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COMPREHENSIVE EXAMINATION

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Committee Chair:
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Collaboration

This work is being performed in collaboration with

Brimrose Technology – Sudhir Trivedi and Susan Kutchner
Sandia Laboratories –Mark Derzon, Jedidiah Styron, and Paul Galambos

High Resolution Room Temperature Radiation Detection Using Correlated Scintillation and Charge Measurements

1. Motivation for work
2. Scintillation Detection
3. Charge Collection
4. Prior Work on Dual Mode Collection
5. Samples
   - *Mercurous Bromide,* Hg_2Br_2
   - *CdMgTe*
6. Experimental Setup
7. Present Results

Overview

- This work seeks to develop a path toward a high resolution room temperature gamma detector through the use of anticorrelation of scintillation and charge measurements of Hg_2Br_2 and CdMgTe.

- How work came about

Higher resolution provides greater information content in each collected gamma ray

- Improved resolution
  - *requires fewer counts for the same level of information*
  - *Allows for discriminating between similar isotopes which would not be possible with a low resolution detector*

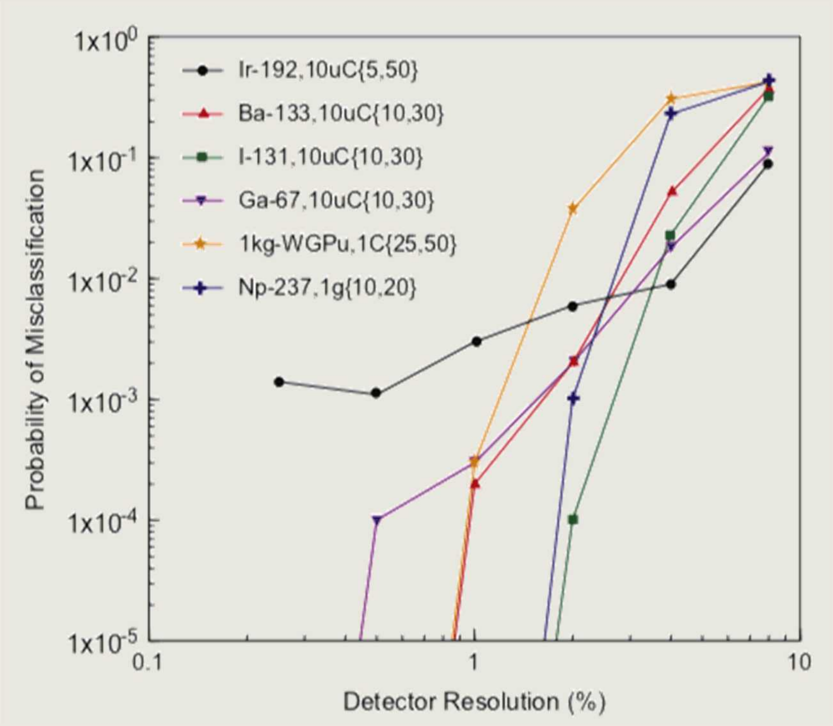


Image from [3]

Higher resolution room temperature detectors have numerous applications

- Improved resolution
  - requires fewer counts for the same level of information
  - Allows for discriminating between similar isotopes which would not be possible with a low resolution detector
- Applications
  - National Security
  - Surveying
  - Laboratory

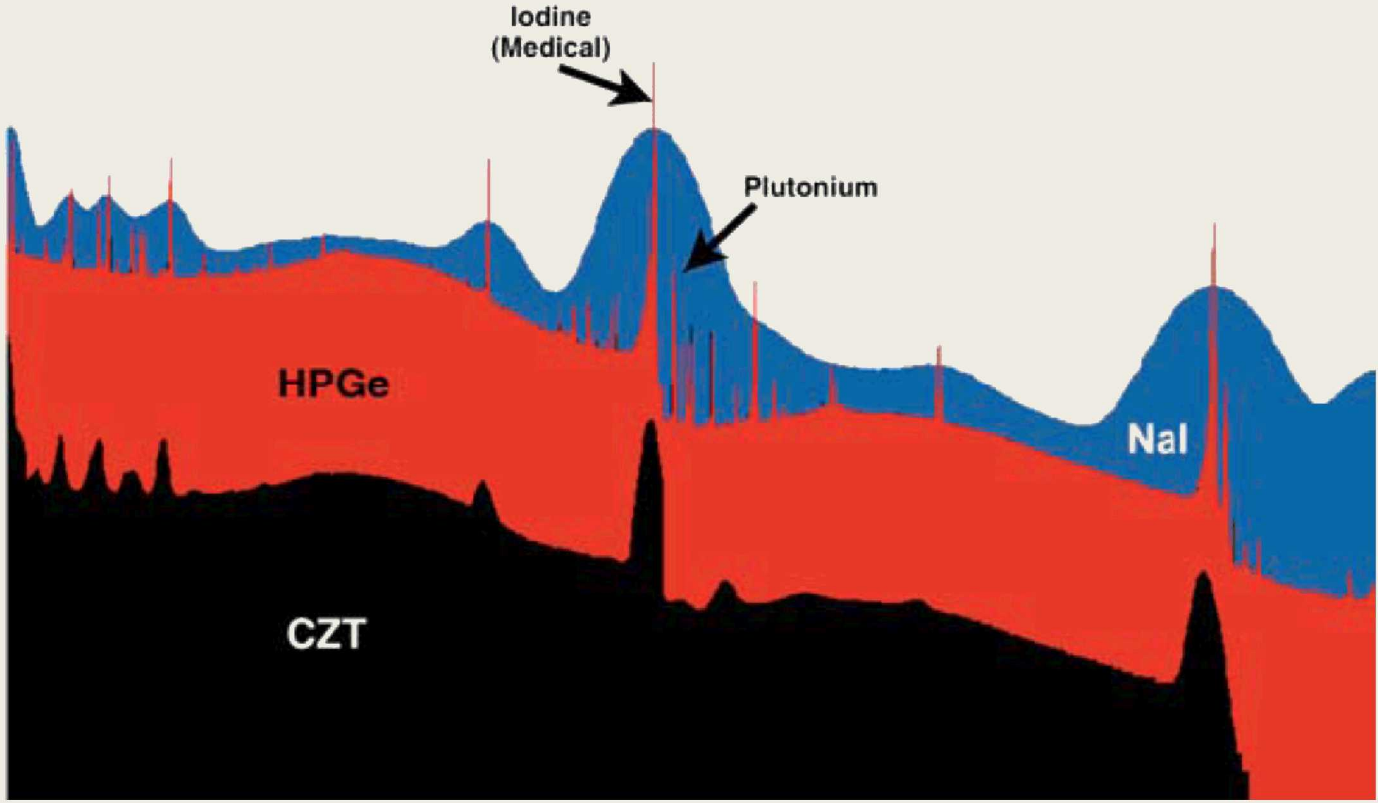
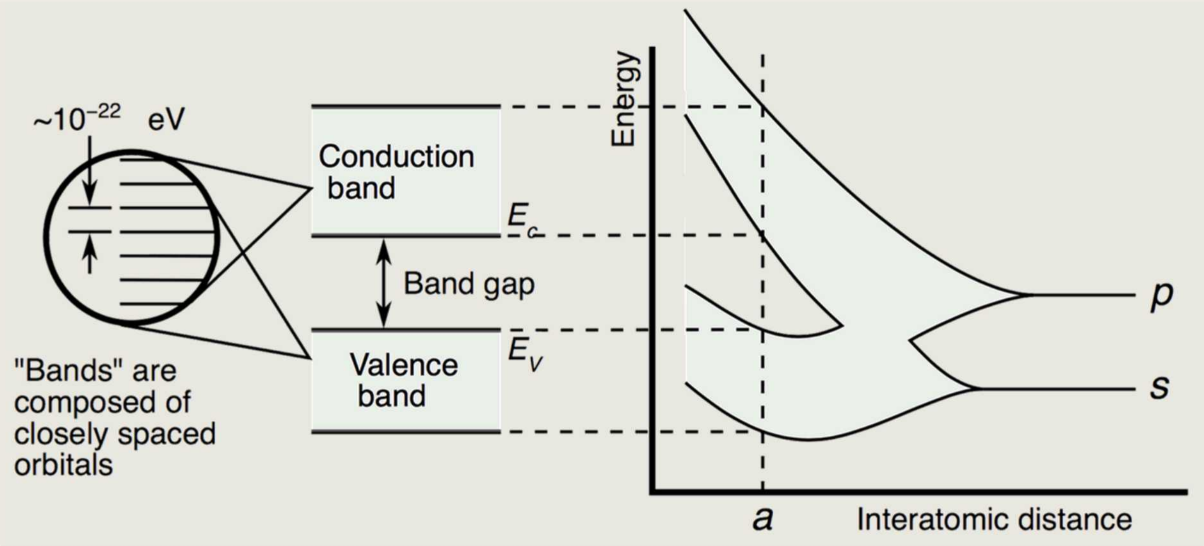


Image from [4]

Radiation Detection is Requires use of Semiconductors

- Detection of gamma spectrum is relies on the use of *semi-conductors* for both scintillation and charge collection mechanisms



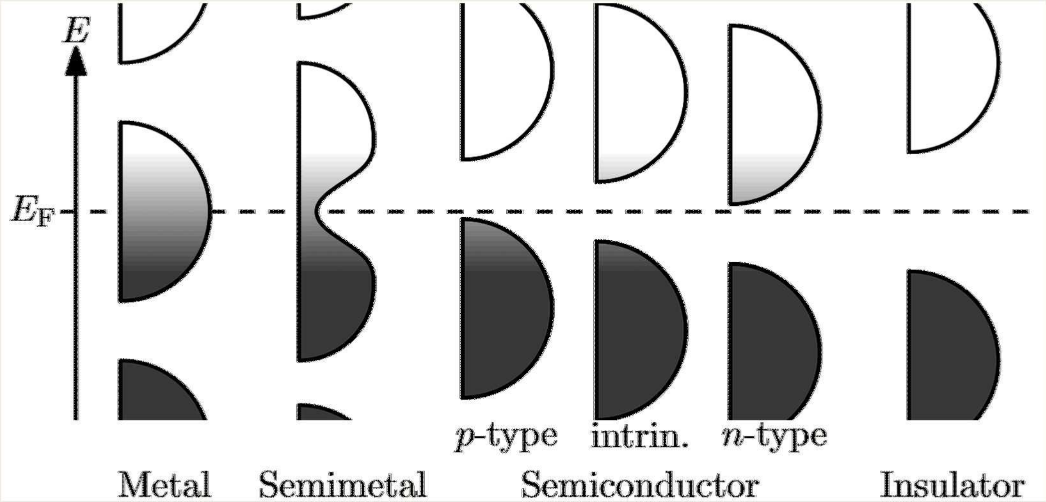
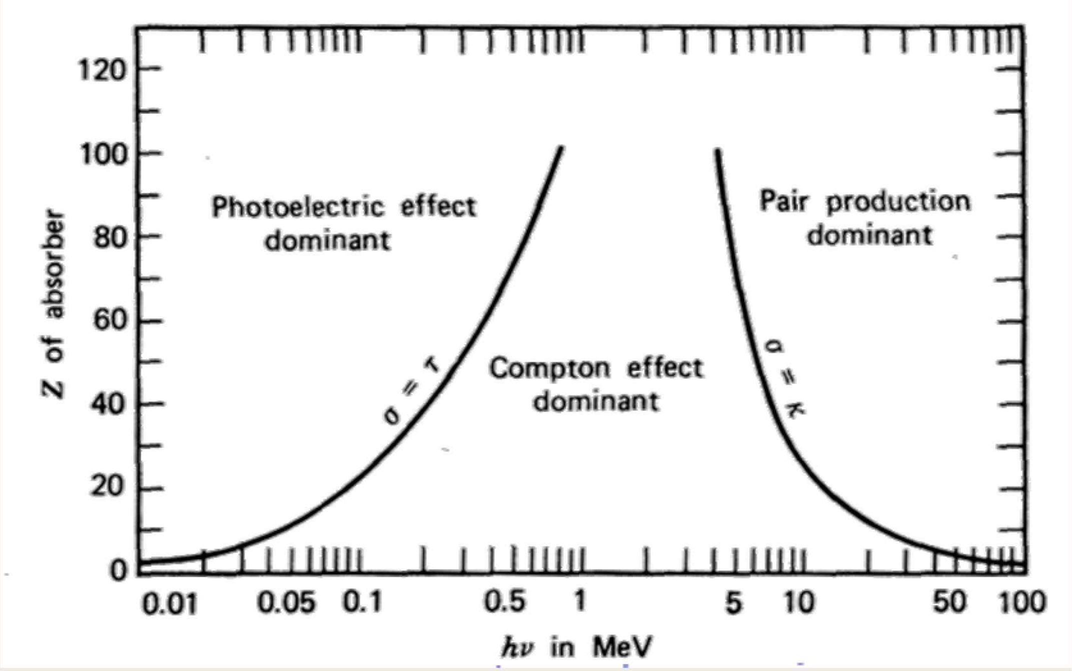


Image from [2] and [3]

Material Properties Influence the Information Content of Absorbed Radiation

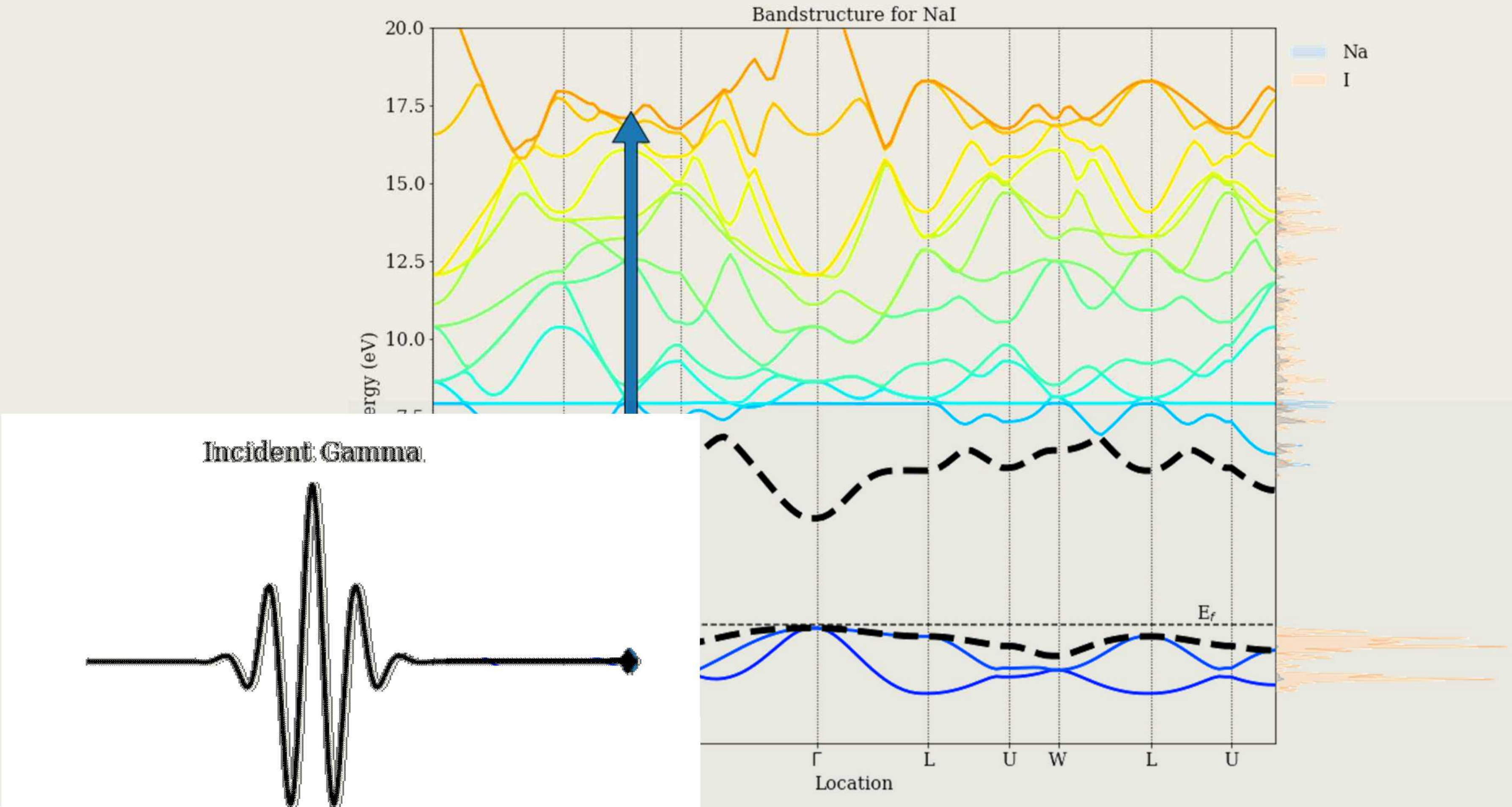
- Key spectral features (photoelectric peak, Compton continuum, pair production) vary with the atomic number of the detection material.

- High Z number preferred for collection efficiency as well as photoelectric peak production.



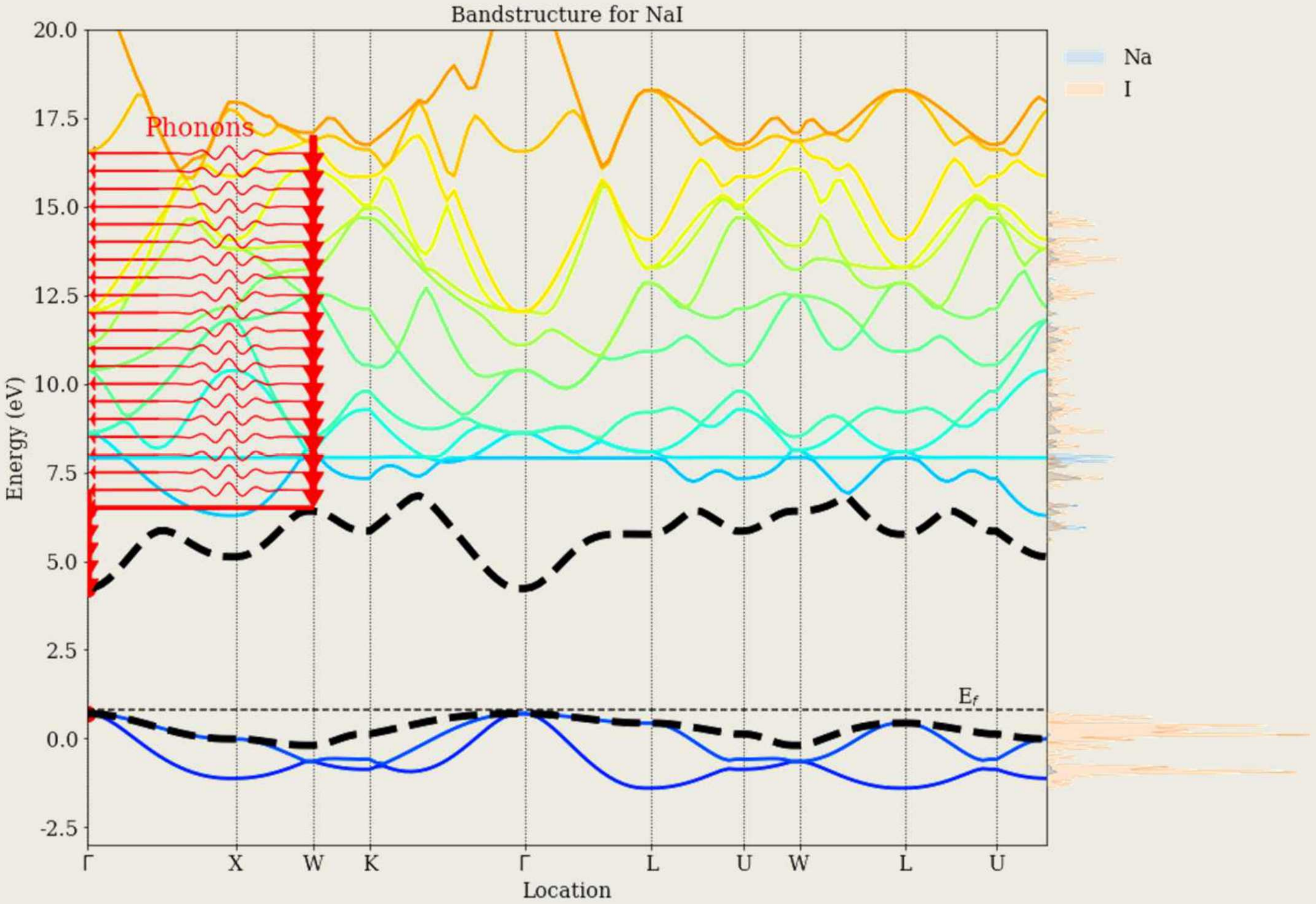
Scintillation Detectors: Desired Process

Absorbed radiation excites electron to conduction band



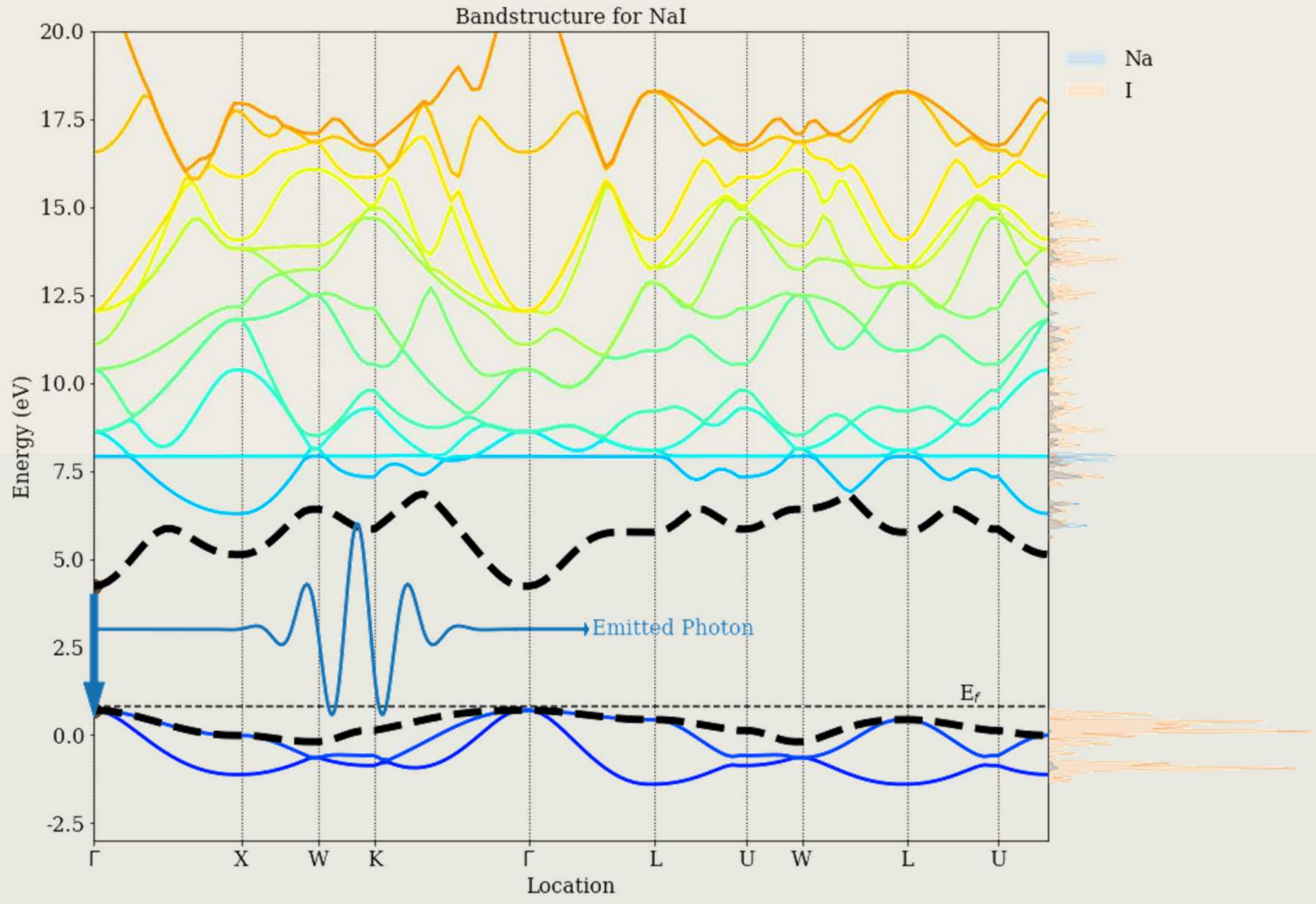
Scintillation Detectors: Desired Process

Excited electron relaxes (via phonons) to lowest energy of conduction band



Scintillation Detectors: Desired Process

Electron drops to valence band and emits a photon which will be measured



Scintillation Detectors: Desired Process

Emitted Photons are then converted to photoelectrons in the *photocathode* of a PMT. (peak efficiencies for PMT cathodes ~25%)

Photoelectrons are then amplified (on order of 1-10 E6) in the dynodes of the PMT to achieve measurable signals at the anode.

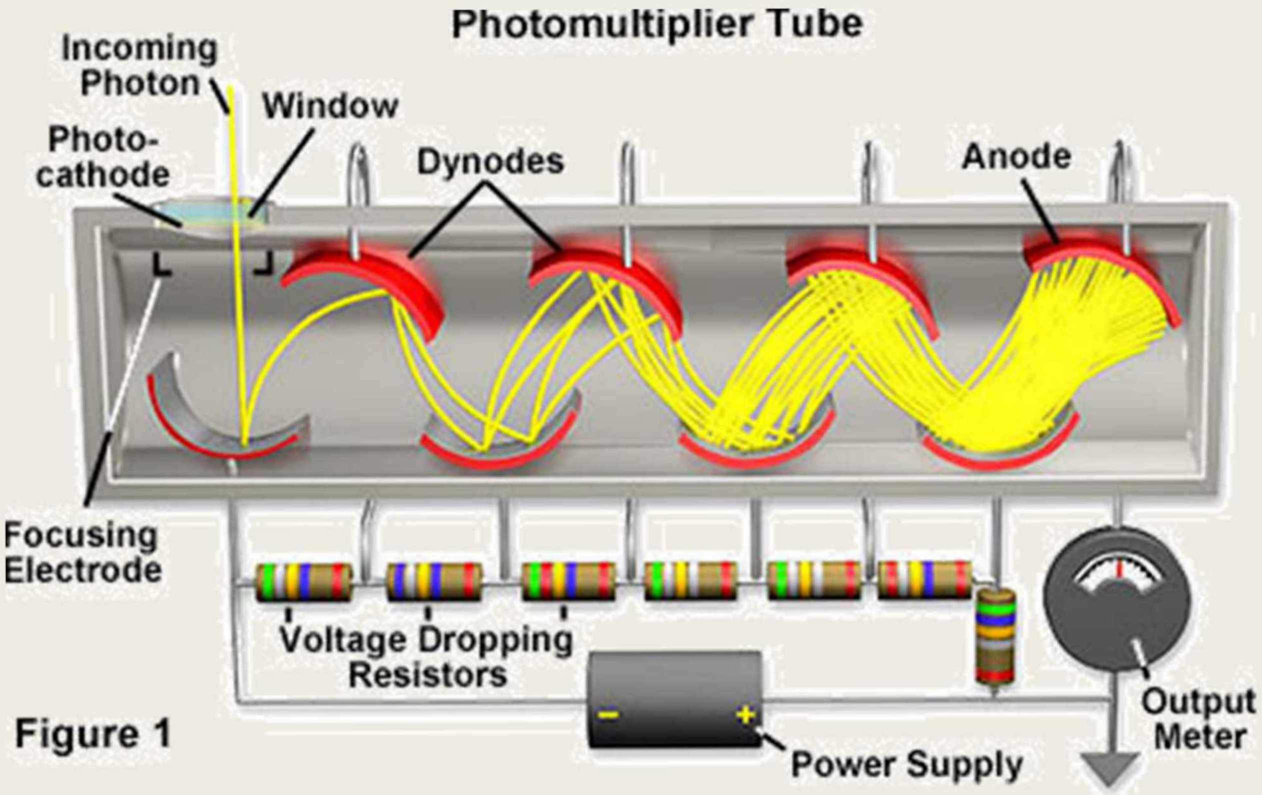
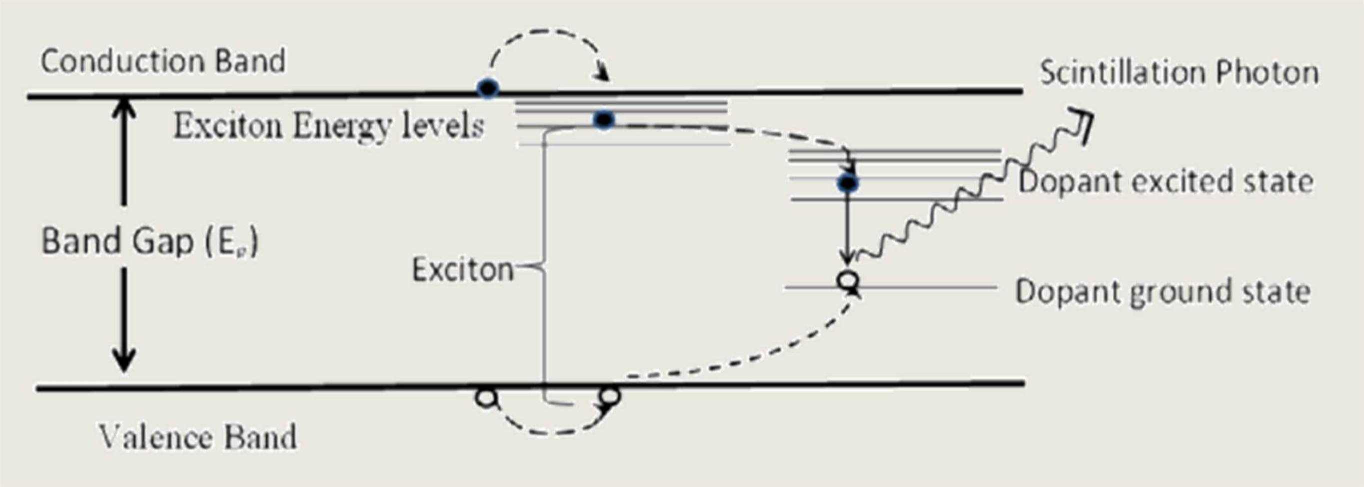


Figure 1

Image taken from [1]

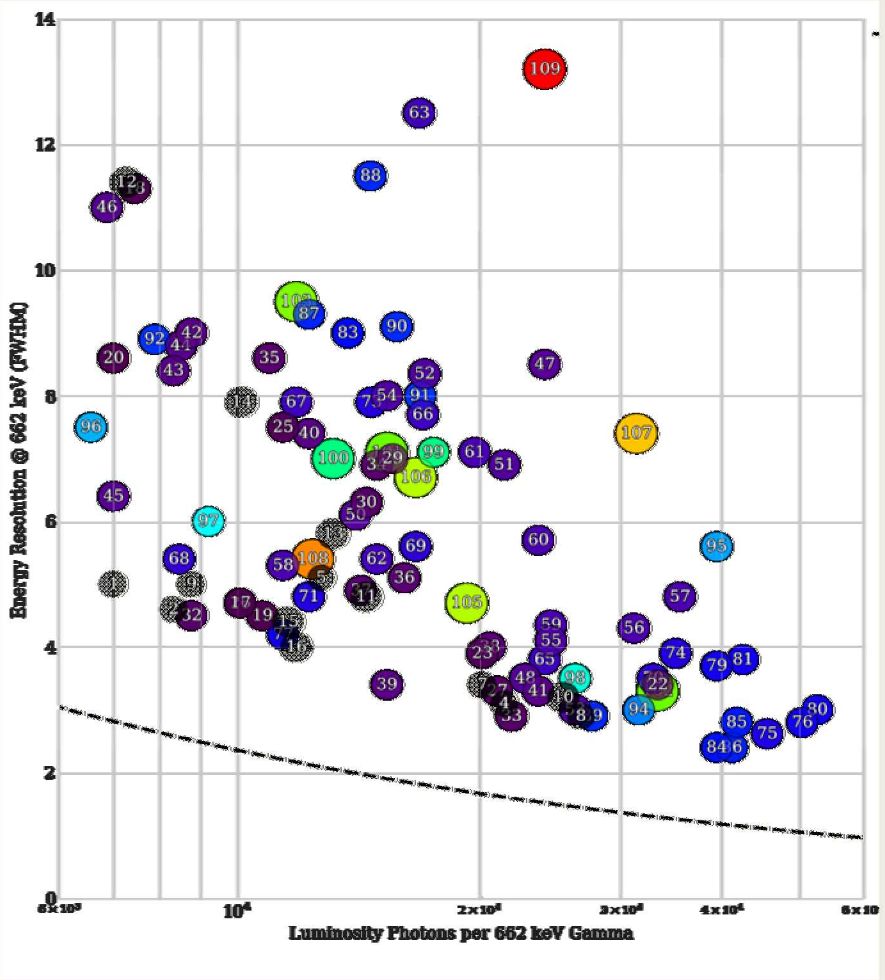
Scintillation Detectors Use Doping to Increase Light Yield and Resolution

- Doping (order of 1/1000th) has been found to increase light yield, or us used to place emission wavelength in a range which is more efficiently collected.



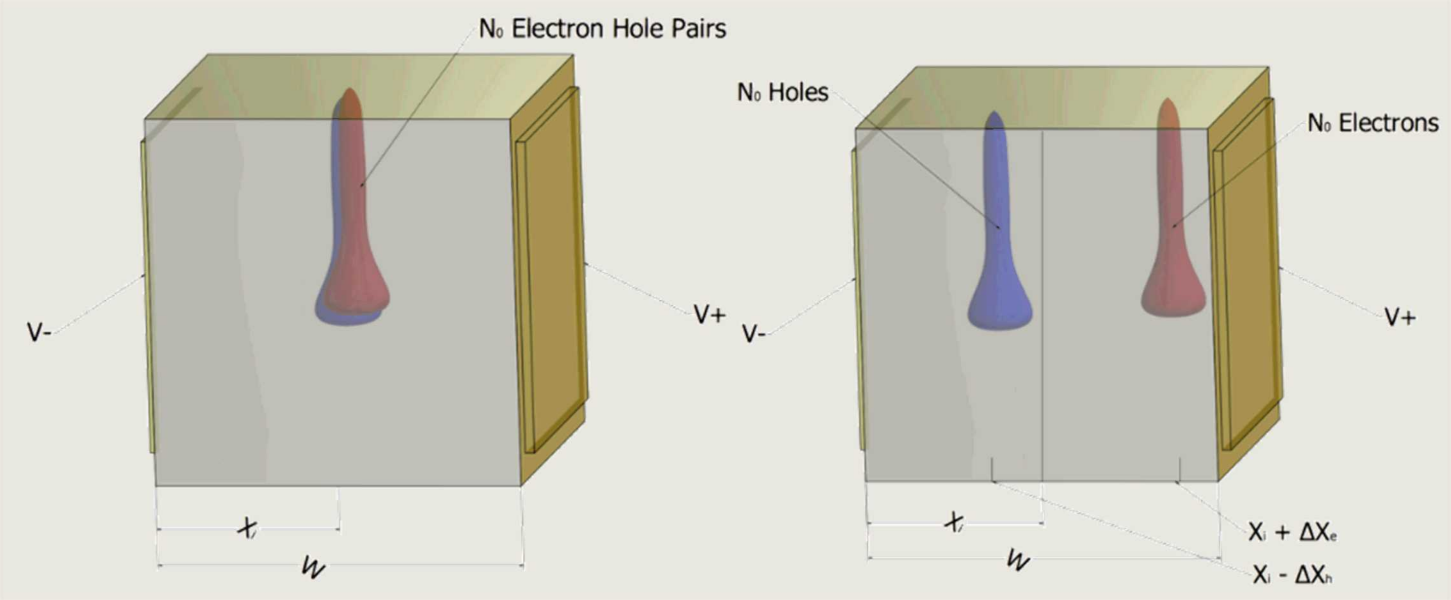
Poisson Statistics Limit Theoretical Limit of Scintillation Detectors

- Scintillator detectors are limited by Poisson statistics
- Theoretical best full width at half maximum (FWHM) is limited to $2.35 \times \sqrt{\#\ photo\ electrons}$



Charge Collection Detectors: Overview

1. Absorbed energy excites electrons into conduction band in quantities proportional to absorbed energy
2. Applied bias migrates electrons and holes to opposing material faces
3. Moving charge is measured (and is proportional to absorbed radiation)

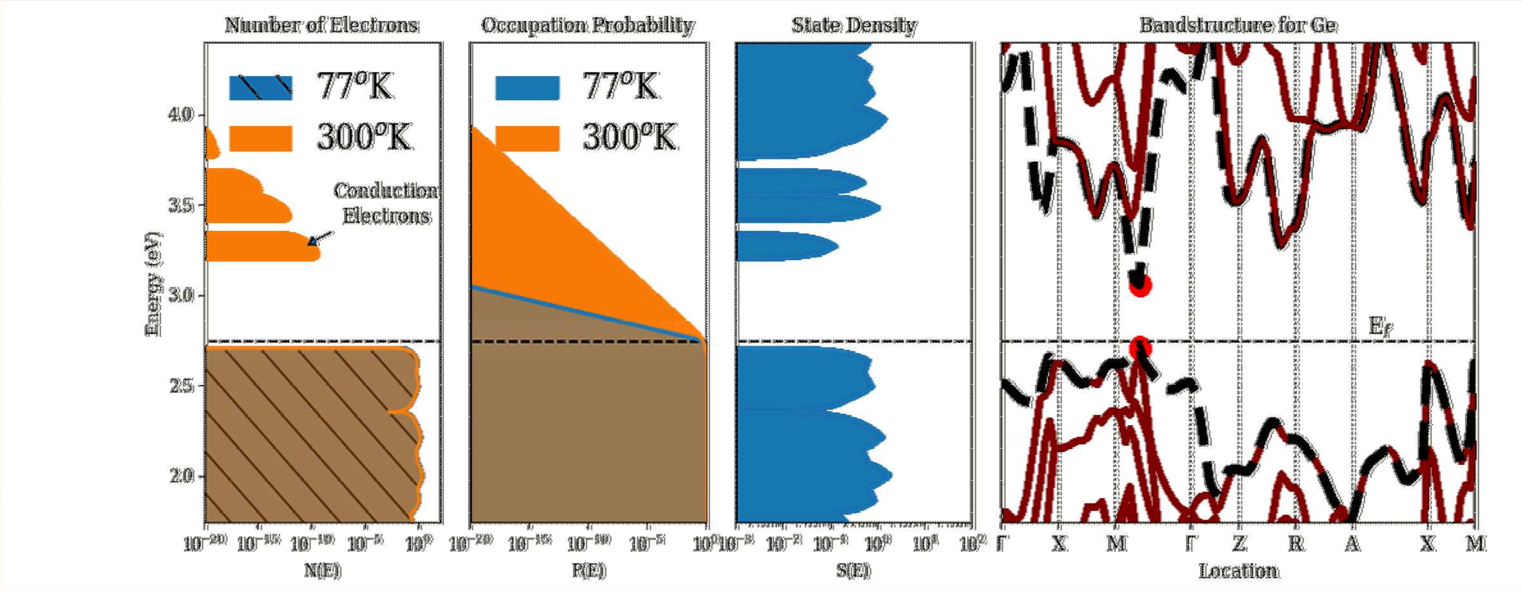


Charge Collection Measurement Loss Sources

- Moving charges will be lost to collection by two primary mechanisms:
  - *Trapping: Electron-holes may get fixed in lattice locations due to impurities in the lattice and are no longer free to migrate through*
  - *Recombination: Electron-holes may recombine before reaching the electrodes of the material*

Conduction of Semiconductors Is Dependent Upon Temperature

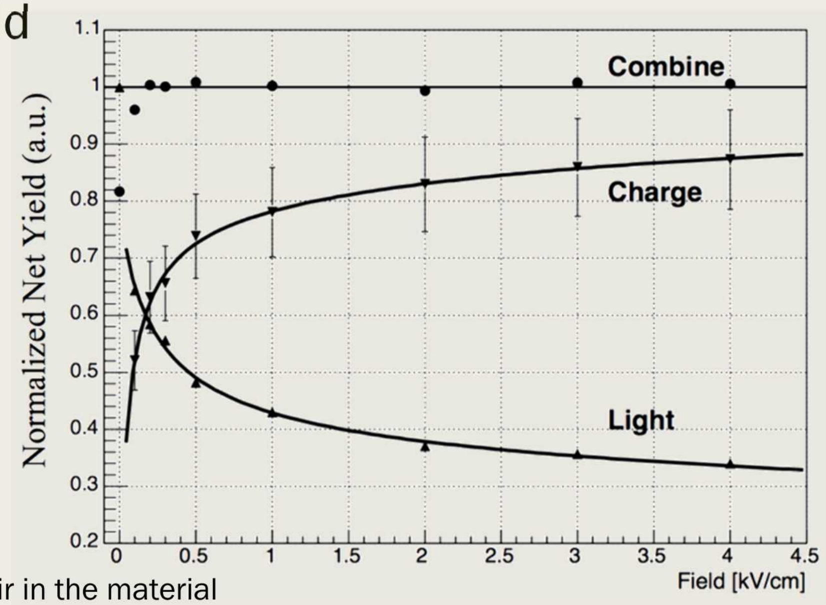
- Population of the conduction band is a function of the:
  - *Fermi energy of the mat*
  - *temperature of the mate*
  - *Density of states of the material*
- The highest resolution comm detectors (HPGe) require cryo temperatures



- Room temperature collection requires larger band-gap/lower E_F

Dual Mode Work: Scintillation and Charge Measurements are Inversely Related

- Electron-hole pairs which are collected in charge collection will not produce scintillations.
- Electron-hole pairs which migrate to the electrodes will not produce scintillation
- Increasing the bias improves charge collection efficiency (due to reduced recombination and trapping) but reduces scintillation yield



$$\frac{S(E)}{S_0} = \frac{1 + {N_{ex}}/{N_i} - {Q(E)}/{Q_0}}{1 + {N_{ex}}/{N_i} - \chi}$$

S_0: the charge yield normalized to the charge at infinite electric field.
χ: the fraction of electrons which do not recombine even at zero field
$S(E)$: is the scintillation emission collection at a given electric field strength, E.
${N_{ex}}/{N_i}$: the ratio of excitons to ion pairs produced.
$Q(E)$: the collected charge at a given electric field.
Q_0: the energy deposited by the γ-ray divided by the average energy required to produce an electron hole pair in the material

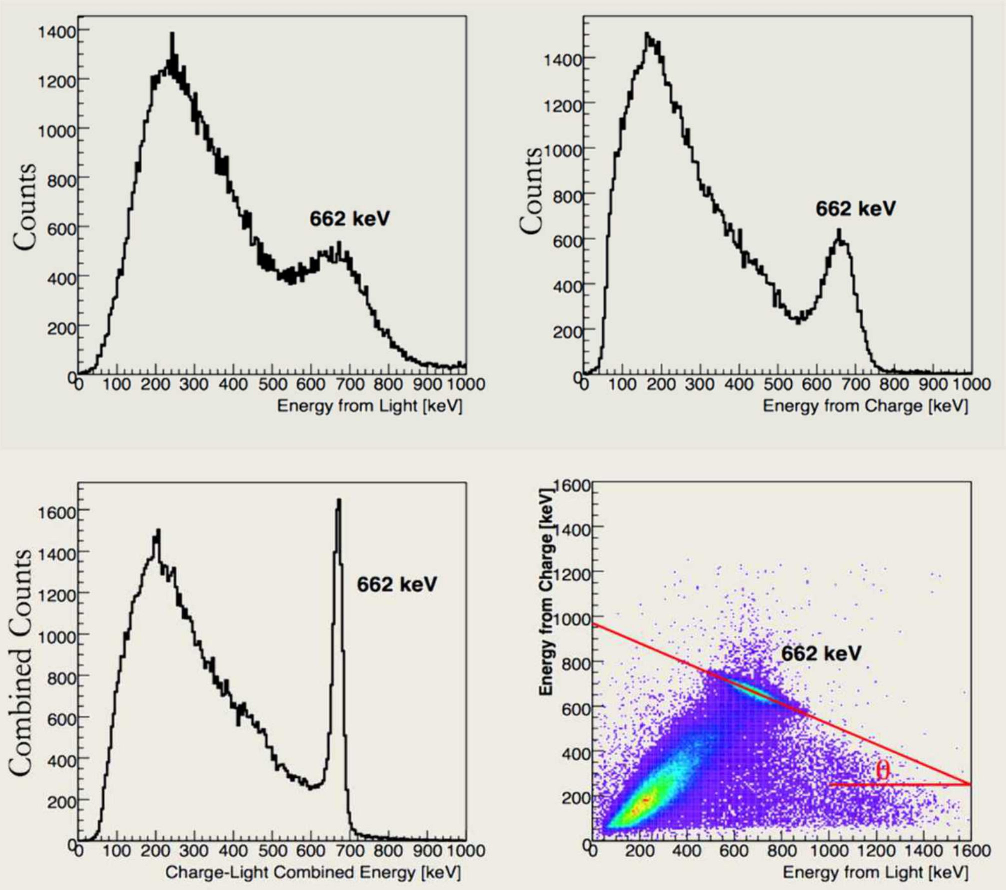
From [6] and [7]

Prior Work Showed Improved Resolution from Combined Measurements

- Prior work by Aprile et. al. demonstrated simultaneous spectra on liquid Nitrogen and liquid Argon capable of improved resolution

$$R_c^2 = \frac{\sin\theta^2 R_s^2 + \cos\theta^2 R_q^2 + \sin\theta\cos\theta R_s R_q \rho_{sq}}{(\sin\theta + \cos\theta)^2}$$

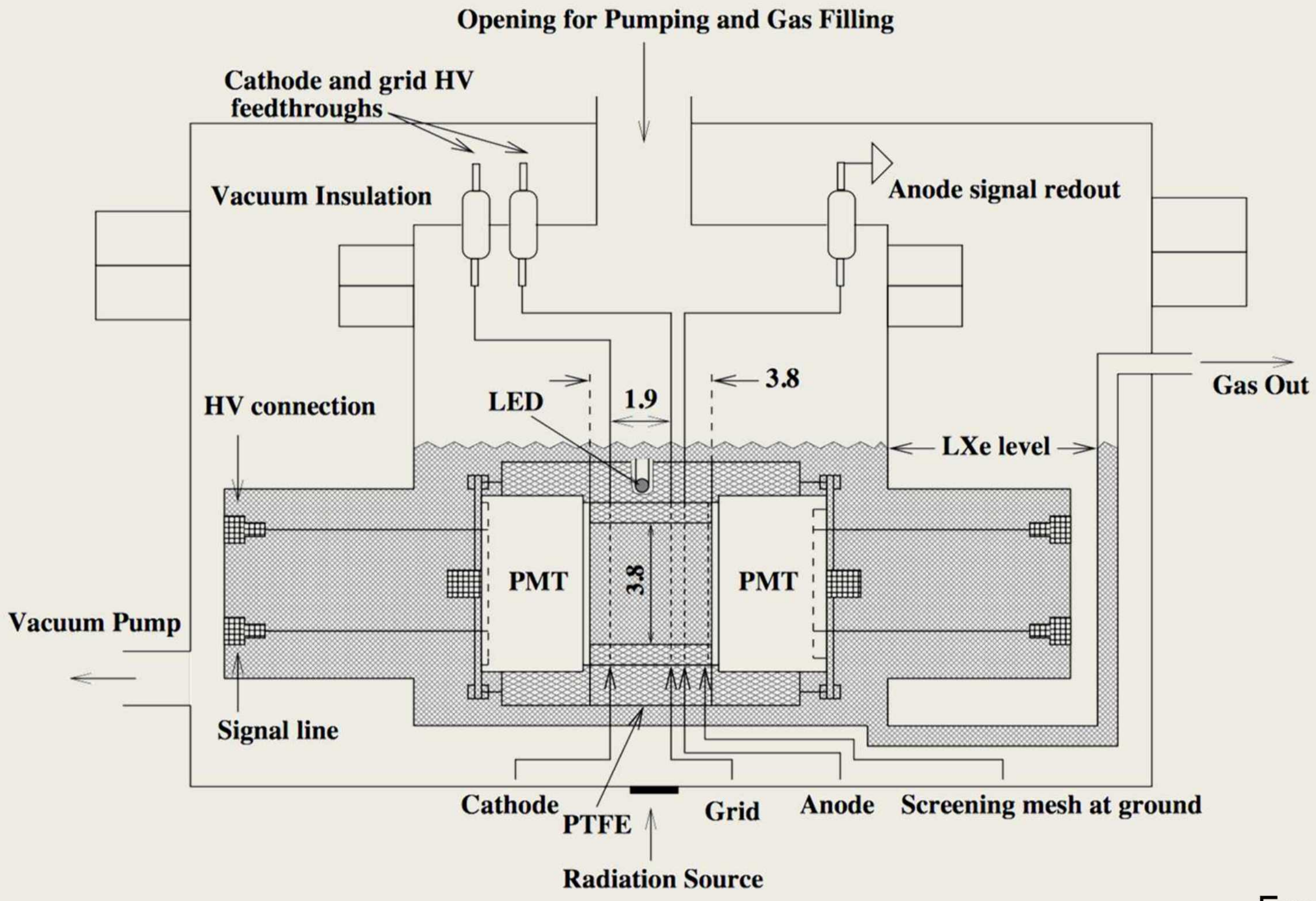
R_c is the combined resolution
R_s is the scintillation resolution
R_q is the charge resolution
ρ_{sq} is the correlation coefficient between charge and scintillation measurements
θ is angle of the correlation between charge and scintillation measurements



From [5]

Experimental Setup for Prior Dual Mode Collection Work

- Prior work



From [5]

Dual Mode Collection

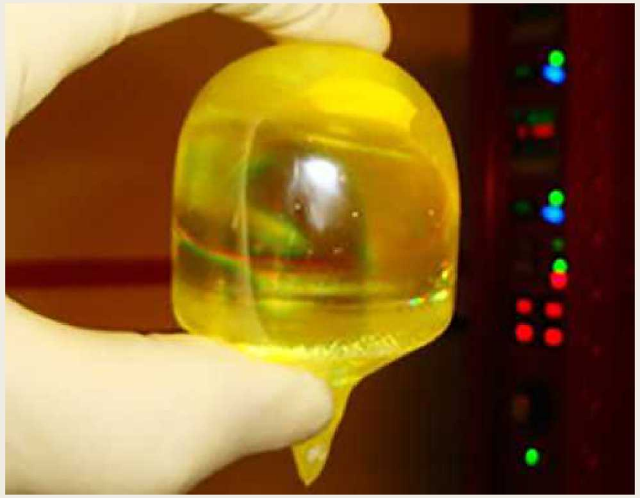
- Two room temperature materials have been noted to exhibit properties of simultanious scintillation and charge collection but have not yet been characterized for this purpose.
  - *Mercurous Bromide,* Hg_2Br_2
  - *Cadmium Magnesium Telluride,* $Cd_{(1-X)}Mg_XTe$

Mercurous Bromide, Hg_2Br_2

- Mercurous Bromide was developed for for Opto-Acoustical applications as early as the 1970s

- Demonstrated growth of high purity samples to several cubic inches dimensions.

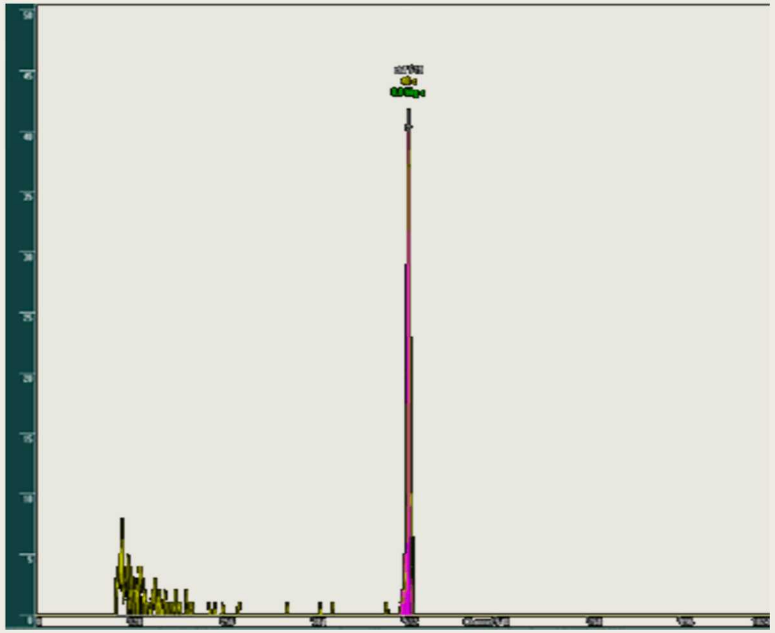
- Later measurements demonstrated that this material can be used in radiation detection applications



Mercurous Bromide, Hg_2Br_2

- Preliminary radiation measurements for charge collection have show resolutions as low as 0.48% for gamma measurements

- Initial scintillation spectrum show resolutions ~20%



From [9]

CdMgTe

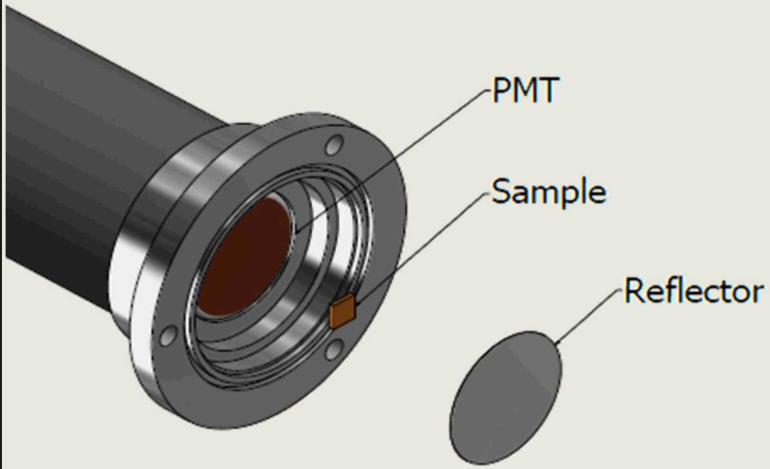
- $Cd_{.92}Mg_{.08}Te$:
  - *Ge and In doped samples have achieved resolutions as low as 1.5%*
  - *Opaque and cannot be used for dual mode collections*

- $Cd_{.6}Mg_{.4}Te$ and $Cd_{.55}Mg_{.45}Te$:
  - *transparent*
  - *display scintillation properties*
  - *will be investigated for dual collection applications*

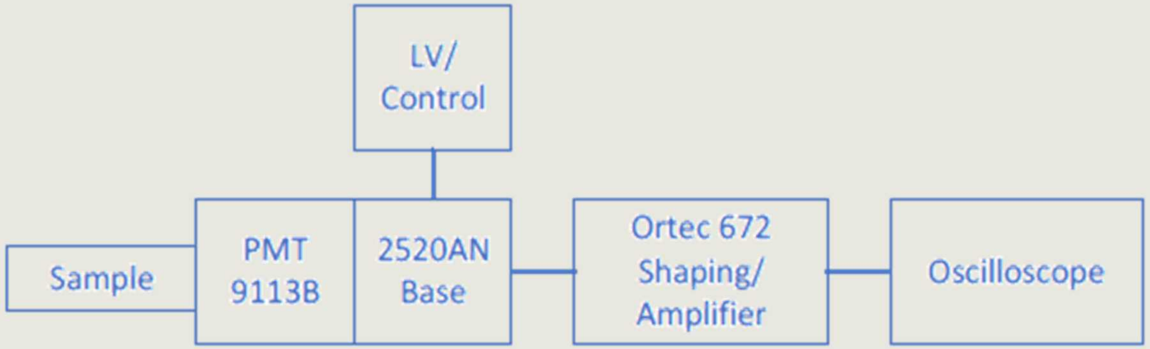
Experimental Setup

- Measurements will be made in 3 states
  - *Scintillation only*
  - *Charge only*
  - *Dual*
- After material properties are understood, the combination of scintillation and charge will be carried out

Experimental Setup: Scintillation

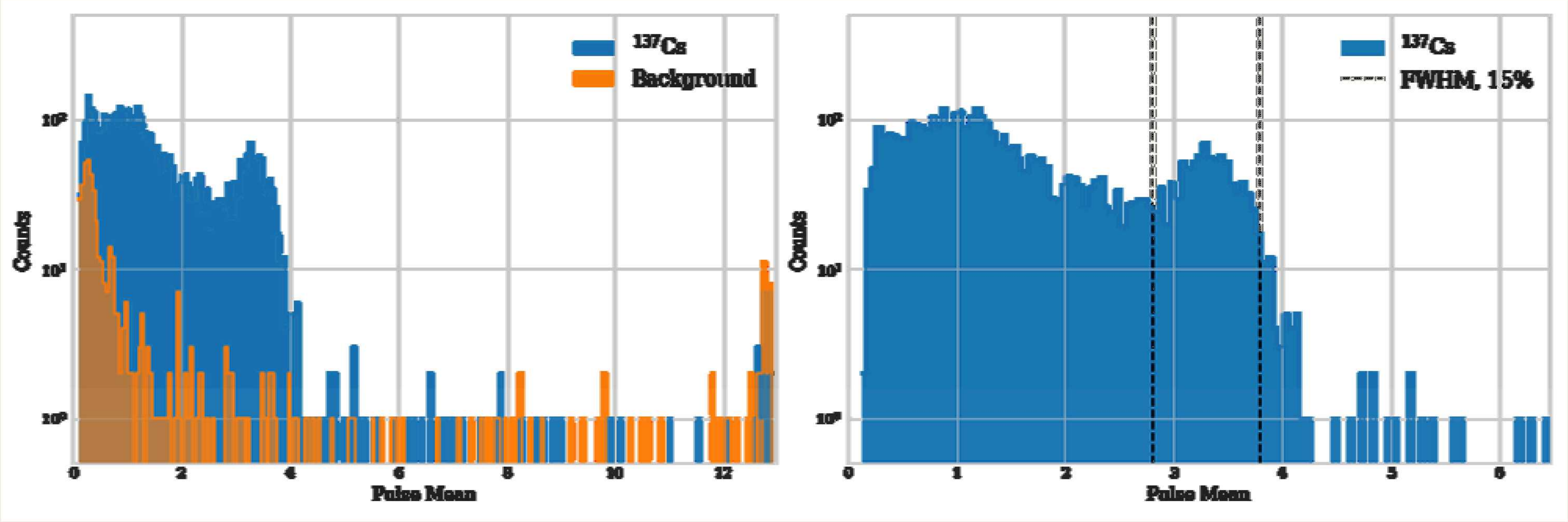


- Samples will be placed directly on the face of a PMT with a reflective backing applied.
- Preamplifiers and shaping amplifiers will be used as needed to achieve higher resolution spectra.

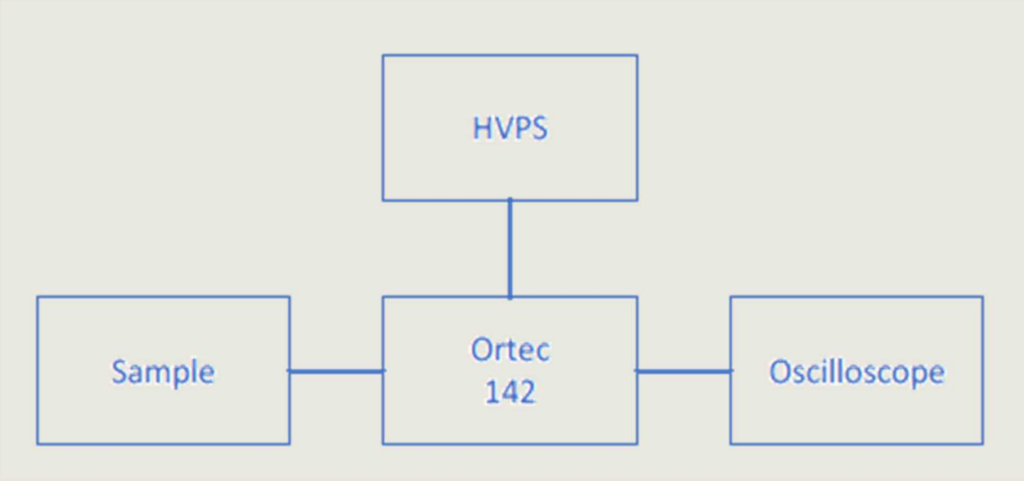


Experimental Setup: Scintillation

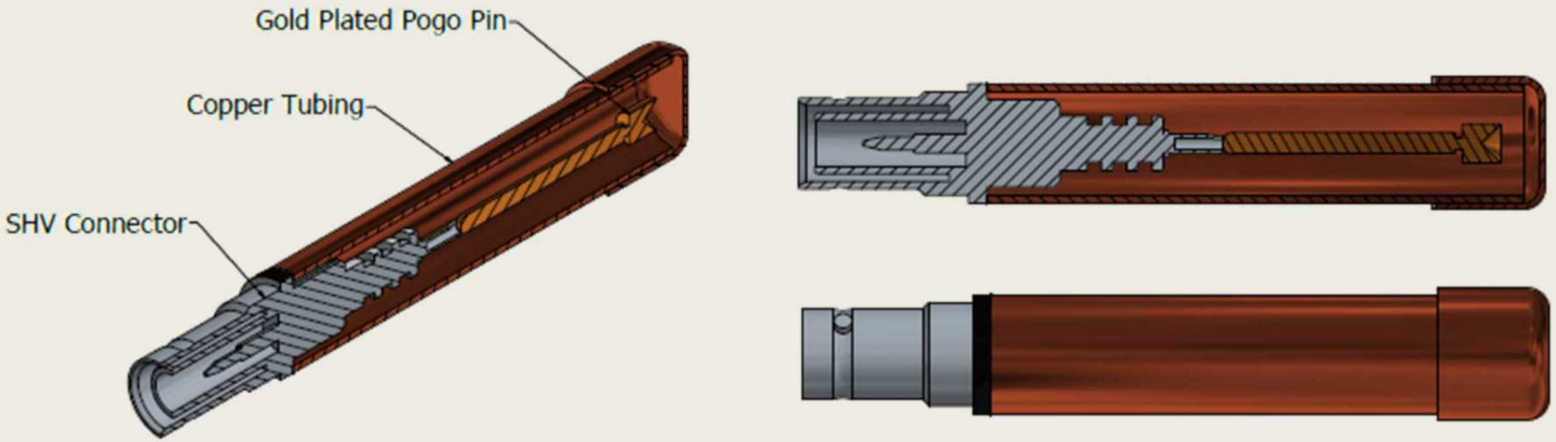
- Initial scintillation spectra have been obtained on 5mm x 5mm x 1mm samples of Hg_2Br_2 showing resolution ~15 - 25%
- This is the first scintillation spectrum to be obtained from this material



Experimental Setup: Charge



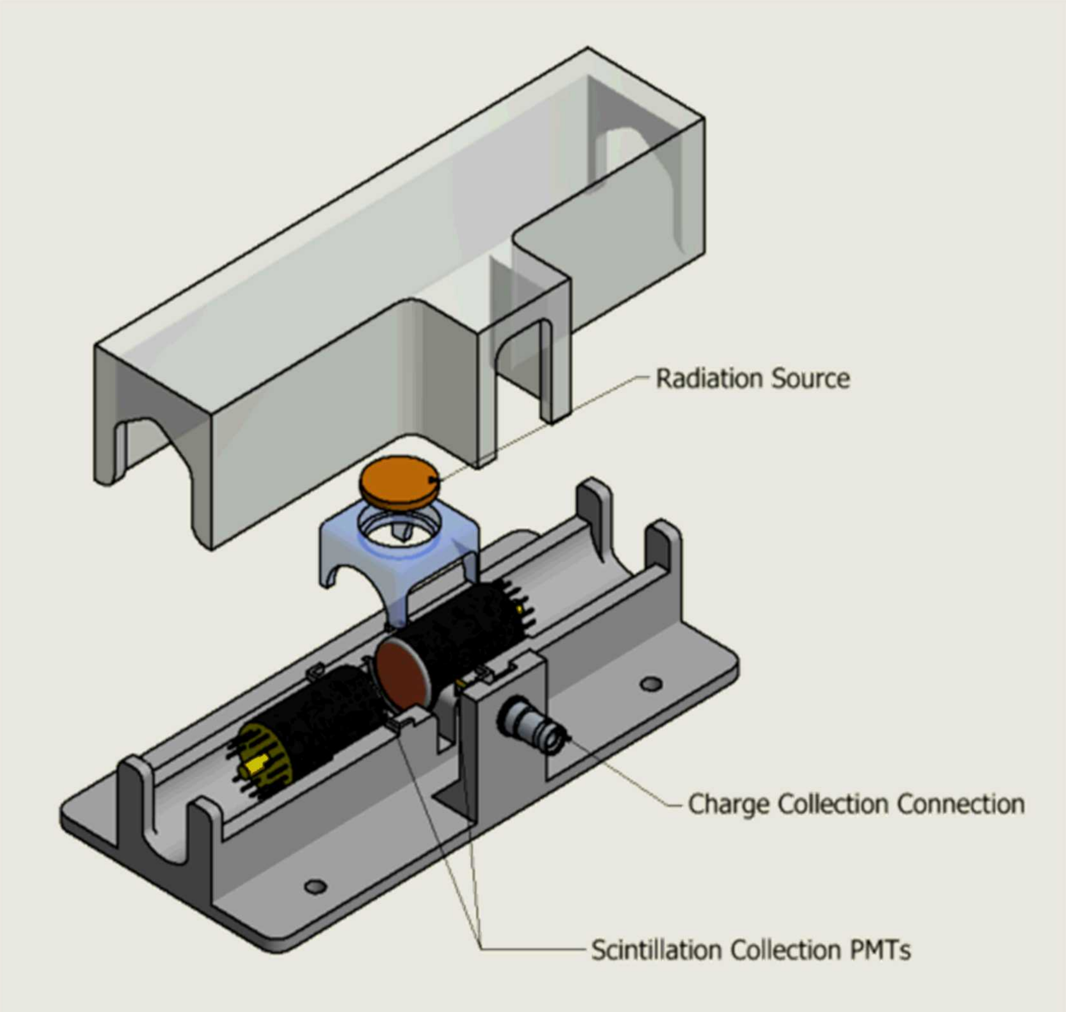
- Charge measurements will be made in a low noise fixture.
- Expected bias vary with material :
  - *on order of 100 V/cm CdMgTe*
  - *on the order of 5-10 kV/cm for* Hg_2Br_2
- Methods of pulse shape discrimination will be applied where possible.



Experimental Setup: Dual Mode

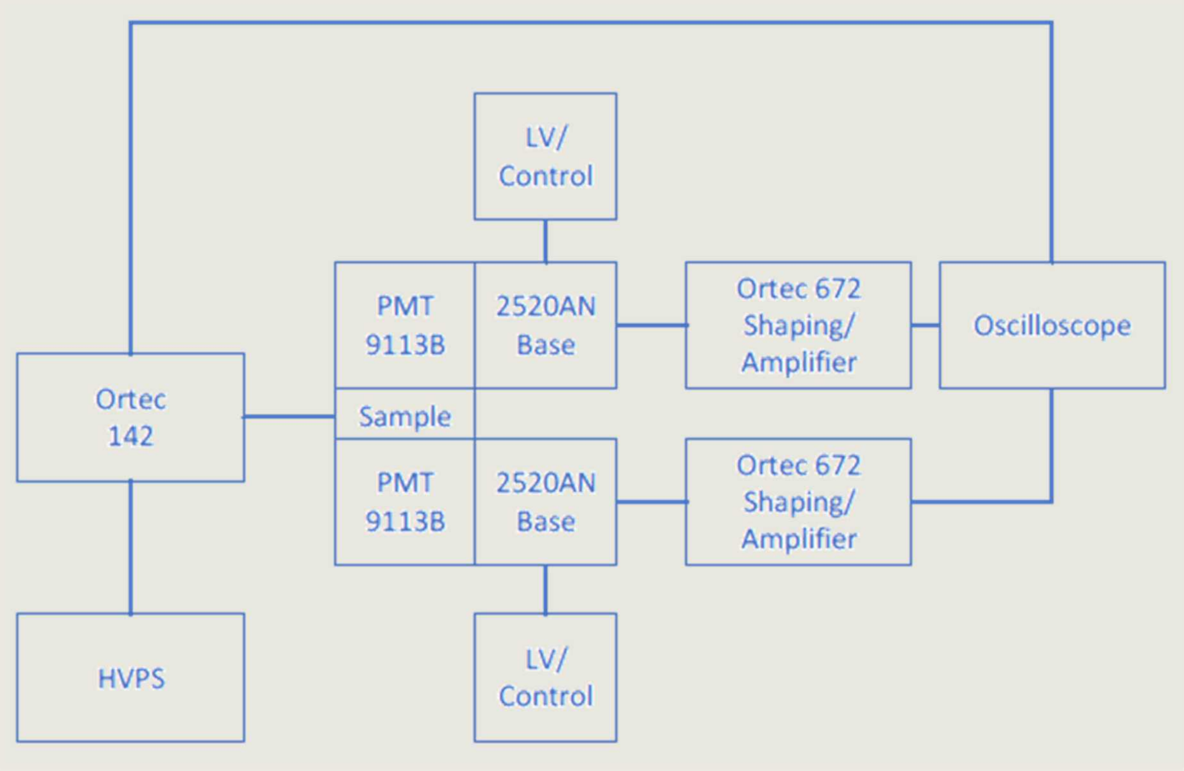
- A prototype fixture for the collection of dual mode measurements has been constructed which will allow for high light collection (dual PMTs) and close positioning of charge preamplifier.

- Further development will likely be required for this fixturing



Experimental Setup: Dual Mode

- All signals will be simultaneously recorded on an oscilloscope.
  - *Allows for post processing of pulse shape discrimination*
  - *Allows for synchronization from multiple data channels*



Experimental Setup: Analysis

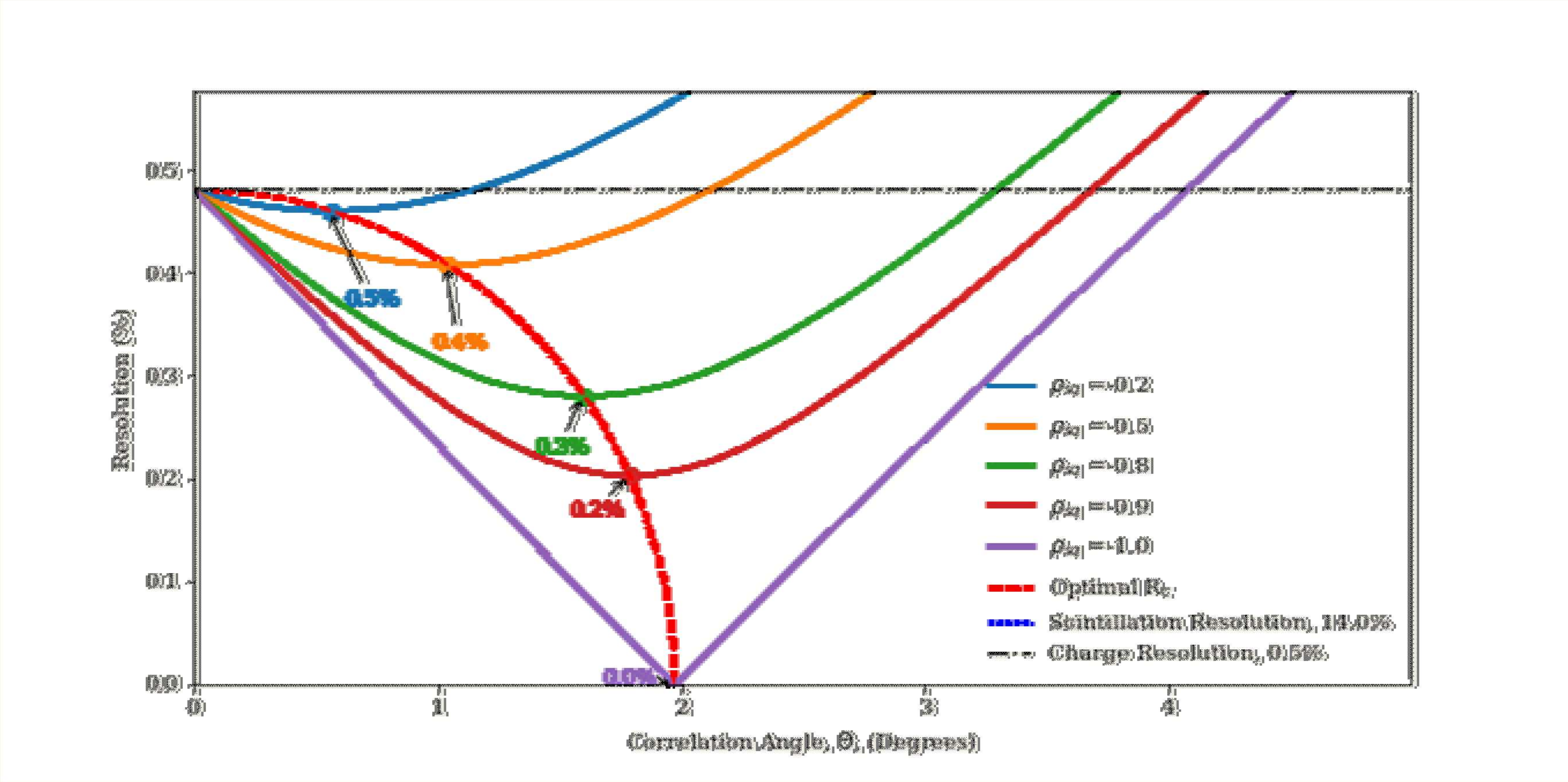
- Several methods of aggregating the data will be explored.
- Each measured waveform will have several summary measurements applied:
  - *Maximum*
  - *Integral Area*
  - *Rise Time*
  - *Fall Time*
  - *Goodness of fit to exponential decay*
- Histograms from these measurements will then be made in order to obtain spectrum

Combined Resolution Estimates for Hg_2Br_2

The combined resolution is only dependent upon θ and ρ_{sq}

Estimates were can be made with R_s and R_q estimates

$$R_c^2 = \frac{\sin\theta^2\, R_s^2 + \cos\theta^2\, R_q^2 + \sin\theta\cos\theta\, R_s R_q \rho_{sq}}{(\sin\theta + \cos\theta)^2}$$



Summary

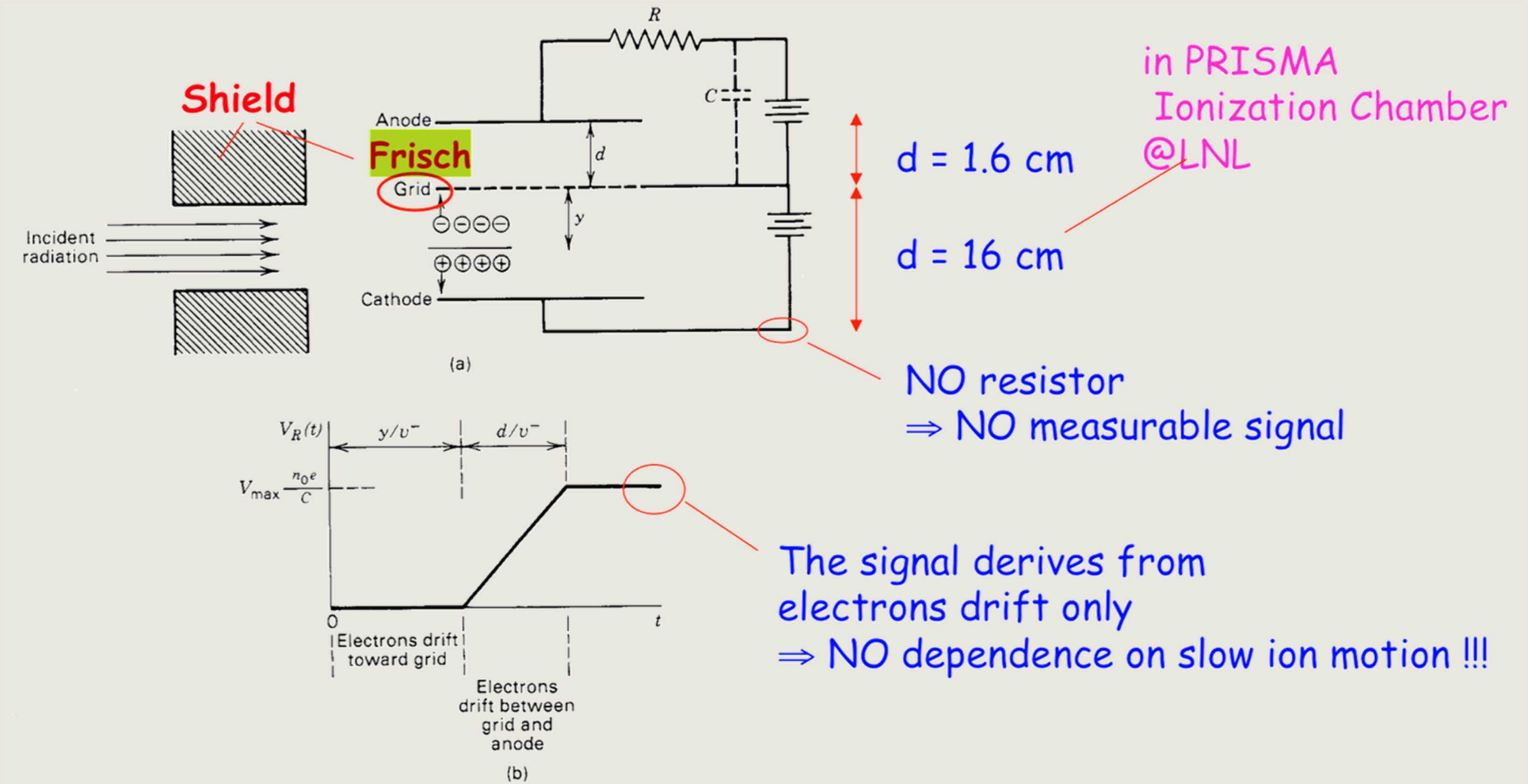
- This work will investigate room temperature dual mode collection radiation detection materials which could provide a path to state of the art room temperature radiation detectors.

Questions/Discussion

Works Cited

- [1] https://micro.magnet.fsu.edu/primer/digitalimaging/concepts/photomultipliers.html
- [2] https://en.wikipedia.org/wiki/Semiconductor#/media/File:Band_filling_diagram.svg
- [3] https://upload.wikimedia.org/wikipedia/commons/e/ef/Solid_state_electronic_band_structure.svg
- [4] Ortec, "Why High-Purity Germanium (HPGE) Radiation Detection Technology is Superior to Other Detector Technologies for Isotope Identification," [Online]. Available: https://www.ortec-online.com. [Accessed 21 March 2019].
- [5] E. Aprile, K. L. Giboni, P. Majewski, K. Ni and M. Yamashita, "Observation of Anti-correlation between Scintillation and Ionization for MeV Gamma-Rays in Liquid Xenon," *Physics Review,* vol. B, no. 76, p. 014115, 2007.
- [6] S. Kubota, A. Nakamoto, T. Takahashi and T. Hamada, "Recombination Luminescence in Liquied Argon and in Liquid Xenon," Physical Review, vol. 17, no. 6, pp. 2762-2765, 1978.
- [7] M. Ichige, E. Aprile, T. Doke, K. Hasuike, K. Itoh, J. Kikuchi and K. Masuda, "Measurement of Attenuation Length of Drifiting Electrons in Liquid Xenon," Nuclearl Instruments and Methods in Physics Research, vol. A, no. 333, pp. 355-363, 1993.
- [8] H. Chen, S. B. Trivedi, F. Jin, R. Rosemeier and A. Burger, "Mercurous Bromide - A Novel Material to Enhance Detection Capability for Gamma Rays and Neutrons," SIBR Report FA8051-15-P-0 Final, 2016.
- [9] H. Chen, S.B. Trivedi, F. Jin, R. Rosemeier, A. Burger, “Mercurous Bromide—A Novel Material to Enhance Detection Capability for Gamma Rays and Neutrons”, Phase I Proposal SBIR Topic: AF151-009; Proposal #: F151-009-0647

Backup: Frisch Grid Description



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