Lawrence Berkeley National Laboratory
LBL Publications

Title
Evaluation of Si(Li) Detectors for Use in Compton Telescopes

Permalink
https://escholarship.org/uc/item/6b3836pv

Authors
Tindall, C
Hau, I D
Luke, P N

Publication Date
2002-05-01

eScholarship.org Powered by the California Digital Library
University of California

LBNL-50234

Ernest Orlando Lawrence Berkeley National Laboratory

Evaluation of Si(Li) Detectors for Use in Compton Telescopes

C. Tindall, I.D. Hau, and P.N. Luke

Engineering Division

May 2002

Presented at the
Symposium on Radiation Measurements and Applications,
Ann Arbor, MI,
May 21–23, 2002,
and to be published in
the Proceedings

REFERENCE COPY
Does Not
Circulate
Copy 1
Library Annex Reference
Lawrence Berkeley National Laboratory
LBNL-50234

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor The Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or The Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof, or The Regents of the University of California.

Ernest Orlando Lawrence Berkeley National Laboratory
is an equal opportunity employer.

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

LBNL-50234

Evaluation of Si(Li) Detectors for Use in Compton Telescopes

C. Tindall[1], I.D. Hau[1,2], P.N. Luke[1]

[1]Engineering Division
Ernest Orlando Lawrence Berkeley National Laboratory
University of California
Berkeley, California 94720

[2]Department of Nuclear Engineering
University of California
Berkeley, California 94720

May 2002

This work was supported by the Defense Threat Reduction Agency, Department of Defense, and the National Aeronautics and Space Administration, through the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

recycled paper

Evaluation of Si(Li) Detectors for Use in Compton Telescopes

C. Tindall [a], I. D. Hau [a,b], P. N. Luke [a]

[a] Lawrence Berkeley National Laboratory, Berkeley, CA 94720
[b]Department of Nuclear Engineering, University of California, Berekeley, CA 94720

Abstract

Si(Li) detectors are currently being developed for use in large Compton telescopes. A major advantage of silicon when compared with germanium is its ability to operate at significantly higher temperature. To determine the feasibility of using Si(Li) detectors in a Compton telescope, their performance as a function of temperature has been studied. We present leakage current, noise data and gamma-ray spectral performance at various temperatures for single 6-mm thick planar devices. It has been determined that for detectors without a guard ring, the noise began to rise significantly around 210K. Adding a guard ring improved the leakage current by about an order of magnitude and reduced the total noise (detector plus electronics) by about 25%. The noise of the detectors with ~130 mm^2 area and a guard ring did not exceed our performance goal of 2 keV FWHM until the temperature was approximately 240K. For 122 keV gamma rays, no evidence of ballistic deficit was seen at 8 μs peaking time and bias voltages corresponding to an internal electric field of ~1150 V/cm. Some evidence of ballistic deficit was seen for 662 keV gamma rays at temperatures above 220K.

Keywords: Lithium-Drifted Silicon; Si(Li) Detectors; Advanced Compton Telescope;gamma-ray spectroscopy;Si(Li) strip detectors

1.) Introduction

Traditional Compton telescope designs require that the incident gamma-ray scatter in the first detector (typically a low-Z material), and that this scattered gamma-ray then be completely absorbed in a second detector (typically a high Z material). However, a new approach to gamma-ray detection has recently been conceived that will provide a substantial improvement in sensitivity and resolution, as well as eliminating the need for high Z detectors.[1] This detection scheme is based on the fact that the incident gamma-ray's energy and direction can be reconstructed from the energy loss and position of interaction of the first three Compton scattering events in the telescope. For this reason, it has been dubbed the "3-Compton technique". Since full absorption of the γ-ray is not required, this concept allows the use of lower Z detector materials, in particular silicon. This in turn dramatically reduces the need for cooling of the detector arrays when compared with what is needed for germanium detectors. However, as in traditional Compton detection schemes, excellent position and energy resolution is required of the detectors in order to accurately determine the energy and direction of the incoming γ-ray.

For this application, we are currently developing lithium-drifted silicon (Si(Li)) orthogonal strip detectors. As the first step in this program, we have thoroughly characterized the performance of Si(Li) detectors that have been fabricated with Lawrence Berkeley National Laboratory's (LBNL) standard process. Because silicon is relatively transparent to gamma-ray photons, conventional applications of Si(Li) detectors have been in the fields of charged particle and X-ray spectroscopy.[2] However, performance requirements for Si(Li) detectors used for γ-ray Compton telescopes are different than those needed for the more conventional applications mentioned above. A reasonable baseline performance goal is for the detectors to have a resolution of 2 keV FWHM per strip, with 3-dimensional positional resolution of better than one millimeter. This will allow the final instrument to have significantly improved sensitivity and energy resolution when compared with current generation instruments.[3]

The most important advantage that silicon has over competing detector materials is a combination of good energy resolution and potentially high operating temperature (most likely between 210K and 240K). While a significant amount of data exists on Si(Li) detectors at low temperatures (77K and below) when used as x-ray detectors and at ambient temperature as charged particle detectors, no systematic study appears to have been undertaken at the temperatures of interest for this instrument.[5,6] Furthermore, there is only very limited data available on the performance of these detectors when used to detect energetic γ-rays [4]. Thus, a thorough study of detector performance vs. temperature was needed to determine their characteristics, in particular their highest useful operating temperature for this application.

2. Experimental arrangement and detector fabrication

The detectors were fabricated using the standard LBNL Si(Li) process which has been described previously.[7,8] They had an overall diameter of 24mm with a deep circular groove cut in the silicon to define the active area. The diameter of the active area was ~16.5mm and its thickness was 6mm. No surface passivation treatment was applied to the groove. The n^+ contact consisted of diffused lithium, while the p^+ contact was a Au surface barrier. The detectors were tested in a liquid nitrogen cooled cryostat. The temperature of the cold stage can be continuously varied from 77K to 396K. Detector leakage current and detector noise were measured. The detector signal was collected using an LBNL custom-built low noise pre-amplifier.[9] The electronic noise of the pre-amplifier (at 6.7 μs peaking time, no detector attached) was approximately 1.1 keV FWHM. For the noise measurement the output was fed into a shaping amplifier followed by a True RMS voltmeter. The shaping amplifiers were custom built by Canberra with an especially wide range of peaking times available so that a measurement of the limiting cases of noise could be made. That is to say, the noise was measured both at very short shaping times where series noise dominates, and also at very long shaping times where parallel noise is the major component. The leakage current measurements were made with a picoammeter.

Tests were performed on two types of detectors: 1.) "full-area" detectors with a deep groove, but no guard-ring, and 2.) detectors with a deep groove and an active area that has been divided into an outer annular guard-ring (~1.5mm wide) and a circular center contact; the center contact is therefore isolated from the lateral surface of the detector by the guard-ring. Separation between the center contact and the guard ring was accomplished by cutting a shallow groove in the silicon material that is deeper than the diffused lithium contact. The area of the center contact is comparable to the anticipated area of a single strip contact in the final orthogonal strip detector design. The detector geometries are shown schematically in Figure 1. All measurements using the guard ring detectors were made with the guard ring grounded. The bias voltage was applied to the Au surface barrier contact. As will be discussed below, the detectors with a guard-ring performed much better than the "full-area" detectors because of the reduced surface leakage current.

3. Results and Discussion

Figure 2 shows the leakage current of a full-area detector (#8906) as a function of the bias voltage at several temperatures. The leakage current for a similar detector with a guard ring (#8905) is shown in Fig. 3. The diameter of the center contact of 8905 is 12.7mm. Thus, 8905 has approximately 60% of the area of 8906. However, at a bias of about 700V the leakage current is reduced by about an order of magnitude between 200K and 240K compared with a detector with no guard ring. The most likely explanation for the additional rise in leakage current seen around 200V is charge injection from the Au surface barrier contact. We have observed that the material remains slightly p-type after the drifting process, so the detector should deplete starting at the n-type contact. As the edge of the depleted volume nears the p-type contact, charge injected through the surface barrier begins to contribute to the bulk leakage current. The approximate height of the barrier may be calculated from the magnitude of the charge injection at different temperatures using a thermionic emission model. This yields a barrier height of 0.75 eV. This is in reasonable agreement with the accepted value of the barrier height of a Au Schottky barrier when used as a p-type contact. In the case of the full-area detector (Fig. 2), the inclusion of surface leakage leads to a much higher measured current, which obscures any effect due to charge injection from the surface barrier.

The noise of the detector with no guard ring vs. peaking time is plotted in Figure 4. Since a $10^9\ \Omega$ feedback resistor was used in the preamp feedback network, leakage currents of more than a few nanoamps could not be tolerated because it would saturate our DC coupled pre-amp. Unfortunately, AC coupling resulted in a dramatic increase in the electronic noise. Even at 80K, AC coupling resulted in noise that was higher than our goal of 2 keV FWHM. For that reason, the pre-amp was DC coupled for all of our noise measurements.

It can be seen from Fig. 4 that the optimal peaking time to obtain the lowest noise is between four and six microseconds at 220K. The dashed lines show the amount of shot noise that is theoretically expected from the measured leakage current at the given temperature. The total measured noise (detector plus electronics) is significantly less than what is expected. A plausible explanation for this is that the surface leakage current, unlike the bulk leakage current, does not contribute full shot noise. As noted above, the amount of bulk leakage current in the detector is much less than the amount of surface leakage. In the noise calculation, we assumed that the surface leakage current also contributes the full amount of shot noise. In this full area device, the noise began to rise significantly around 210K and is well above 2 keV by 220K. As expected, the total noise at longer shaping times increases more sharply with temperature since the parallel noise component (leakage current) is more important there.

For the guard ring detector, the guard ring carries the surface leakage current, which in this case comprised about 90% of the total leakage current. The noise vs. peaking time at various temperatures of interest is shown in Fig. 5. The noise of the guard ring detector at 240K (slightly less than 2 keV at the minimum) is comparable to that of the detector without any guard ring at 210K. The noise of the guard ring detector and electronics is still significantly lower than 2 keV at 220K. Furthermore, at 260K where the parallel noise from the leakage current becomes significant, the calculated noise based on the measured current from the center contact agrees fairly well with the measured noise.

Gamma-ray spectra have also been acquired using three different sources: ^{241}Am, ^{57}Co and ^{137}Cs. As an example, a spectrum of ^{57}Co taken with the guard ring detector at 240K is shown in figure 6. The two characteristic ^{57}Co γ-peaks appear in the spectrum at 122 keV and 136 keV. The relatively broad peak centered about 84 keV is due to 122 keV photons that have scattered in the material around the detector, e.g. the cryostat cold finger, and are subsequently absorbed in the detector. The sharp peak centered at 67 keV is caused by x-ray fluorescence from the gold foil used to make contact to the n^+ detector contact. The rise in background below about 45 keV is the Compton continuum, which is due to γ rays that Compton scattered in the detector, with the scattered photons leaving the detector. The large fraction of counts that is inside the Compton continuum is as expected given the low atomic number of Si. The full width half maximum (FWHM) of the ^{57}Co 122 keV line vs. temperature is plotted in Figure 7 for the detector without any guard ring. A detector bias of 700V was used with a peaking time of 8 μs. As shown above, the minimum in the electronic noise occurred around 8 μs peaking time. (See Figure 4) The electronic noise has been measured using a step pulse injected into the preamplifier through a 1.1 pF test capacitor. At this relatively long peaking time, the energy resolution was determined by the electronic noise. On the other hand, ballistic deficit, manifested by γ-ray peaks being significantly wider than the noise (pulser) peaks, was seen at 700V bias with short peaking times, e.g. Tp = 2 μs. Increasing the bias from 700V to 1200V eliminated the ballistic deficit and improved the γ-ray resolution, although the noise increased slightly. Increasing the bias further to 1500V led to significantly increased electronic noise that degraded the γ-ray resolution. (See Figure 8) Overall, the FWHM of the γ-peak remained below our baseline performance goal of 2 keV up to a temperature of approximately 210K at an optimal peaking time of 8 μs. The detector with a guard ring performed significantly better, maintaining a γ-ray peak FWHM of about 2 keV or less up to 240K. This is shown in Figure 9.

The FWHM of the ^{137}Cs 662 keV peak vs. temperature is plotted in Figure 10. The detector was biased at 700V and a peaking time of 8 μs was used throughout. At this energy, some broadening of the photopeak is observed at temperatures above 200K. At 240K the broadening amounts to approximately 0.1% of the photopeak energy. Using the known carrier mobility and the applied voltage, the variation in signal rise time is estimated to be about 0.5 μs, which translates to a calculated pulse height variation of 0.1% at 8 μs peaking time, in agreement with the measurement. At lower temperatures, the carrier mobility is higher and the effects of ballistic deficit are reduced. Another mechanism that can lead to peak broadening is carrier trapping, and the effect could be temperature dependent as well, but we have not found any clear evidence of that at this time.

4. Conclusion

The leakage current and noise performance of Si(Li) detectors has been measured between 80K and 260K. Si(Li) detectors without a guard ring had about one order of magnitude higher leakage currents and significantly higher noise than that of detectors with a guard ring. The total noise at the optimal peaking time remained lower than our baseline goal of 2 keV FWHM up to a temperature of about 210K. Adding a guard ring allowed the detectors to be operated at substantially higher temperatures. In this case it was possible to operate the detectors up to 240K without exceeding the 2 k eV limit. Based on these results, it should be possible to operate a Compton telescope utilizing Si(Li) strip detectors at temperatures as high as 240K.

References

[1] J.D. Kurfess, W.N. Johnson, R.A. Kroeger, and B.F. Phlips, 5th Compton Symposium, AIP Conference Proceedings, Volume 510, Issue 1, pp. 789-793 (2000).

[2] Radiation Detection and Measurement, by Glenn F. Knoll, 2nd Ed., John Wiley, 1989.

[3] R.A. Kroeger, W.N. Johnson, J.D. Kurfess, B.F. Phlips, and E.A. Wulf, 2000 IEEE Nuclear Science Symposium. Conference Record (Cat. No.00CH37149), (vol.1), Piscataway, NJ, USA: IEEE, p.7, (2000).

[4] G. S. Hubbard, R.E. McMurray Jr., R.G. Keller, P.F. Wercinski, J.T. Walton, and Y.K. Wong, IEEE Transactions on Nuclear Science, **41**, p. 1338 (1994).

[5] M. Martini, T.A. McMath, and I.L. Fowler, IEEE Transactions on Nuclear Science, **NS-17**, p. 139 (1970).

[6] M. Martini, and T.A. McMath, Nuclear Instruments and Methods 79, p. 259 (1970).

[7] D.A. Landis; Y.K. Wong; J.T. Walton; F.S. Goulding, IEEE Transactions on Nuclear Science **36**, p. 185 (1989).

[8] A. Fong, J.T. Walton, E.E. Haller, H.A. Sommer, and J. Guldberg, Nuclear Instruments and Methods, **199**, p. 623 (1982).

[9] L. Fabris, private communication.

Acknowlegements

This work was supported by the Defense Threat Reduction Agency, Department of Defense, and the National Aeronautics and Space Administration, through the U.S. Department of Energy under Contract. No. DE-AC03-76SF00098.

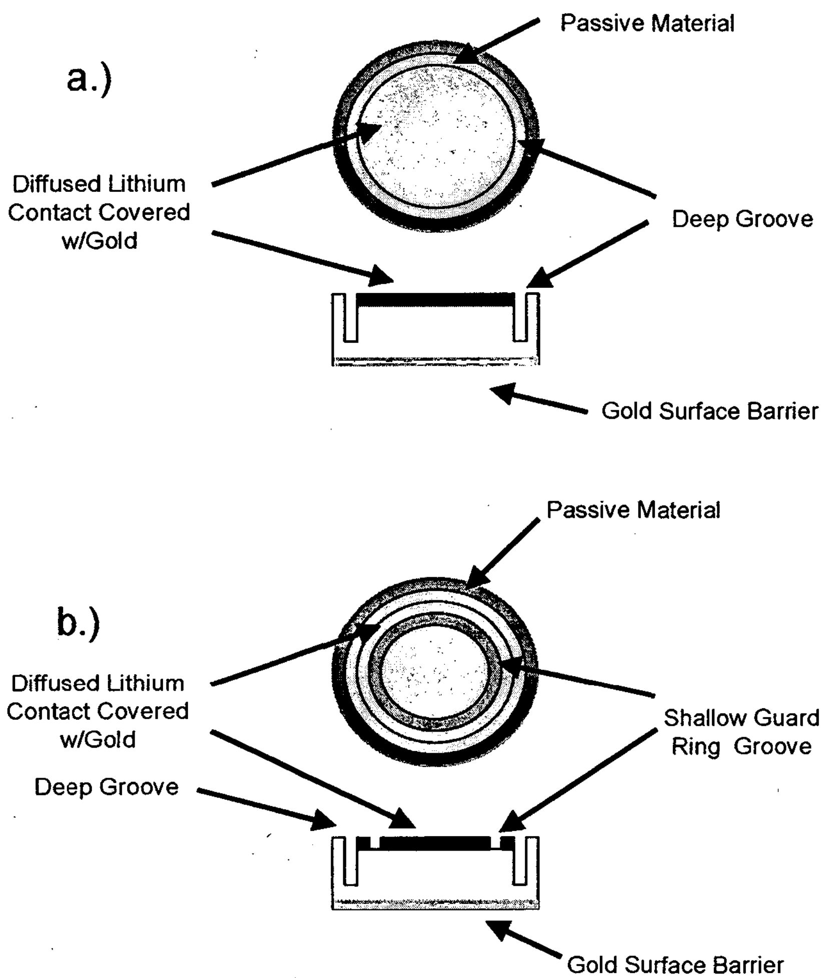

Figure 1 - a.) Top view of the geometry of the "full-area" detector and a side view of this detector showing the "deep groove" structure. b.) The guard ring structure in the lithium contact and a side view showing the groove structures.

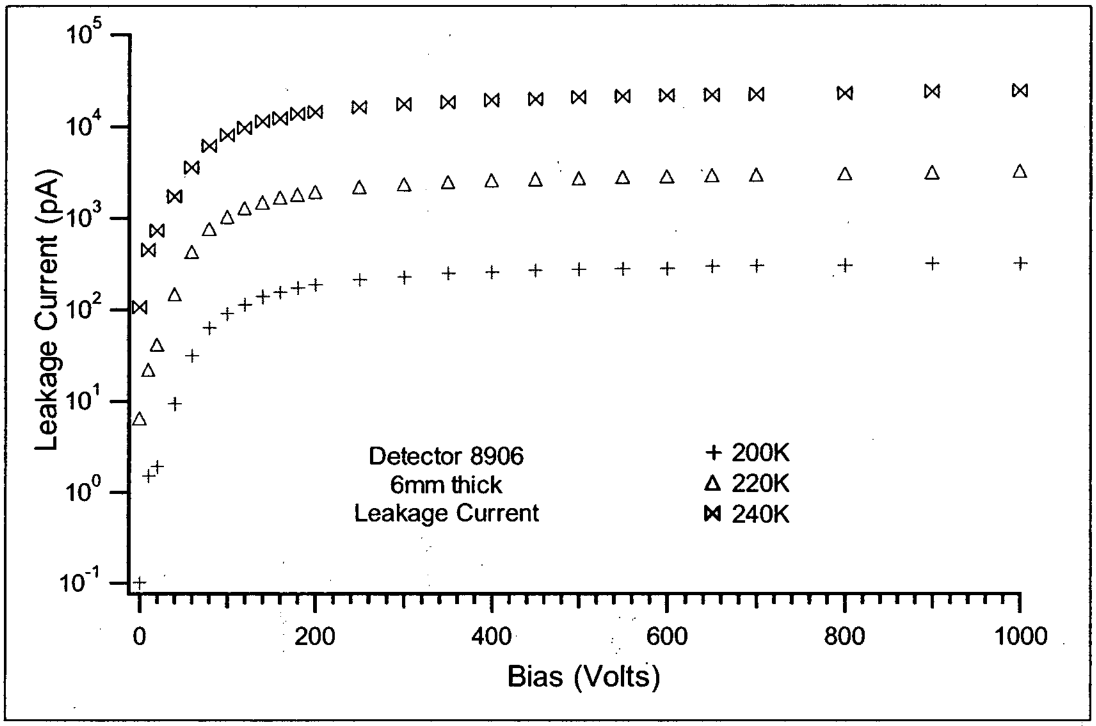

Figure 2 - Leakage current vs. bias voltage of a 6mm thick Si(Li) detector with a deep groove structure, but no guard ring.

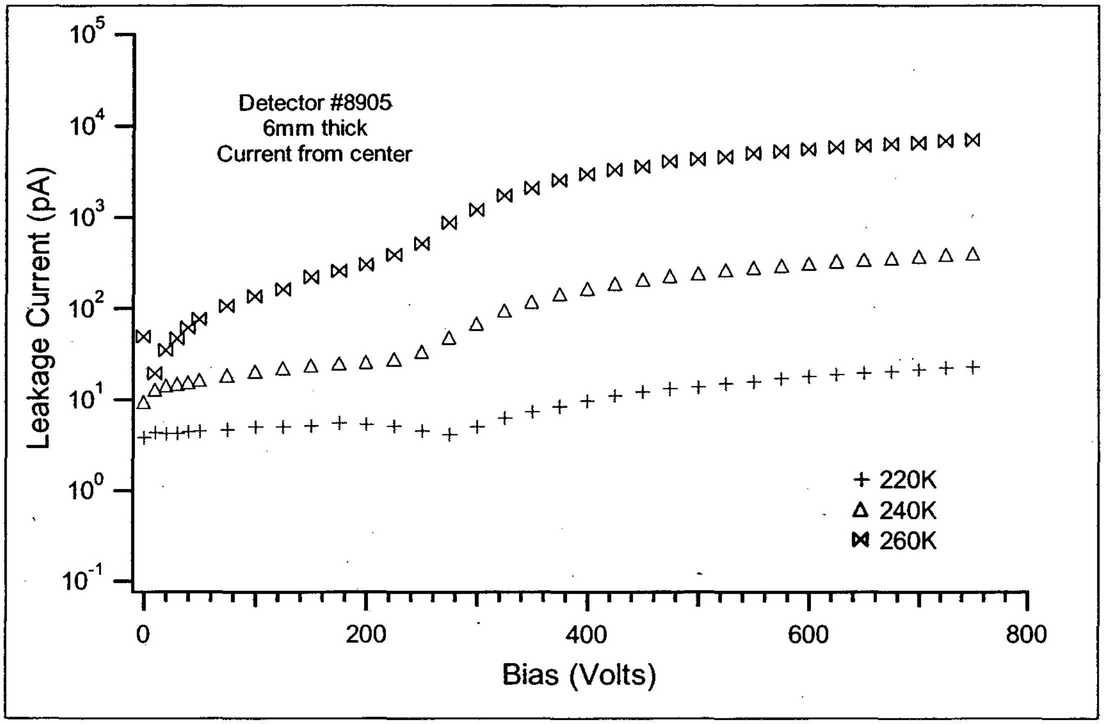

Figure 3 - Leakage current vs. bias voltage for a Si(Li) detector with a deep groove structure and a guard ring as shown in Fig. 1.

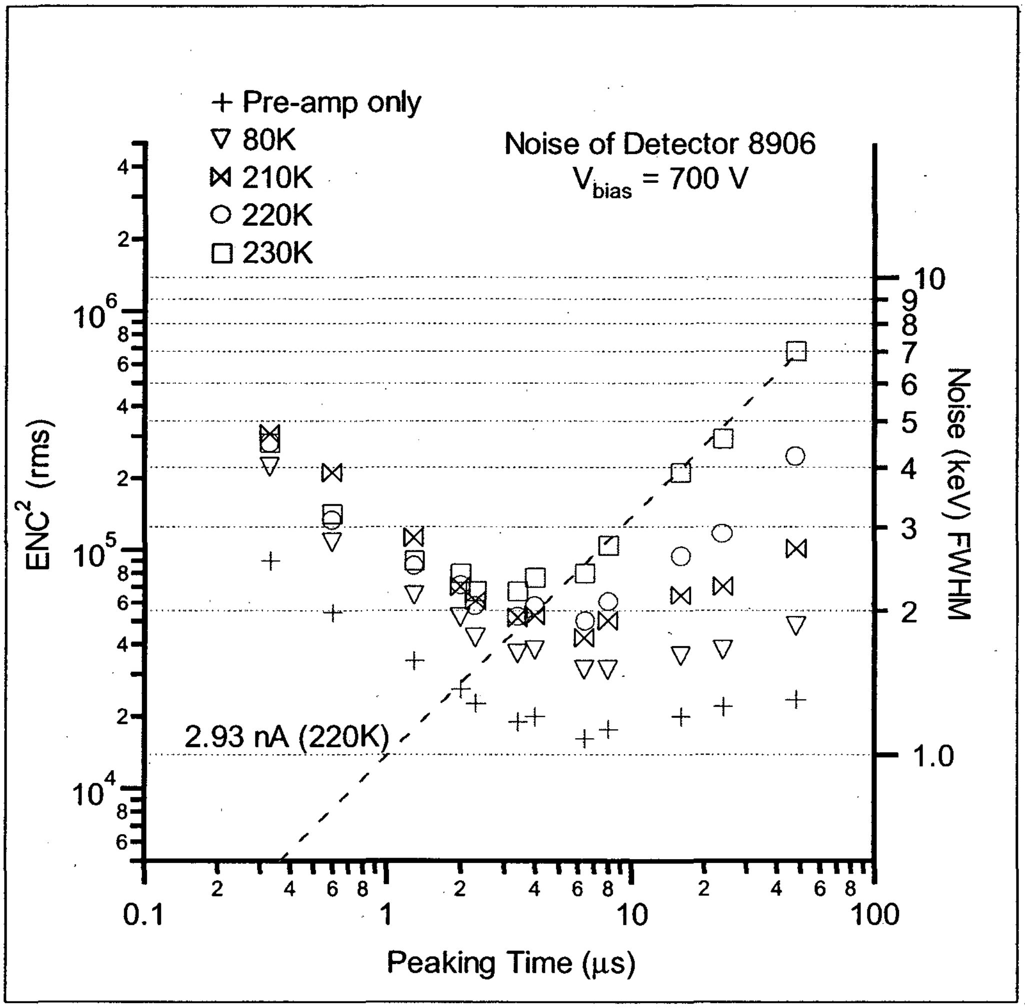

Figure 4 - Noise vs. peaking time of a Si(Li) detector with a deep groove structure but no guard ring. The shot noise expected from the measured leakage current at 220K is shown by the dashed line.

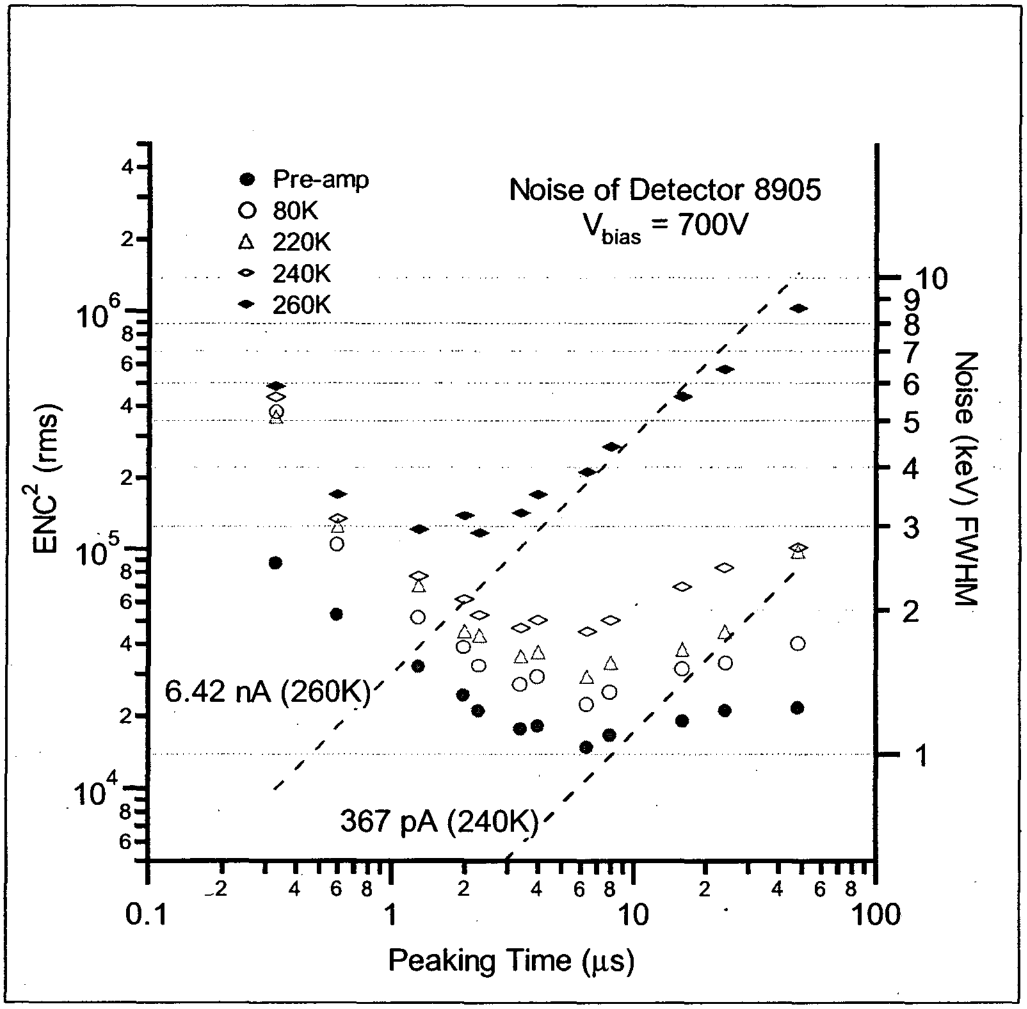

Figure 5 - Noise vs. peaking time of a Si(Li) detector with a deep groove structure and a guard ring in the lithium contact.

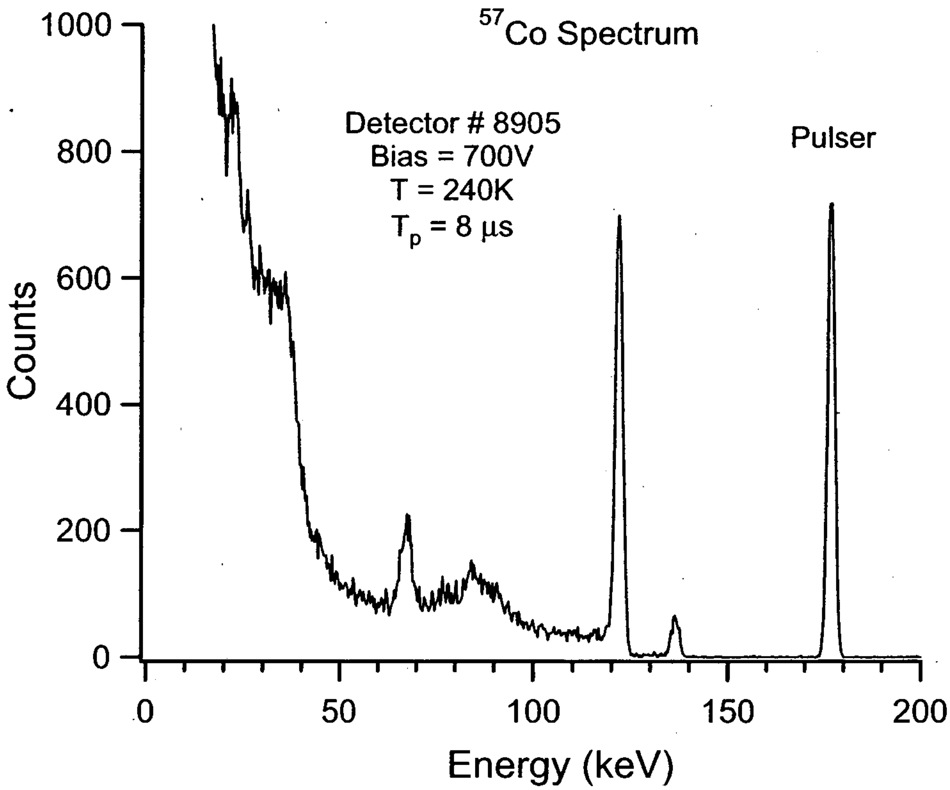

Figure 6 - A spectrum of ^{57}Co taken using a 6mm thick Si(Li) detector operating at 240K, 700V bias and T_p = 8 µs. The FWHM of the 122 keV peak is 2.1 keV.

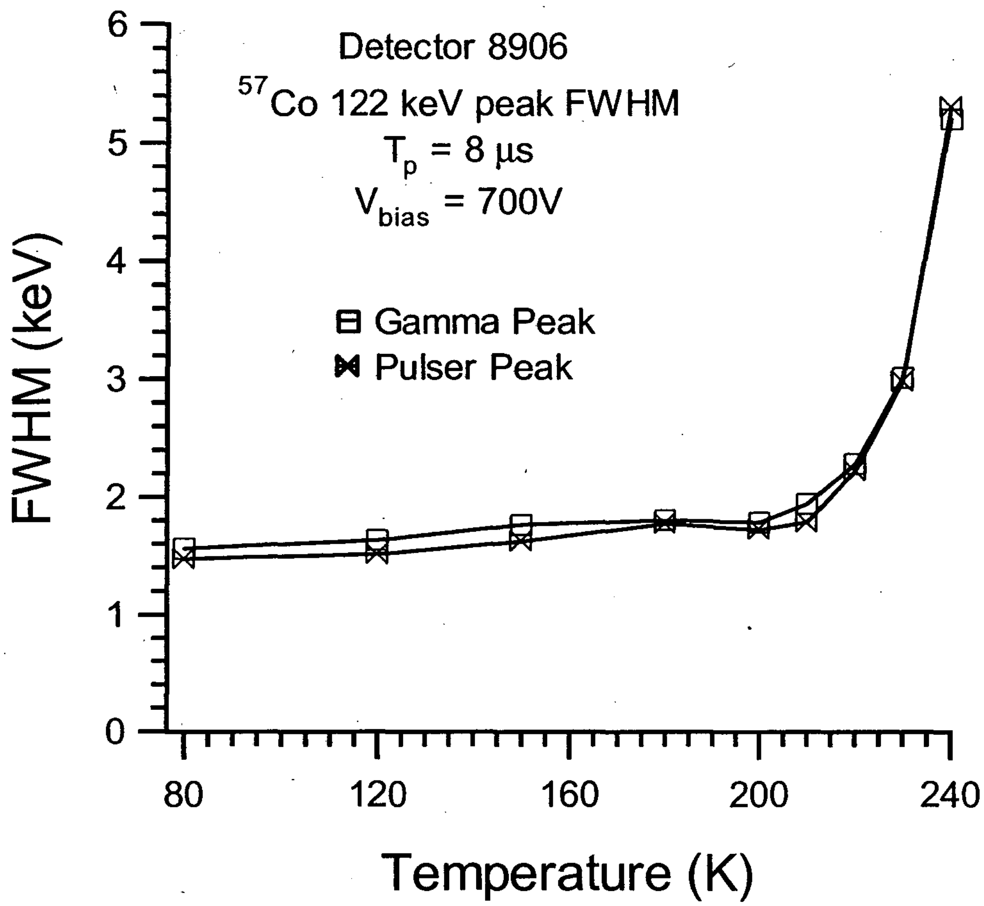

Figure 7 - Full Width Half Maximum (FWHM) of the ^{57}Co 122 keV peak vs. Temperature for a Si(Li) detector with a deep groove, but no guard ring.

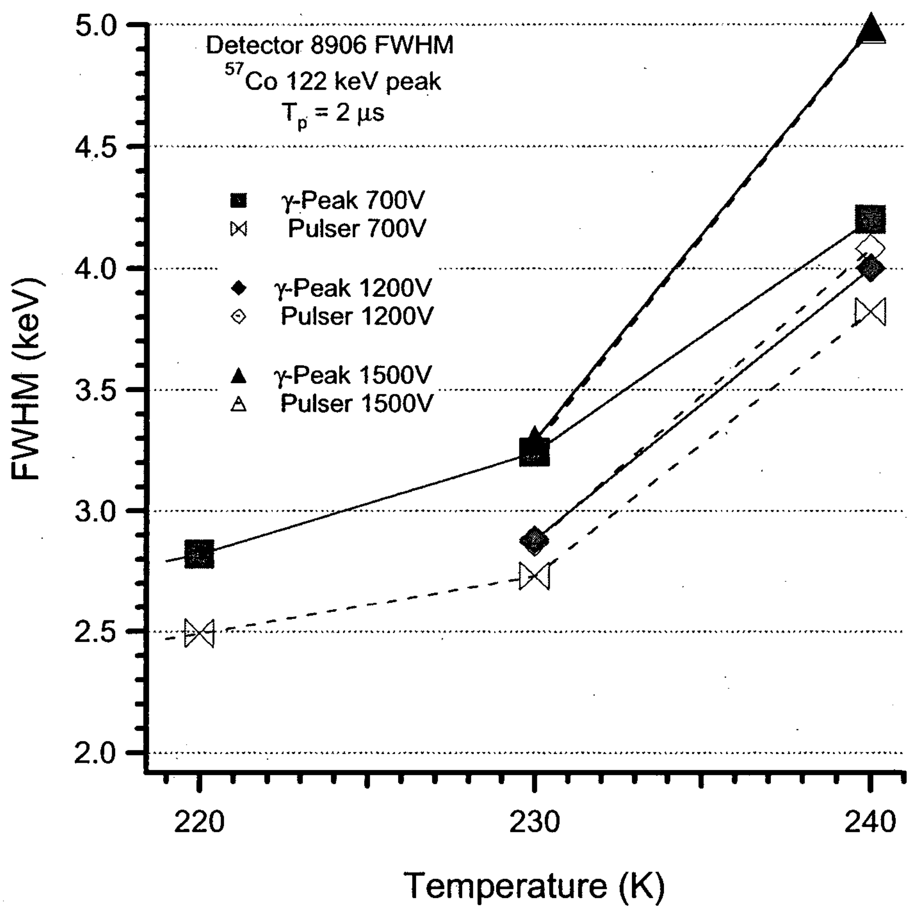

Figure 8 - Width of the ^{57}Co 122 keV peak vs. temperature at three different bias voltages, compared with the electronic noise for a Si(Li) detector with a deep groove but no guard ring.

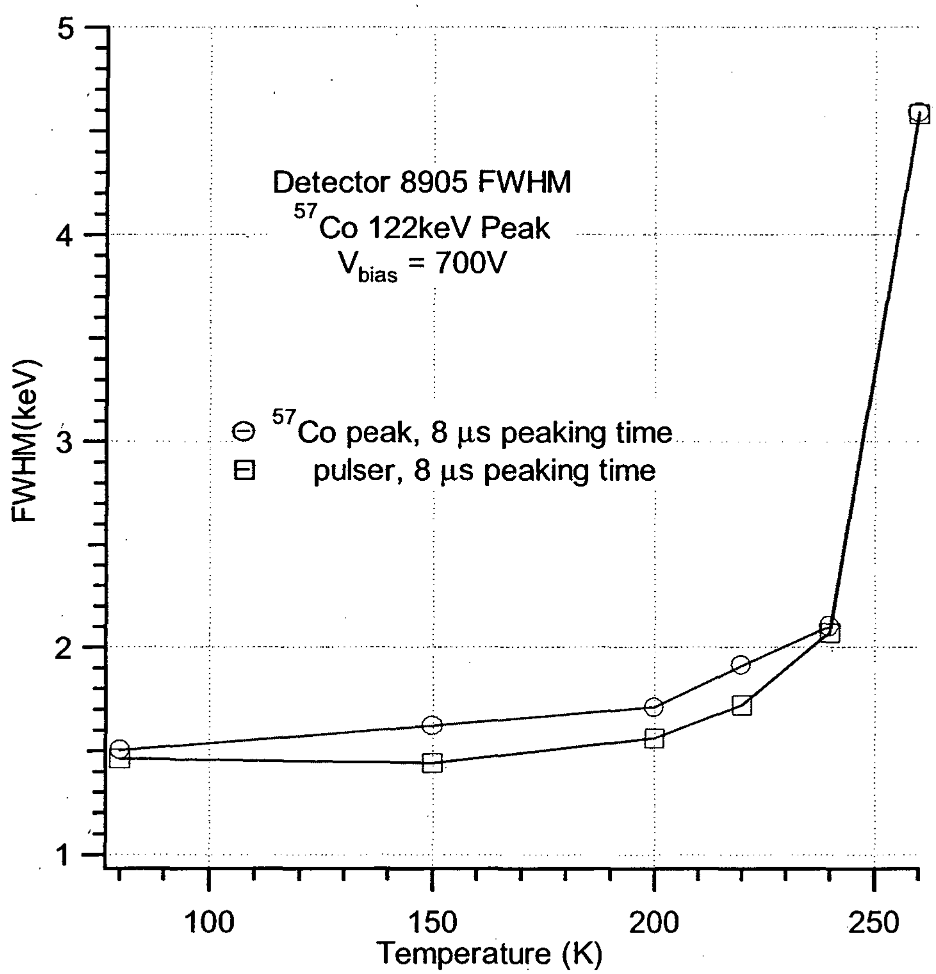

Figure 9 - Full width half maximum of the ^{57}Co 122 keV peak vs. temperature for a Si(Li) detector with a deep groove and a guard ring.

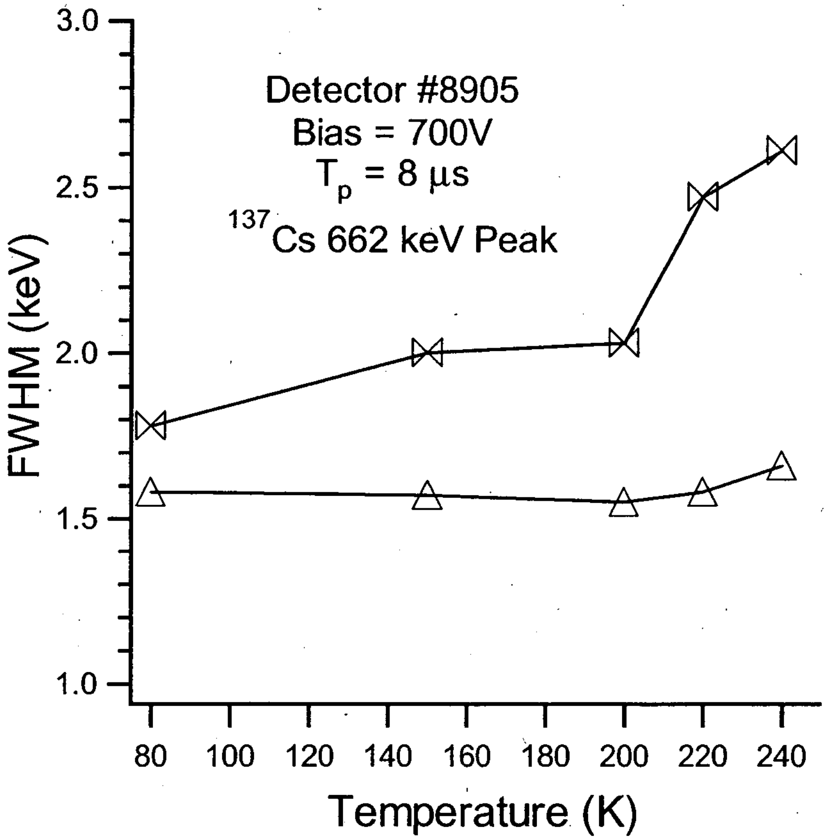

Figure 10 - Full width half maximum of the ^{137}Cs 662 keV peak vs. temperature for a Si(Li) detector with a deep groove and a guard ring.

ERNEST ORLANDO LAWRENCE BERKELEY NATIONAL LABORATORY
ONE CYCLOTRON ROAD | BERKELEY, CALIFORNIA 94720

Prepared for the U.S. Department of Energy under Contract No. DE-AC03-76SF00098