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BY

Emily G. Jackson
B.A. Knox College (2008)

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF MASTER OF SCIENCE
DEPARTMENT OF PHYSICS AND APPLIED PHYSICS
UNIVERSITY OF MASSACHUSETTS LOWELL

Signature of

Author: _____ **Date:** _____

Signature of Thesis Chair: _____

Name: Prof. Partha Chowdhury

Signatures of Other Thesis Committee Members

Committee Member Signature: _____

Name: Prof. Christopher J. Lister

Committee Member Signature: _____

Name: Prof. James Egan

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2013

Thesis Supervisor: Partha Chowdhury

Professor, Department of Physics and Applied Physics

Abstract

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Family, friends.

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Chapter 1

Introduction

1.1 Gamma Rays in Nuclear Physics and Applications

My intro. Germanium detectors are used in laboratories worldwide for fundamental research in nuclear physics.

1.2 Detection Approaches

There are many methods for collecting time and energy information from nuclear radiation but all detectors use the same basic method.The radiation enters the detector, interacts with the detector material, electrons are removed from their orbits and then collected by electronics [3]. When timing information is important, detectors with fast charge collection times are most useful. When accurate energy collection is critical, detectors with a proportional output pulse are needed. Balancing the need for these two detector characteristics is the first step in designing a nuclear physics experiment. Consideration must also be given to the geometry of the detector material and the experimental setup. For different applications, coaxial or planar detectors might be better. If the source needs 4π

coverage, economical concerns might influence your detector choice.

say anything about particle energy and stopping power of different detectors?

The simplest type of radiation detector is a gas counter. A gas counter is an ionization chamber filled with a mixture of gas chosen for its low working voltage, high gain, good proportionality, and abliity to handle a high rate [4]. The detector has an electric charge applied to it and essentially behaves as a parallel plate capacitor [3]. When the radiation enters the gas counter, it ionizes the gas and the electric field pulls the ions and electrons towards each plate. Radiation intensity is recorded as a current that is proportional to the activity of the source and energy of the radiation [3]. To record individual pulses, signal amplification is needed. This is accomplished by increasing the applied voltage, causing the charge carriers to be pulled to the plates more quickly and causing additional collisions with the gas. This creates more ionized atoms, amplifying the signal. Timing from these types of detectors comes from the drift time of the charge carriers; the time it takes for the ion to travel from where it was created to where it gets collected [3]. –tons more in Leo ch 6.

Developed in the 1950s, scintillation detectors are unique in the sense that the electrons formed by ionization are not what forms the detected pulse [3]. Instead, radiation entering and interacting with the detector material excites the material's atoms which then emit light [3]. This light enters a photomultiplier tube and is collected as a pulse. Scintillation detectors can be made from organic or inorganic materials and can contain activator impurities to increase the probability for photon emission and reduce self-absorption [3].

Scintillators are some of the most widely used detectors used today because of their sensitivity to energy, fast response, and ability to discriminate pulse shapes. Most scintillators have a linear response to deposited energy making the light output proportional to the energy [4]. While other options exist, scintillation detectors can be used for energy spectrometers. The fast response time allows for

obtaining time differences between events and also means less dead time while collecting data [4]. Some scintillators can distinguish between different incident particles by pulse shape discrimination. Scintillators can be organic crystals or liquids, plastic, inorganic crystals, gases and glasses. There are challenges for each type of scintillator material. Crystals can be very brittle and their resolution is dependent on the orientation of the axis while liquids can be extremely sensitive to impurities [4]. Plastics can be damaged by organic solvents and need to be handled with plastic gloves [4]. In general, inorganic crystals have a slower response time and must be used in a protective housing to protect from moisture [4]. Gas scintillators emit a light that is difficult for photomultiplier tubes to detect and glass has low light output. –Leo ch 7 Development of semiconductor detectors really progressed in the 1960's when they became commercailly available. Soon these detectors were being put to use for nuclear physics research. Semiconductor detectors are solid crystals with energy gaps smaller than the gap in insulator materials. The crystal materials, usually germanium or silicon, have higher densities giving a larger interaction probability. Semiconductor detectors can both handle a large electric field and have easily removable electrons that move easily through the material [3].

Semiconductor detectors create nearly two orders of magnitude more charge carriers than a scintillation detector. This provides the semiconductor detectors greatest advantage, vastly improved energy resolution [4].

Semiconductor detectors are usually operated at liquid nitrogen temperatures to reduce the noise from the thermal motion of the electrons. Common crystal shapes are coaxial and planar where the charge carriers move radially or laterally to be collected by the contacts.

HPGe Intrinsic germanium detectors, often called high-purity germanium (HPGe), have impurities of less than $10^10 atoms/cm^3 and only need to be cooled to LN2 temps when a voltage is a$

1.3 Major Germanium Arrays in Labs Worldwide

Greta/Gretina, Gammasphere, Euroball...

see proposal

1.4 Segmented Detectors

cost/benifit electronics to match - risk of cross talk - more money resolution with large detectors - spatial vs energy resolution

see proposal for this section

1.5 The Need for New Contact Technologies

see DNP ppt

Chapter 2

Gamma Rays, X-rays and their interaction with matter

2.1 X-Rays and Gamma Rays

energy range of gammas and xrays

2.2 Conduction band in semiconductors

Ge crystal, insulators, conductors, and semiconductors

Dopants can be added to change the material's conduction by replacing some of the crystal's atoms with dopant atoms that have either one more or one less valence electron. With one more valence electron, the detector is said to be n-type because of the extra negative charge carriers. One less valence electron makes a p-type detector due to the extra positive charge carriers. These positive charge carriers are the absence of electrons and called "holes".

Leo: energy per electron pair leakage current

Bringing n- and p-type detectors together the excess electrons and holes combine to create a depletion region of no excess electrons or holes. The electric field

created by the diffused charges eventually fixes the size of the depletion region [3]. Applying a large reverse-bias (negative bias is applied to the p-type material) forces more excess charge carriers to combine. This increases the size of the depletion region thereby increasing the effective volume of the crystal.

manufacture methods of HPGe

2.3 Three major interactions in matter

Upon entering the detector material, the gamma ray will most likely undergo one of three processes: photoelectric absorption, Compton scattering, or pair production. Each of these processes dominates in a particular energy range therefore, depending on the type of studies a researcher is engaged in, will have ..... Photoelectric absorption is most likely for a gamma ray up to a few hundred keV and this probability increases with the increasing atomic number of the crystal [2]. In photoelectric absorption, a gamma is absorbed by an atom of the detector's crystal and an atomic electron is released [3]. The energy of the electron is the incident gamma's energy less the binding energy of the electron. This process is ideal for gamma spectroscopy because the total energy of the gamma ray is observed interacting with the crystal thereby giving a true account of the interaction.

The second interaction process is Compton scatering where the gamma ray only deposits a fraction of its energy in the detector crystal. The gamma ray then continues on to either interact with the crystal again or escape the active region entierly. Compton scattering is the dominant process for gammas with energies from 150 keV to 4 MeV [3]. Because of its fractional energy deposition, identification of these events is very important. The Compton gammas are scattered through an angle according to the Compton scattering formula. Where E'_γ is the energy of the scatered gamma, E_γ is the energy of the incident gamma, and θ is

the scattering angle.

$$E'_\gamma = \frac{E_\gamma}{1 + \big(E_\gamma/mc^2\big)\big(1 - cos\theta\big)} \tag{2.1}$$

Compton scattered events that exit the detector crystal without distributing their total energy contribute to the background continuum seen in spectra. In a single gamma spectra, the Compton continuum ranges from zero to the Compton edge. This corresponds to scattering angles of 0° and 180° respectively. The angular distribution of scattered gamma rays in a Compton scattering process is given by the Klein-Nishina formula for the differential scattering cross section [3].

$$\frac{d\sigma_c}{d\Omega} = r_o^2\left[\frac{1}{1+\alpha(1-cos\theta)}\right]^3\left[\frac{1+cos\theta}{2}\right]\left[1+\frac{\alpha^2(1-cos\theta)^2}{(1+cos^2\theta)(1+\alpha(1-cos\theta))}\right] \tag{2.2}$$

The energies of multiple events identified as Compton events can be summed in software to give a more complete picture of the actual interaction. The detection and tracking of these Compton scattering events can be used to either reconstruct a true photopeak from more than one interaction of a single photon in the detector, or use the specific characteristics of Compton-scattered events to measure quantities such as the linear polarization of the incident photon.

In the third process, pair production, the gamma ray is absorbed and an electron-positron pair is produced. There is a threshold of $2mc^2$, or 1.022MeV, for this process and therefore only likely for gammas of high energy [3].

2.4 Applying a reverse bias voltage

depletion region, movement of electrons and holes

All crystalline materials have a structure with th...

Semiconductor detectors have a crystalline structure with their atoms arranged in energy bands. The valence band has tightly bound electrons that stay in place

in the lattice while the conduction band has electrons that are deteched from the atoms and free to move [**?**]. Between the valence band and the conduction band is the energy gap. The energy gap has no available energy levels for electrons to move to and its width depends on temperature and pressure. In a

In an insulator, the energy gap is very wide, prohibiting movement of electrons through the crystal. In conductors, the valence and conduction bands overlap making electron movement, and therefore current flow, easy. Semiconductors are in the middle with a gap of medium size. Thermal excitation of electrons might still promote the electrons into the conduction band when a current is applied. This is the reason a semiconductor detector is operated at liquid nitrogen temperatures. Cooling makes the electrons stay in the valence band and the conductivity of the material decreases.

electrons and holes

At a particular temperature and applied voltage, the electrons and holes will have a specific drift velocity. As the electrons are excited out of their positions in the lattice, they are promoted into the conduction band where the applied voltage sweeps them towards one of the contacts. The spaces left behind, the holes, behave as positive charges and move the opposite direction.

Problems with the charge collection may occur when the separated electons and holes recombine due to impurities in the crystal. The charge carriers become trapped in intermediate energy levels in the energy gap and may either be released after some time-causing a prolonged collection time-or recombine and not be collected at all.

Chapter 3

Achieving Position-sensitivity in germanium

3.1 subsection title

stuff about pixels - maybe about sorting

3.2 next subsection

Chapter 4

The traditional approach: The Ortec LEPS

4.1 subsection title

mention where from

The Ortec Low Energy Photon Spectrometer detector (LEPS) is a square planar detector of high purity germanium measuring 92mm by 92mm with a 20mm thickness. It has 32 electrically segmented contacts;16 one each side. The two sets of contacts are orthogonal to eachother forming 256 pixels. The contacts have a 5mm pitch and a .5mm spacing.There is 2.25mm of Ge crystal on each edge that is not utilized. One set of contacts are made from implanted lithium and the other from boron using photolithography.

The boron contacts have a thickness of ????? and are labeled B00-B15. These contacts make up the AC side of the LEPS detector and have a reverse bias of -1300V applied. Contacts on this side collect the positively-charged holes created when a gamma ray interacts with the crystal. Output appears as a negative pulse.

4.2 next subsection

Chapter 5

New contact technologies: The PhDs detector

5.1 subsection title

a little bit of an intro - mention where its from

The PHD's detector is a cylindrical planar crystal of high purity germanium with a 90mm diameter and 10mm thickness. Like the Ortec detector, it has a total of 32 electrically segmented strips; 2 sets of 16 on either side with one set of contacts running orthogonal to the other such that a 2-dimensional grid of 256 pixels is formed. The contacts have a 5mm pitch and a .25mm spacing. There is a gap of 3.125mm from the edge of the last contact to the edge of the crystal that is not utilized. Both sets of contacts are made with amorphous Ge using a photolithographic process. Thickness ???????. The PHD's detector is mechanically cooled my means of an ion pump to a temperature of 78K.

The "A" side (DC side) of the PHD's detector has contacts running horizontally providing Y axis positioning. These contacts are labeled with numbers 0-15 and are at electrical ground. The A side contacts collect the holes created by an interacting gamma ray. Output appears as a positive pulse.

The "B" side (AC side) of the detector has vertical contacts providing X axis positioning. B side contacts are labeled 16-31 and are operated at 600V. These contacts collect the electrons created when a gamma interacts with the crystal and output appears as a negative pulse.

The benefits of the new amorphous Ge contacts are twofold. One, as a more stable contact it is believed the amorphous Ge will overcome the problems the lithium contacts have with mobility and thickness. With the thinner amorphous Ge, the spacing needed to electrically isolate the contacts can be much shallower and done with photolithography instead of a physical saw cut. Decreased mobility of the contact material allows for an intra-strip spacing of half the width needed in detectors with lithium contacts.

5.2 next subsection

Chapter 6

Electronics and experimental setup

6.1 Detector and source geometry

geometry

6.2 Analog Ele

MSU system, ROOT, SpecTcl

The same set of analog electronics is used for data collection with the Ortec and NP7 detectors. Each detector had its own set of preamplifiers. Signals from the preamps are sent into CAEN N568B spectroscopy amplifiers. The spec amps have 16 channels and are programed with a CAENET cable to roughly gain match the signals. A more precise gain matching is done later in software. (show sort codes in an appendix?) Energy outputs from the spec amps are fed into a Phillips 7164 analog-to-digital converter. Fast timing outputs from the spec amps lead to CAEN C894 discriminators. The OR of the discriminator outputs are the two inputs for a Phillips 755 logic unit and the 16 timing signals from each side go to

Phillips 7186H time-to-digital converters. The Li side of the Ortec detector and the "A" side of the NP7 detector are delayed 150ns so that they always came after the signals from the other side. The logic unit requires the presence of a signal from both the front and back of the detector to produce an output that is sent to another Phillips logic unit. This box provides a 500ns gate to the trigger for the Wiener CC-USB crate controller in the CAMAC crate and a 50ns gate for the ADCs after passing through a Phillips794 gate and delay generator. Also from this logic unit, a common stop signal is sent to the TDCs after passing through a NIM/ECL converter. The CC-USB sends a start signal to a Lecroy 222 gate generator set in latch mode which supplies the veto signal for the logic unit that produces the CC-USB trigger. When its done processing an event, the CC-USB sends a signal, through a 40ns delay box, to release the latch. Time and energy data is collected by the crate controller from the two ADCs and two TDCs in the CAMAC crate. The signals are passed to the computer using a usb cable from the crate controller.

This project utilizes READOUT, software developed at Michigan State University for simultaneous data acquisition of multiple channels.

include electronics diagram .pdf here

6.3 Overcoming electronics problems

switching cables to fix bad strips and bad electronics channels

careful to avoid high count rates as they lead to pile-up events that can distort the spectrum [**?**]

Chapter 7

Comparative data

7.1 Gros et al paper

This project was largely based on the paper published by S. Gros *et al.* [1] outlining performance tests for planar germanium detectors. The paper provided many benchmarks for detector evaluation and explanation of some of the common problems seen in DSSDs. Tests for Ge DSSDs were grouped according to the number of pixels involved in the gamma event. Some tests were performed only with one hit events while others required two pixels. A number of different high-purity Ge detectors were examined in the Gros paper, including one coaxial LEPs, two planar strip detectors with lithium and boron contacts, and two planar strip detectors with amorphous Ge contacts. (Explain more about detectors used?) The Mark 3 detector used in the Gros paper is the Ortec detector used in this master's project.

7.1.1 Single Pixel Tests

The first, and arguably most important, test was resolution of each strip as measured by a single channel MCA. Measuring the resolution of each detector was done one strip at a time while the other strips were not connected to any elec-

tronics. This was done to minimize any equipment-based cross talk or grounding problems.[1] As demonstrated in the Gros paper, it is common to see that large, segmented detectors actually have worse resolution than LEPS detectors. A plot of the resolution across the face of the detector should ideally show all strips having nearly the same resolution. Poor resolution on the edge strips can be a sign of an inadequate guard ring. [1] Below are the lower-energy parts of a ^{152}Eu spectrum collected by the LEPS detector and the amorphous contact planar detector as seen in the Gros paper. As predicted, the LEPS detector clearly has better resolution than the planar strip detector.

Figure 7.1: longer caption to explain the figure

Another one pixel performance test is a comparison of the energy differences between the front and back sides of the detector. When a gamma ray interacts with the germanium crystal, an equal number of electrons and holes are created. A perfect detector would collect the same signal on both sets of contacts. Any dif-

ferences in collected signal could be due to a number of factors including different amounts of impurities in the crystal, an uneven electric field, or a misalignment of the crystal axis and faces. [1] Plotting counts vs. energy difference (ΔE = Energy$_{front}$− Energy$_{back}$) would show any differences in collected signal. With an ideally-preforming detector these ΔE plots would feature a single, well defined peak centered at zero. A comparison of pixels across the face of the detector would highlight any position-dependent deviations from equal energy collection. Gros *et al.* found the most imbalance in charge collection in pixels near the guard ring. A suggestion made for suppressing this affect was collecting a signal from the guard ring to allow for identification of events that lost charge due to the pixel's location on the edge of the crystal. [1]

(show example from Gros paper here?)

The last single pixel test in the Gros paper was a plot of energy on one side vs energy on the other side for single hit events. The main feature of such a plot is a 45° line. Events falling on this line have the same signal collected on both sides of the detector. Photopeak events appear as tall peaks on this line while the Compton continuum can be clearly seen throughout the lower part of the 45° line. Events off this line didn't have the same amount of charge collected by both sides of contacts. One will also note the presence of horizontal and vertical lines from the photopeaks nearly parallel to the axes. These tails can be explained by incomplete charge collection by a strip near the guard ring along with nearly complete collection by another strip. [1] A superior detector will have smaller, sharper, and more symmetric tails demonstrating improved charge collection. [1]

(pic here?)

7.1.2 Double Pixel Tests

Double hit events allow for a measurement of charge sharing and loss between strips. As Gros *et al.* notes, these are the events most likely to show charge sharing and charge loss and to reveal how the strips are electrically coupled. Plotting energy vs. energy and counts vs ΔE for two neighboring strips on one side and one strip on the other side should show the same features as mentioned above for single hit events. Further, comparing nearest neighbor pairs with next nearest pairs should show an inverse dependence of electronic coupling on strip proximity with strips at opposite ends of the crystal displaying nearly no coupling.

An interesting effect can be seen in the plots of counts vs ΔE for two hit events. An upshift in the ΔE peak position brings to light the charge loss "hidden" in one hit events by the gain matching of the strips. One of the first measurements needed when turning on a new detector is a collection of single gamma data to use in gain matching the strips. Noting the position of the photopeak in each strip allows for a calibration, usually to two points, of the energy. If some of the events were actually scatters with the scattered gamma depositing energy below the level of the discriminator, the event will have a multiplicity of one. The energy deposited in the one strip will actually be less than the total energy in the incident gamma but, due to the gain matching, will be artificially raised to the energy of the incident gamma. In that way, strips can be gain matched to show a higher energy than was actually deposited. In two strip events, the effect of this calibration can be seen in a higher energy peak when the energies of two strip events are summed. The energy "lost" to the neighboring strip is effectively added back when the two strips are summed, leading to a peak higher than the incident gamma energy. It is expected that detectors showing less charge sharing will have a ΔE peak closer to zero.

With events where there was one hit on one side and two on the other, a plot

of the energy sum ($\sum E = Energy_{twohitsoneside,onehitonotherside}$) vs energy difference ($\Delta E = Energy_{twohits} - Energy_{onehit}$) is useful in showing the upshift in photopeak energy. [1]

sum vs delta plots and counts vs scattering angle

7.2 Tests run

7.2.1 Single Pixel Tests

7.2.2 Double Pixel Tests

went further than the Gros paper in quantitatively showing that the boron and lithium contacts behave differently. Also confirmed the performance symmetry of the PHD's detector with amorphous Ge contacts on both sides. Not much mention of the asymmetry of the boron/lithium contacts was described int eh Gros paper. Showed a difference in front/back energy plots with illumination on both sides of the Ortec detector. same tests on the NP7 showed no appreciable difference, as expected with the symmetry of the amorphous Ge contacts.

measure the upshift in the peak in deltaE plots as a percent of incident gamma energy to get quant measure of coupling [Gros]

Chapter 8

Findings

8.1 Resolution

the first test of resolution was with a single-channel MCA It was found that the NP7 detector had superior energy resolution than the Ortec detector. R

8.2 Difference in Contacts

B and Li vs amorphous Ge

8.3 Difference in Symmetry

2 contact material vs 1 contact material

8.4 Difference in Inter-Strip Spacing

.5 mm vs .25 mm

Effects showing electronic coupling speak to the detectors' inter-strip spacing. Plots of front-side energy vs back-side energy should show a 45° line

Chapter 9

Potential Applications of the new technology

9.1 Medical Imaging

blah blah blah

9.2 Homeland Security

port monitors, non-proliferation, airport scanners for luggage and people

9.3 Fundamental Research

Position sensitivity - Polarization

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