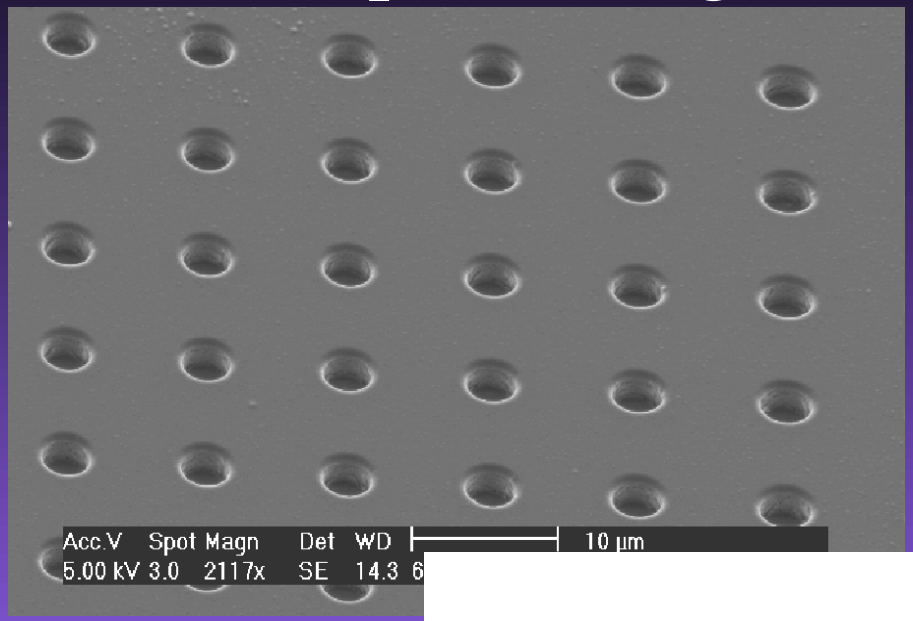
Dimpled Devices

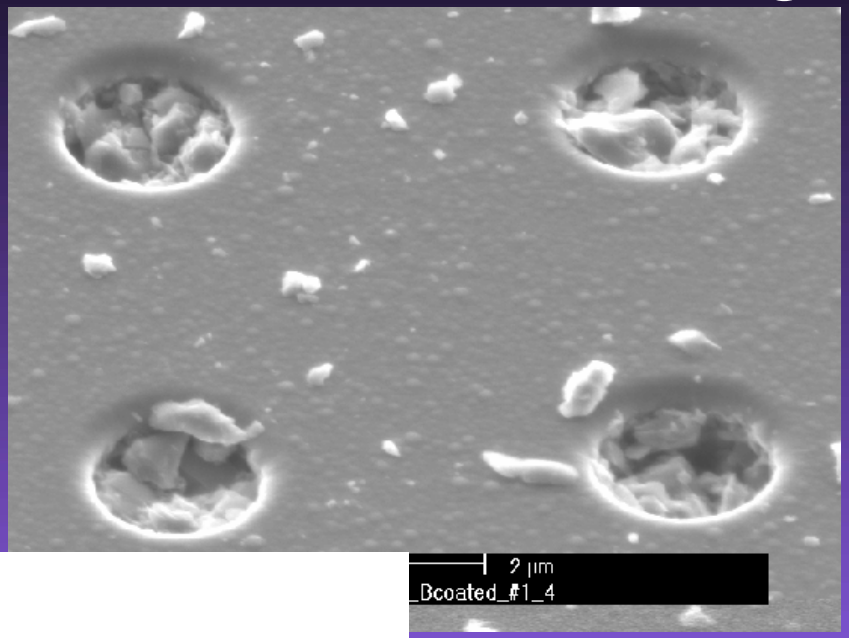


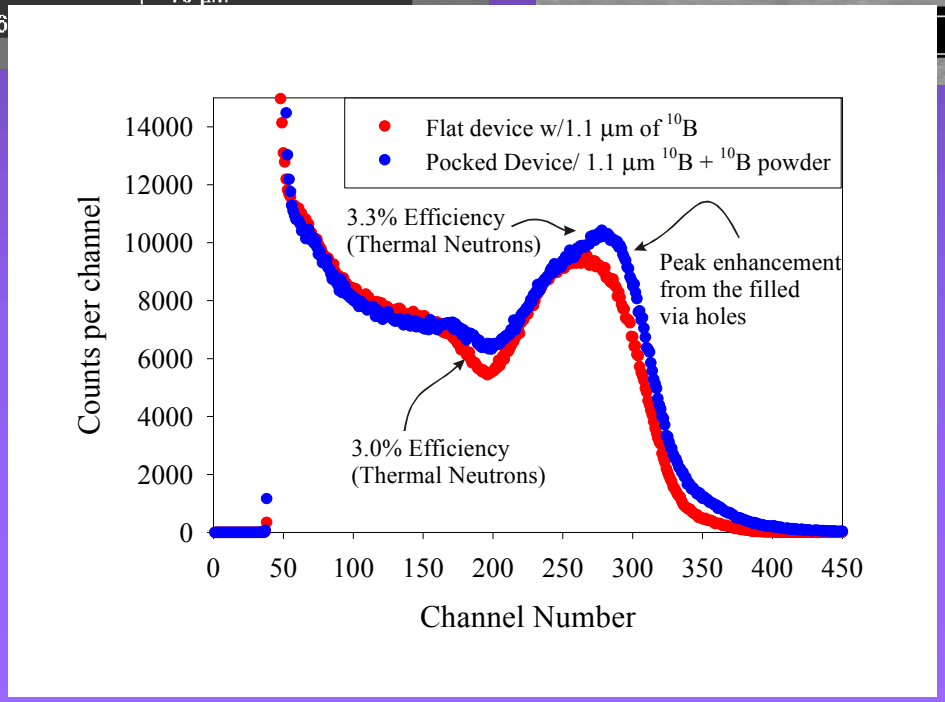
SEM profile of two 3.5 micron diameter holes with a 4.0 micron boron coating



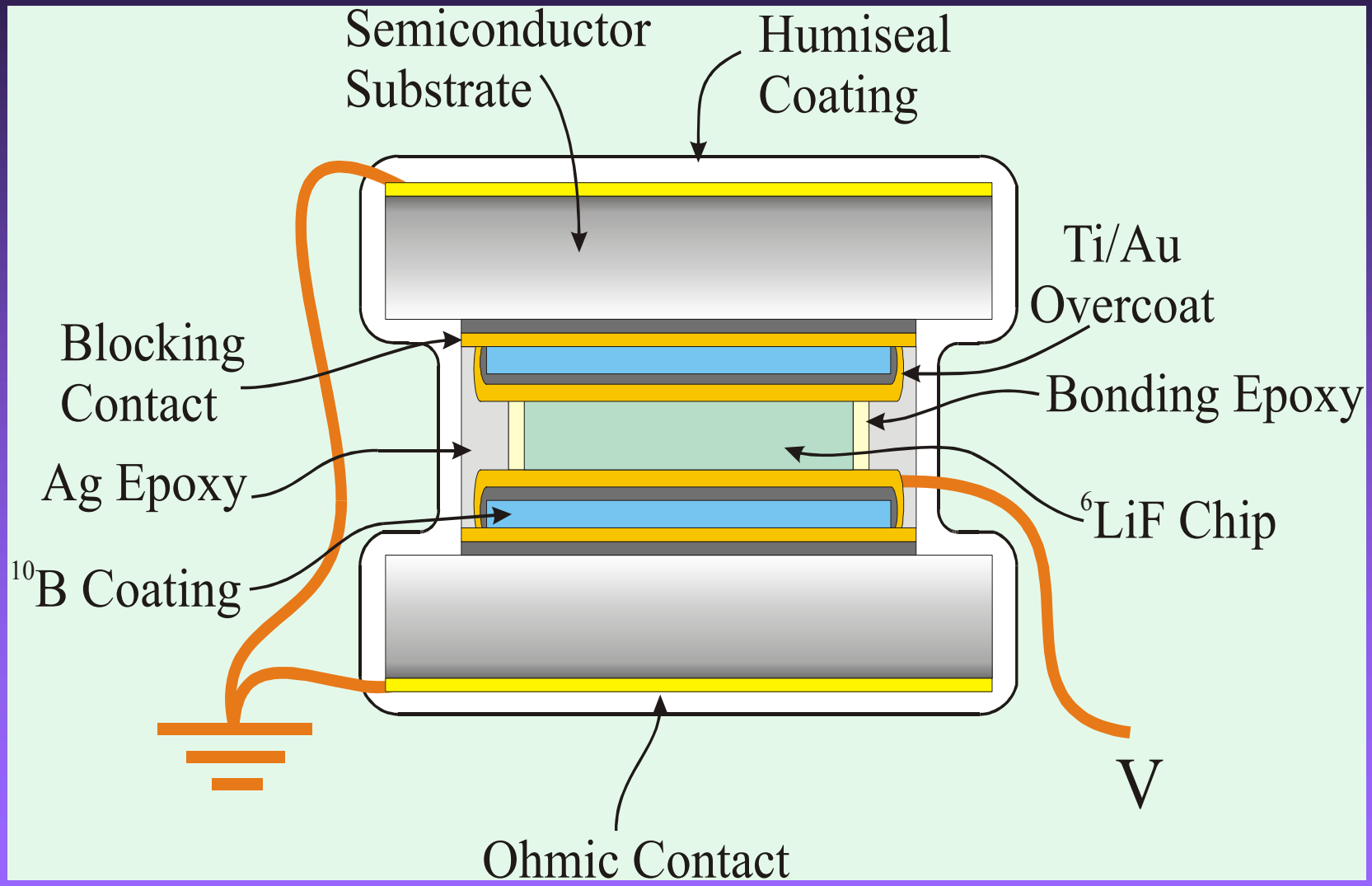
Dimpled Designs with Boron Powder Filling



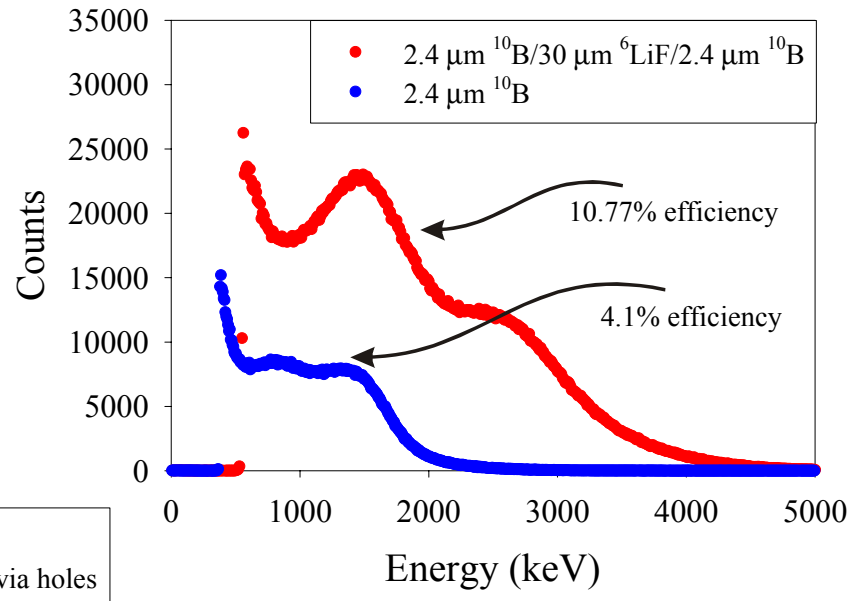


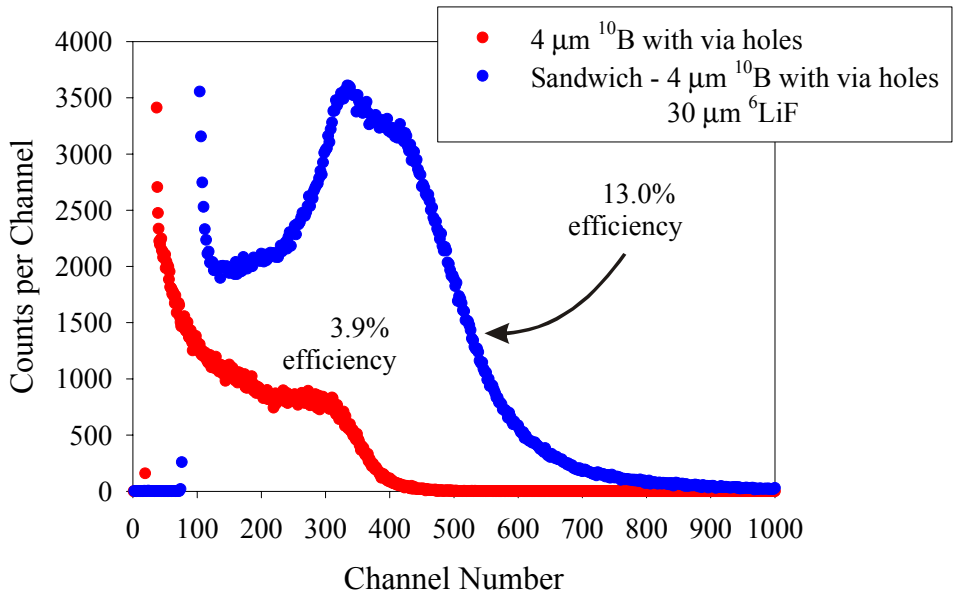


Compound Double-Coated "Sandwich"



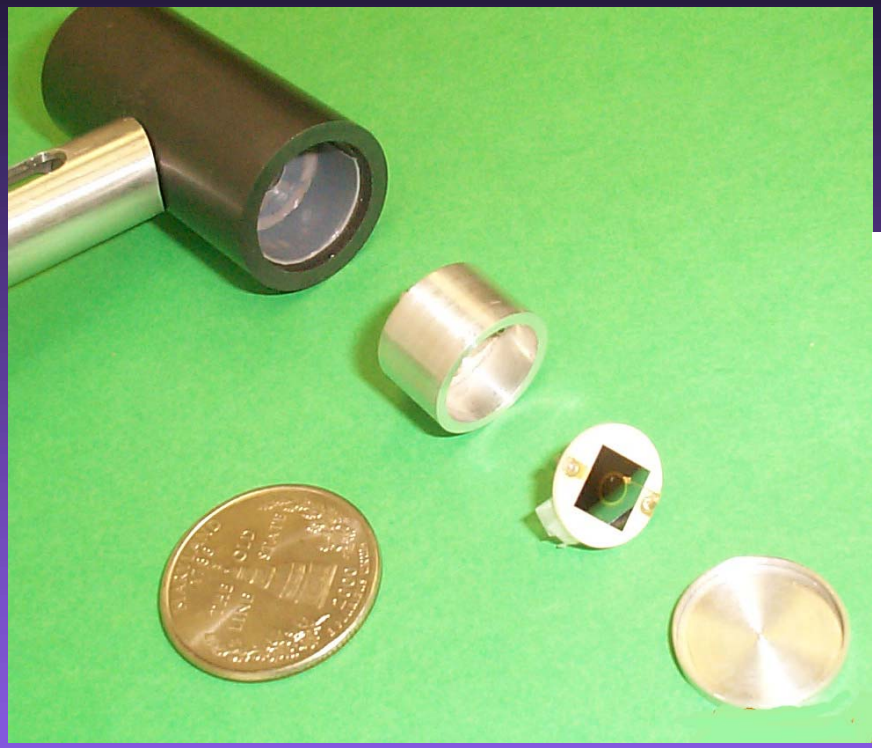
Compound Design



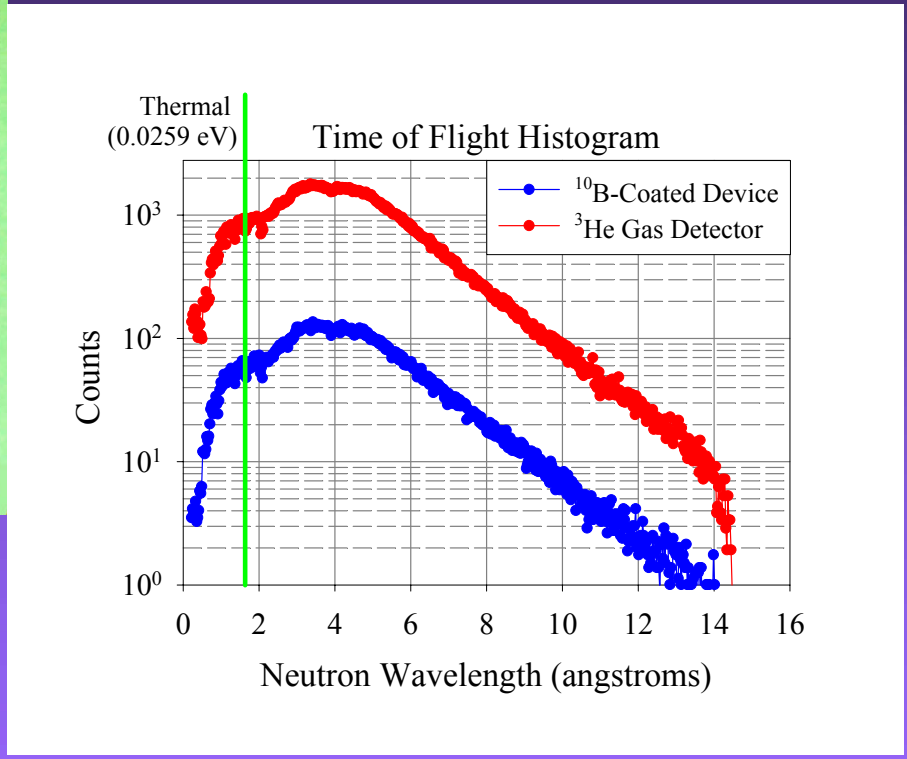


The multiple layers allow for improved thermal neutron intrinsic detection efficiency

Neutron Beam-Stop Monitors

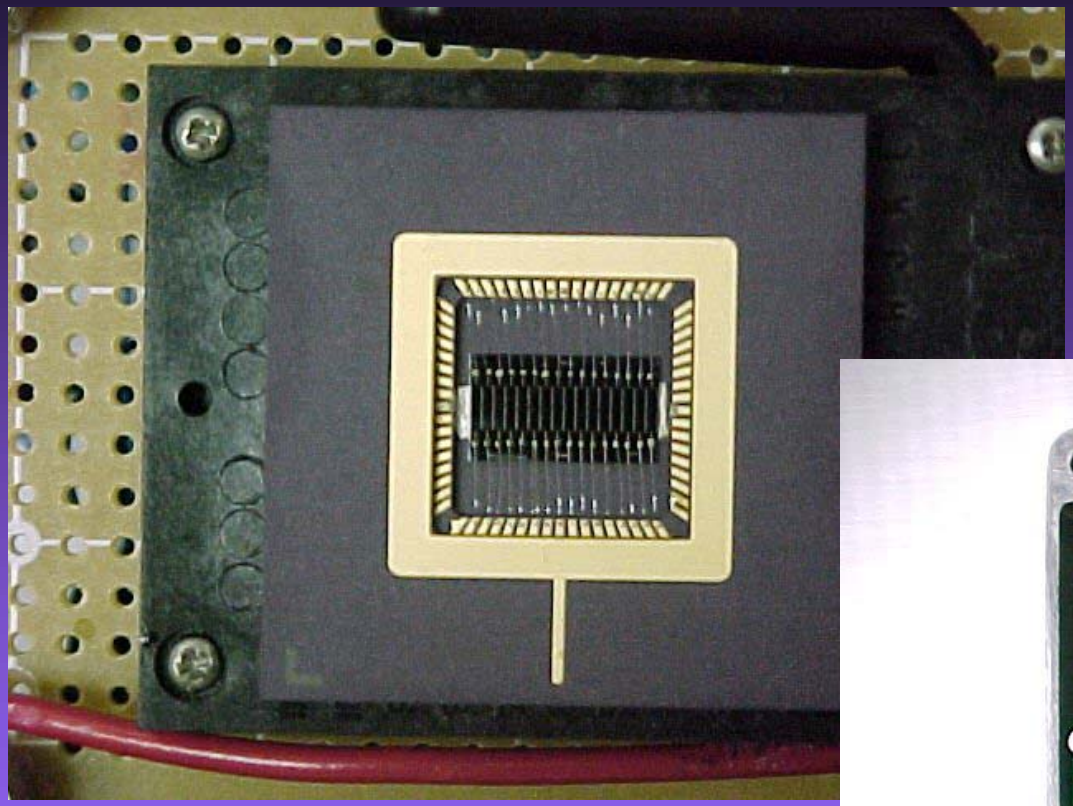


Operated in real time to monitor the transmitted beam of the TOF SAND instrument at ANL



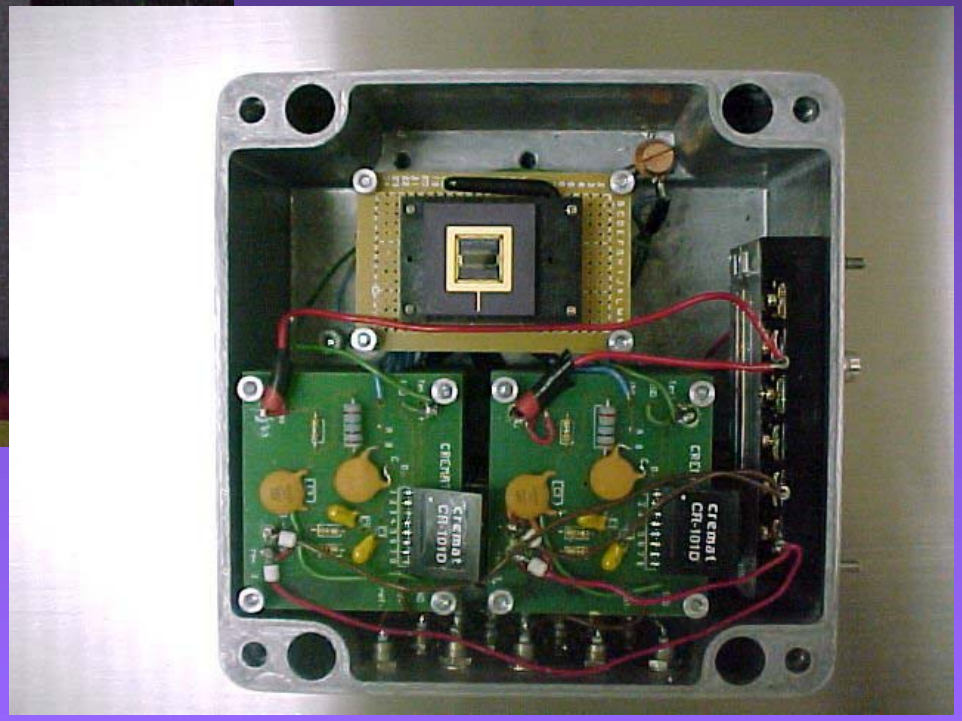
- Small – fits directly in beam stop
- Continuous monitoring
- Relatively insensitive to gamma rays
- Hardened – months of continuous use with no visible degradation
- Concurrent data measurements with other SAND instruments – increases accuracy and effective use of beam time

In-Line Pixel Neutron Detectors



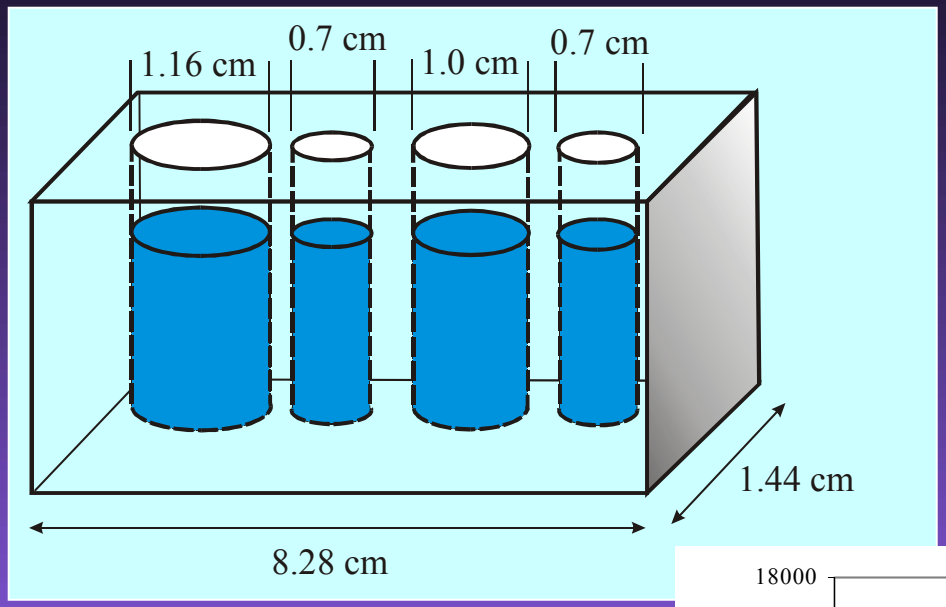
32 Pixel Array –
0.5mm x 1.0 mm pixels

Pixel arrays can yield spatial resolution approaching 10 microns.



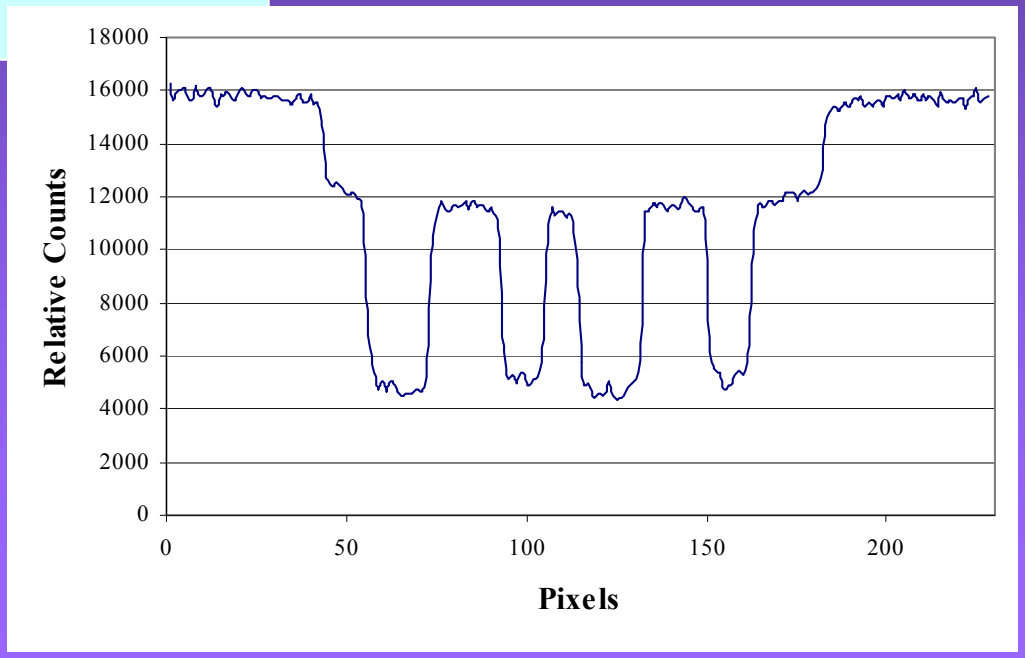
Pixel Array in Testing Box

Profile Results



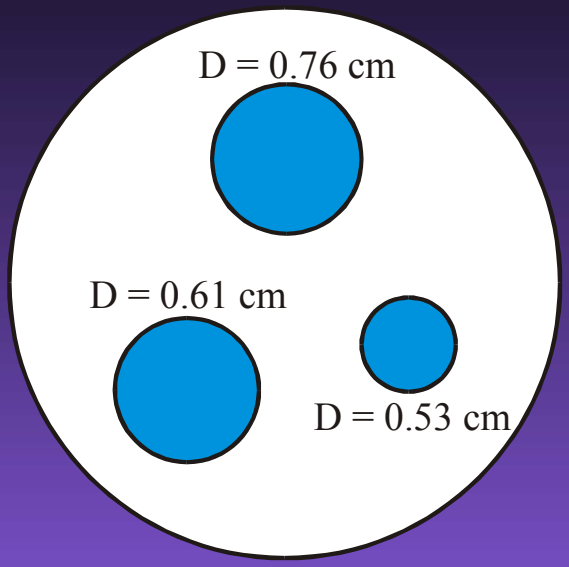
Aluminum test block with water-filled holes

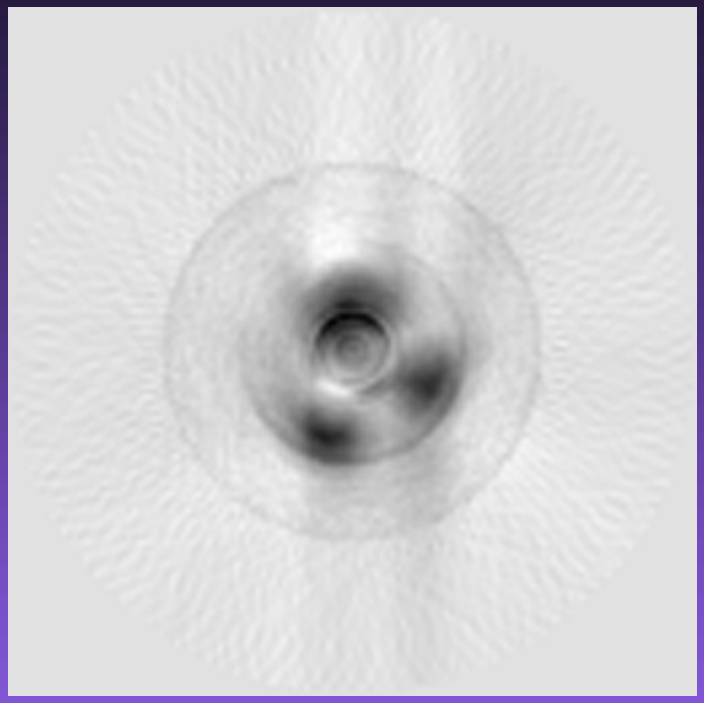
Thermal neutron transmission count rate



Tomographic Slice Results

Al block with water columns

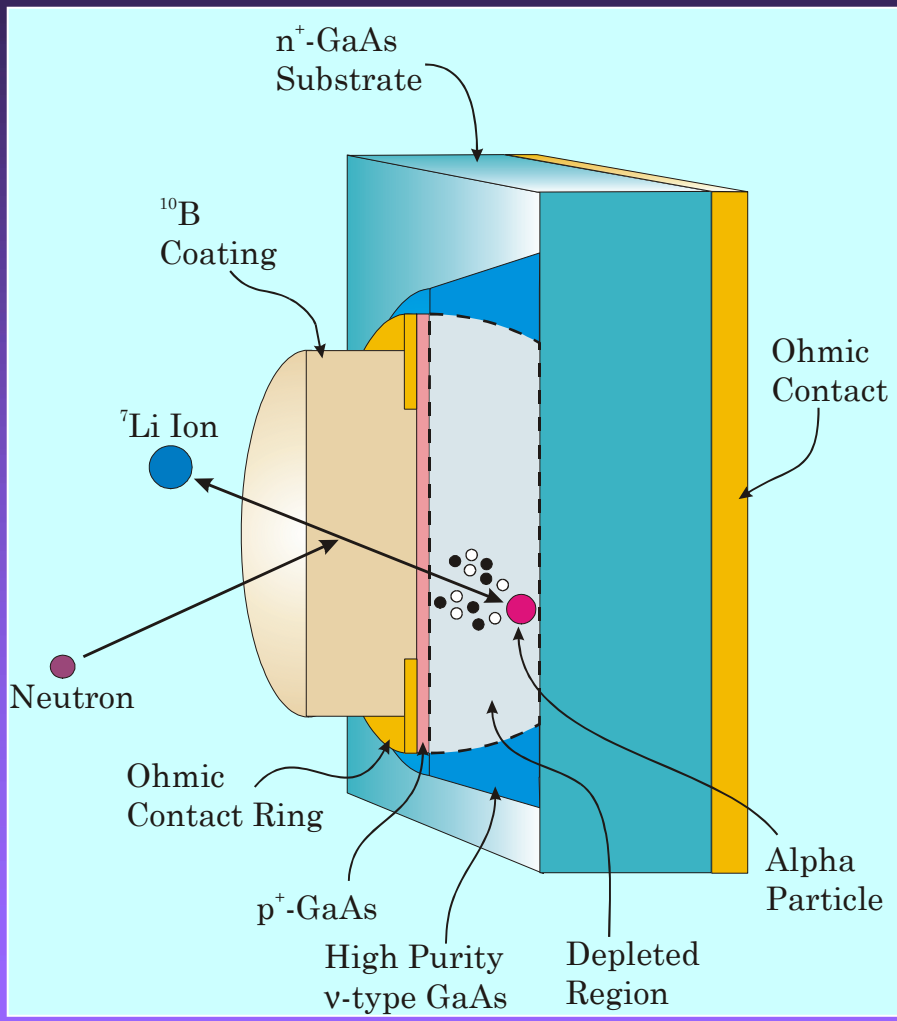


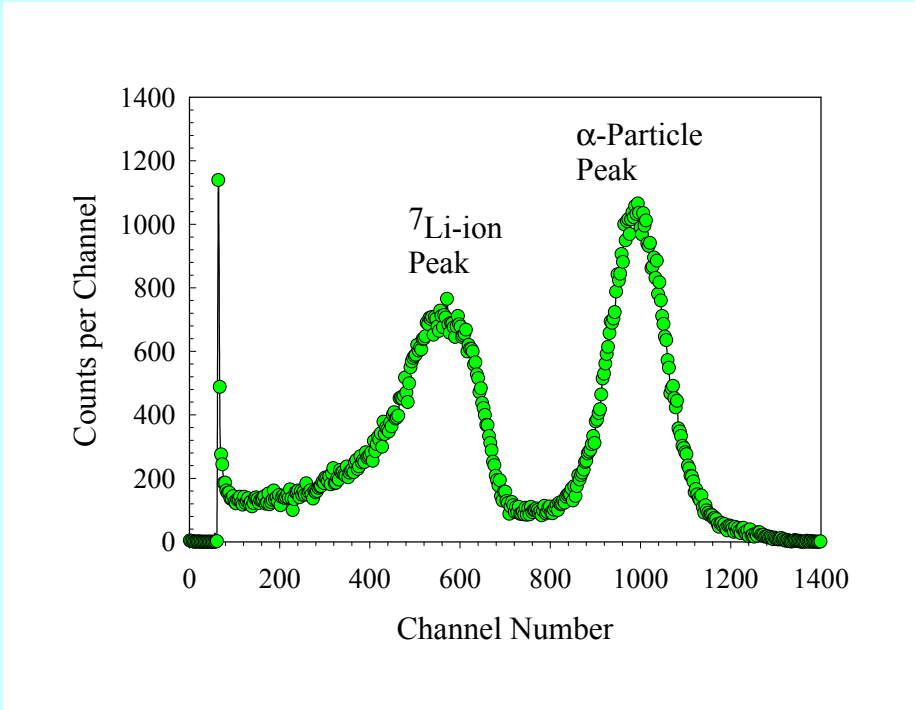


Reconstruction with Shepp and Logan filter

Water column image reconstruction

Self-Biased Designs





The ^{157}Gd Option
- advantages -

- High thermal neutron cross section.

  Natural Gd has a cross section of 46,000 barns for 2200 m/s neutrons (240,000 barns for pure ^{157}Gd).
- Ultimately highest single film efficiency.

  Intrinsic efficiencies for single film devices of 10% (natural Gd) and 22% (^{157}Gd).
- Thinner films required than ^{10}B or ^{6}Li based films (6 microns for natural Gd and 3 microns for enriched ^{157}Gd).

The ^{157}Gd Option
- disadvantages -

- Low energy reaction products for $^{157}Gd(n,\gamma)^{158}Gd$ reactions

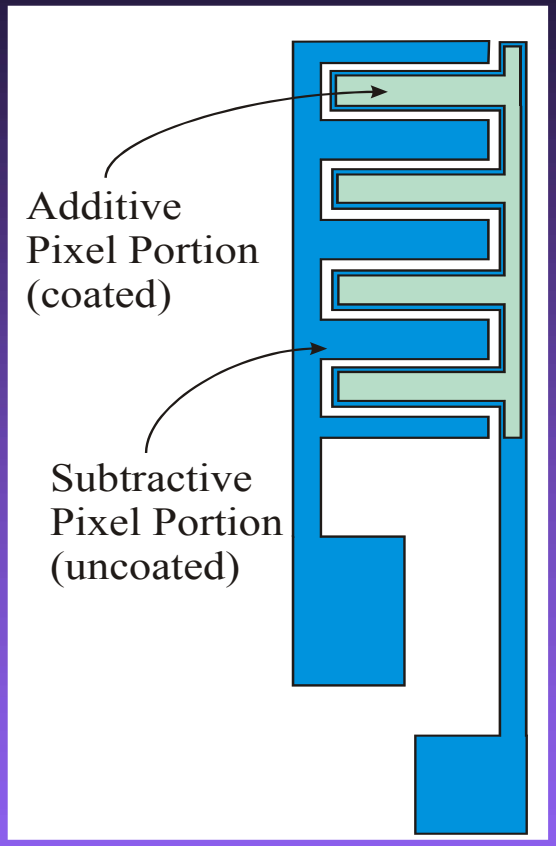
  Low energy conversion electrons ranging from 29 keV up to 228 keV. Most abundant emission is at 71 keV.
- *LLD* setting reduces number of neutron events recorded, thereby reducing Gd effectiveness.
- Enriched ^{157}Gd can be costly.

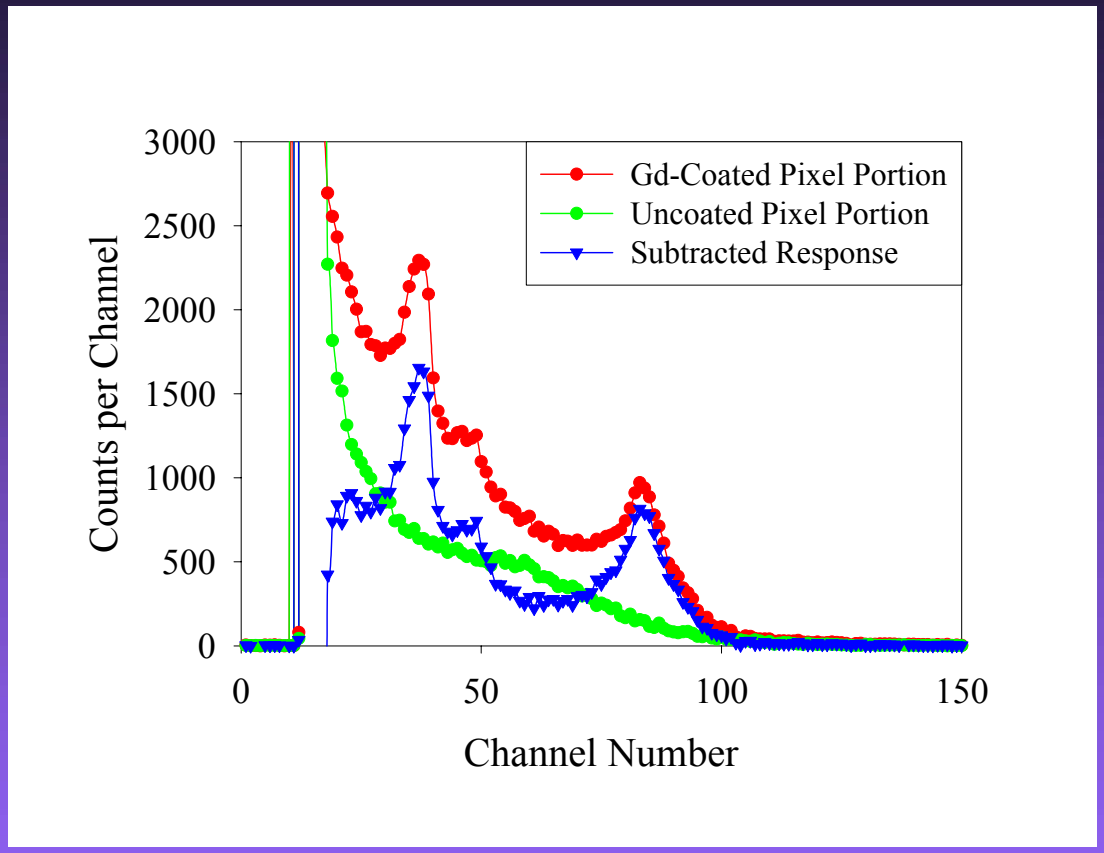
- Single pad detectors have been developed on Si,amorphous Si, GaAs, and diamond substrates.
- Pixel detectors have been developed on Si, amorphous Si, and GaAs substrates.

- B. Feigl, H. Rauch, Nucl. Instr. and Meth., 61 (1968) 349.
- T. Aoyama et al., Nucl. Instr. and Meth., A314 (1992) 590 .
- A. Mireshghi et al., IEEE Trans. Nucl. Sci., NS-41 (1994) 915.
- F. Foulon et al., Proc.MRS, 487 (1998) 591.
- D.S. McGregor et al., Proc. SPIE, 4784 (2002) 164.

-- ***many others***

Compensated Pixel Design





Gd-coated compensated pixel devices with the self-biased configuration are under investigation.

Solid Form Neutron Detectors

Gamma ray emitting semiconductors (examples):

CdTe, CdZnTe, HgI_2

- Kansas State University
- Sandia National Laboratories

Particle emitting semiconductors (examples):

BN, BP, BAs, BBO, B_4C, $Li_2B_4O_7$

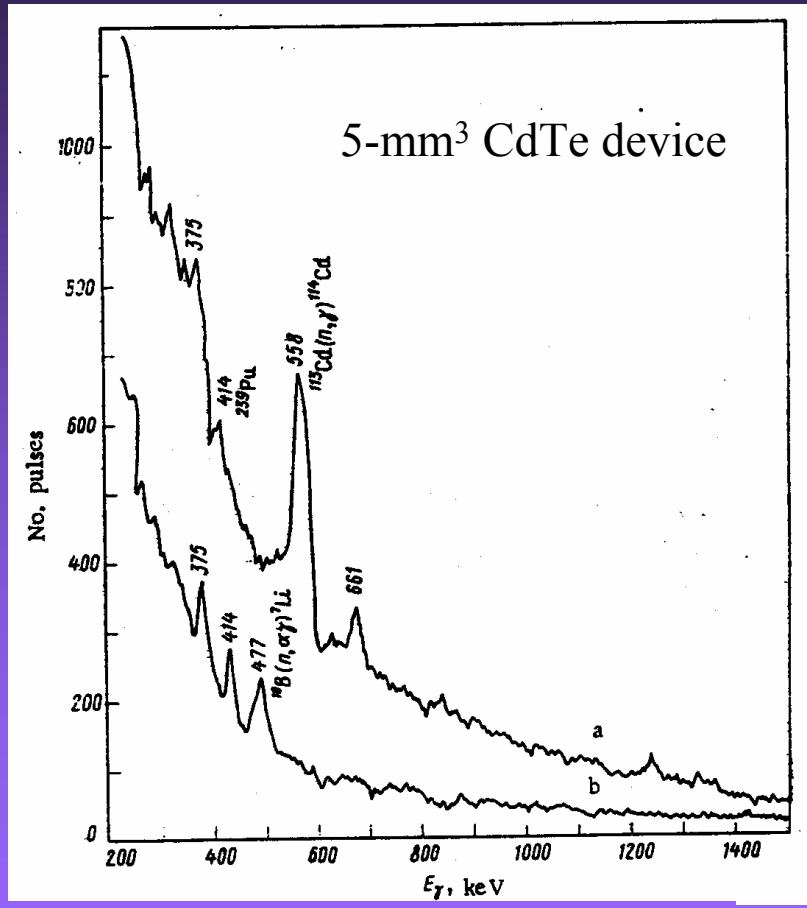
- Sandia National Laboratories
- University of Nebraska
- Kansas State University
- Radiation Monitoring Devices

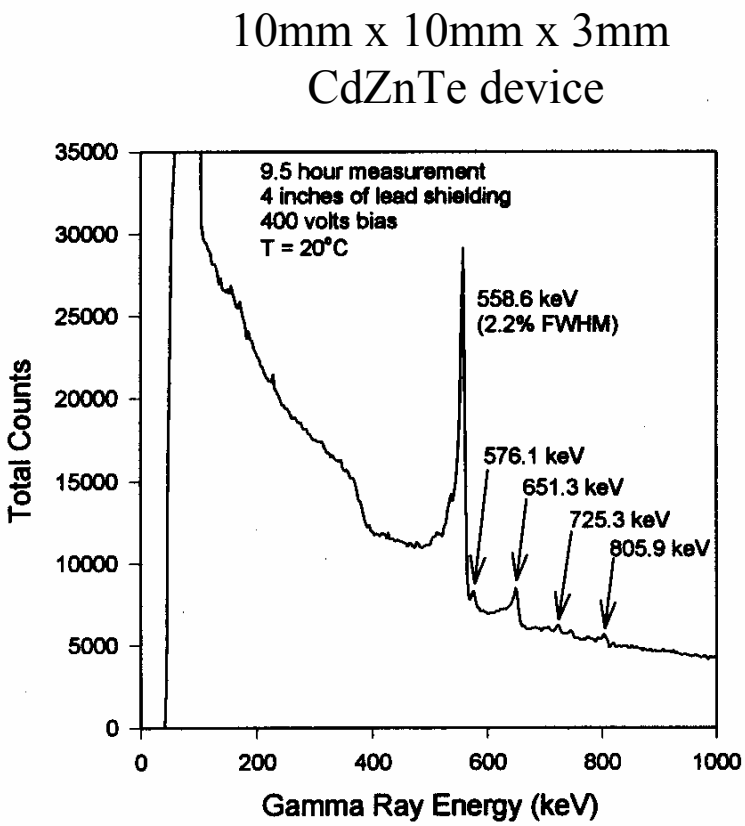
Cd-based devices

- The concept utilizes the $^{113}Cd(n,\gamma)^{114}Cd$ reaction.
- ^{113}Cd occurs at a natural abundance of 12.26%.
- 20,000 barn thermal neutron cross section
- A 3mm thick CdTe device is virtually opaque to thermal neutrons.
- Numerous gamma ray energies are emitted, yet prominent emissions are at 558.6 keV and 651.3 keV.

Although highly efficient for neutron absorption, the devices do not efficiently absorb the neutron induced prompt gamma rays. As a result, detection efficiency is much smaller than absorption efficiency.

Devices from CdTe and CdZnTe have been explored

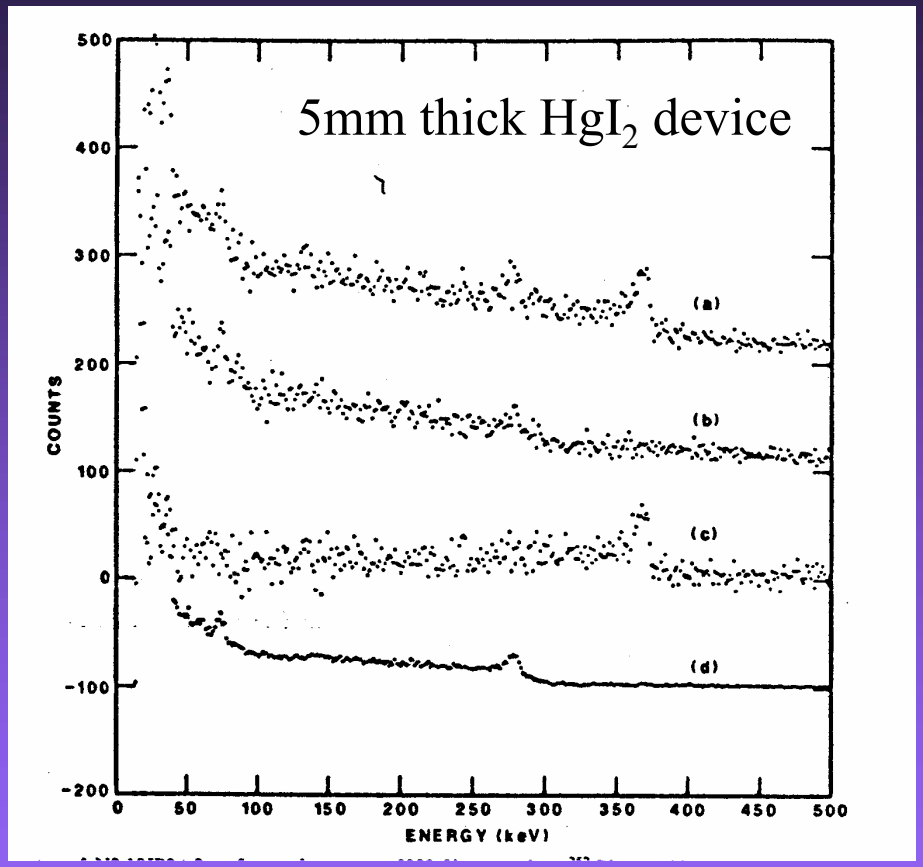




A.G. Vradii, et al., Sov. Atomic Energy, 42 (1977) 633.

D.S. McGregor, et al., Nucl. Instr. and Meth., A381 (1996) 498.

HgI_2 Device Concept



A.G. Beyerle and K.L. Hull, Nucl. Instr. and Meth., A256 (1987) 377.

The neutron induced response is shown in spectrum (c).

- The concept utilizes the $^{199}Hg(n,\gamma)^{200}Hg$ reaction.
- ^{199}Hg occurs at a natural abundance of 17%.
- 2000 barn thermal neutron cross section.
- Prominent emission at 370 keV.
- Increased capture of prompt gamma rays.

Boron-based devices

Commonly studied materials include BP, BAs, and BN – other materials include BBO, B_4C, and $Li_2B_4O_7$

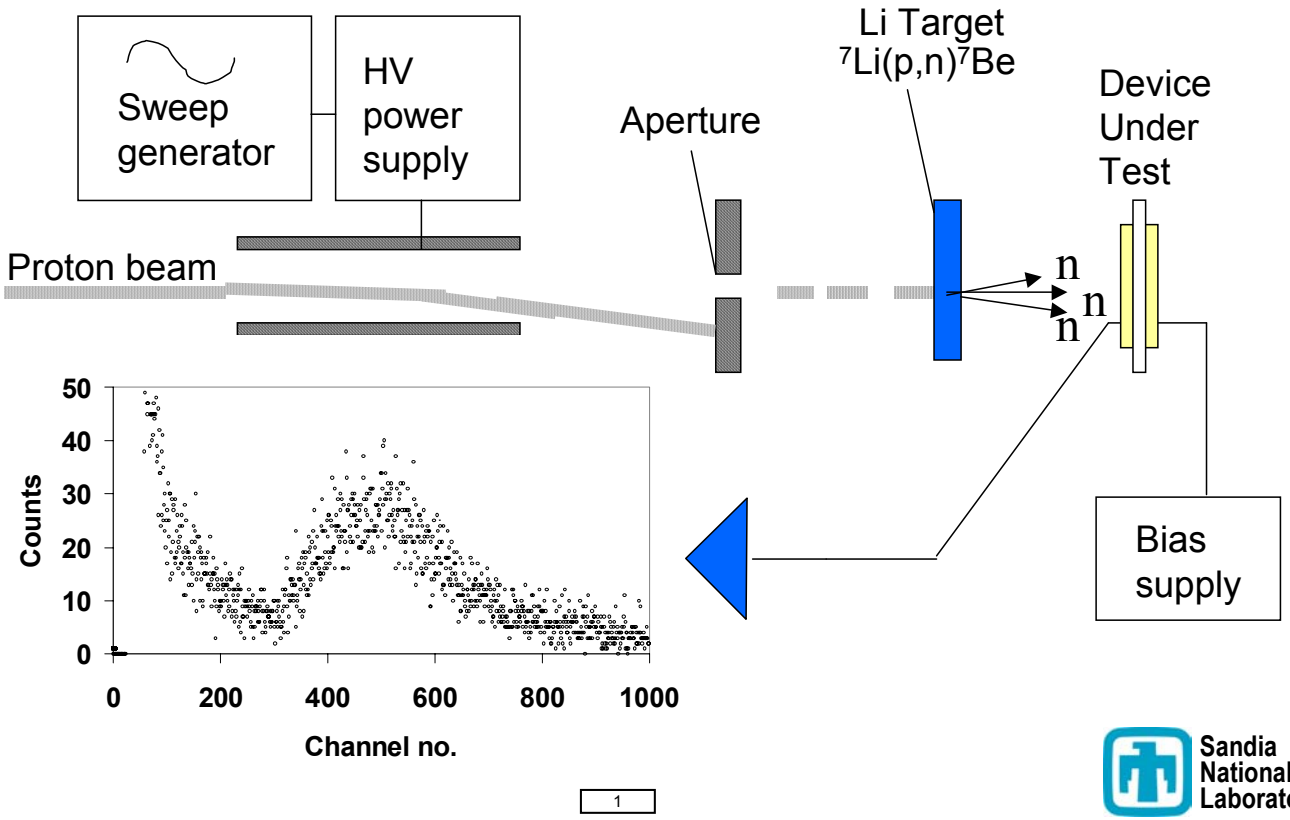
-to date, no clear success has been claimed.

BP and BAs decompose in the high temperatures required for melt growth. Usually, the materials are grown through chemical vapor deposition.

Attempts at producing BP devices through CVD methods (as with other boron compounds) were performed on n-type Si wafers, resulting in B-coated Si diodes rather than BP devices.

Barium Borate Devices

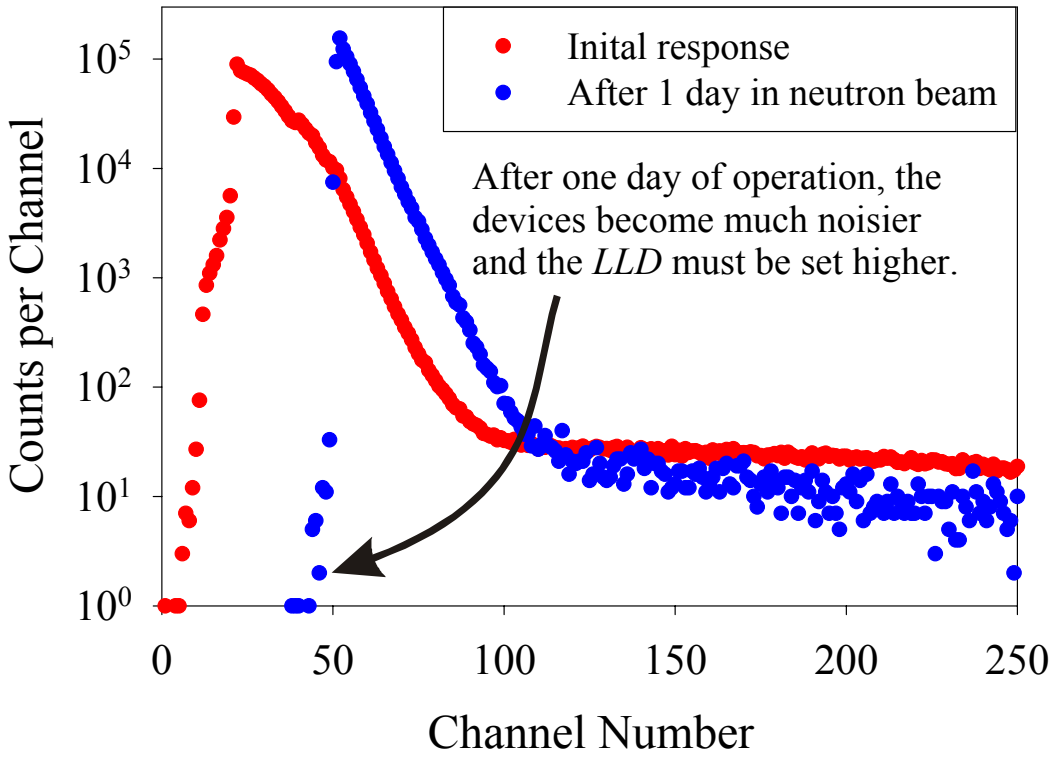
Pulsed microprobe operation



Sandia National Laboratories

F. P. Doty, I. Zwieback, W. Ruderman, patent US-6,388,260.

Results from solid pyrolytic BN material (from Advanced Ceramics)



The device was 2mm thick and 5mm x 5mm in area. It required 900 volts to operate. Pulses were observed, but device degradation was obvious after one day.

Summary

- Thin-Film-Coated Semiconductor Diodes can be used as thermal neutron detectors.
- The detectors are compact, operate at room temperature, and are rugged.
- Efficiency for simplistic devices is limited.
- Compound device designs offer improved thermal neutron detection efficiency.
- Pixel devices can be developed for imaging.

Summary (cont.)

- Solid form semiconductor neutron detectors offer superior neutron absorption to thin-film-coated devices.
- Prompt gamma ray emitting devices function, but a high percentage of prompt gamma rays escape.
- Boron and lithium based solids have shown limited performance and are still in the materials development and research phase.

A few references regarding thin-film-coated pixelated devices:

1. A. Mireshghi et al., IEEE Trans. Nucl. Sci., 39 (1992) 635.
2. A. Mireshghi et al., IEEE Trans. Nucl. Sci., 41 (1994) 915.
3. C. Petrillo et al., Nucl. Instr. Meth. A378 (1996) 541.
4. D.S. McGregor et al., IEEE Trans Nucl. Sci., 43 (1996) 1357.
5. M. Campbell et al., Nucl. Instr. Meth., A395 (1997) 457.
6. J. Schelten et al., Nucl. Instr. Meth., A398 (1997) 447.
7. C. Petrillo et al., Nucl. Instr. Meth., A424 (1999) 523.
8. A.J. Peurrung, Nucl. Instr. Meth., A443 (2000) 400.
9. D.S. McGregor et al., Nucl. Instr. Meth., A500 (2003) 272.