Lawrence Berkeley National Laboratory

Recent Work

Title

GAMMA-RAY SPECTROSCOPY USING SMALL, COOLED BISMUTH GERMANATE SCINTILLATORS AND SILICON PHOTODIODES

Permalink

<https://escholarship.org/uc/item/4ss3g0b0>

Author

Derenzo, S.E.

Publication Date

1983-08-01

Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

RECEIVED

LAWRENCE
BERKELEY LABORATORY

OCT 19 1983

LIBRARY AND
DOCUMENTS SECTION

To be published in Nuclear Instruments and Methods

GAMMA-RAY SPECTROSCOPY USING SMALL, COOLED BISMUTH
GERMANATE SCINTILLATORS AND SILICON PHOTODIODES

S.E. Derenzo

August 1983

TWO-WEEK LOAN COPY

*This is a Library Circulating Copy
which may be borrowed for two weeks.
For a personal retention copy, call
Tech. Info. Division, Ext. 6782.*

Donner Laboratory

Biology &
Medicine
Division

LBL-16628
c2

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.

Gamma-ray Spectroscopy using Small, Cooled
Bismuth Germanate Scintillators and Silicon Photodiodes

Stephen E. Derenzo

Donner Laboratory and Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

Abstract

Gamma-ray scintillation spectra were measured using a $3 \times 3 \times 3 \text{ mm}^3$ bismuth germanate (BGO) crystal and a 4 mm diam silicon photodiode (SPD) at temperatures from $+20^\circ\text{C}$ to -190°C . At $+20^\circ\text{C}$, the optimum amplifier peaking time (τ) was 2 μsec , and the 662 keV photopeak pulses had 3200 electrons (e^-) and a full-width at half-maximum (FWHM) of 27%. For $\tau = 1 \mu\text{sec}$, the minimum FWHM was 20% at -75°C . The narrowest 662 keV photopeak seen in this work had 7.2% FWHM at -150°C using $\tau = 10 \mu\text{sec}$. Cooling from $+20^\circ\text{C}$ to -100°C increased the photopeak amplitude by a factor of 2.4 and reduced amplifier noise by a factor of 1.9. Relative to phototubes, SPDs can be made smaller, and in a wider variety of shapes; they have higher quantum efficiencies, and are insensitive to magnetic fields. This work describes the factors that enable small BGO crystals and SPDs to detect gamma rays with an unprecedented combination of detection efficiency, spatial resolution, and energy resolution.

To be published in Nuclear Instruments and Methods, 1983.

This work was supported in part by the Director, Office of Energy Research, Office of Health and Environmental Research of the U.S. Department of Energy, under Contract No. DE-AC03-76SF00098, and in part by the National Institutes of Health, National Heart, Lung, and Blood Institute under grant No. P01 HL25840.

1. Introduction

Solid state photodetectors, such as silicon, GaAs, and HgI₂ have quantum efficiencies in excess of 60%, considerably higher than that of phototubes in common use for scintillation detection. In addition, solid-state devices are not affected by magnetic fields, can be made much smaller than phototubes, and in a wider variety of shapes. Silicon photodiodes and BGO crystals have been used in the measurement of X-ray fluxes for X-ray computed tomography¹⁾, but electronic noise has discouraged their use for the detection of individual X-rays and γ -rays.

Two potential applications for the use of solid-state photodetectors and BGO scintillators for the detection of individual events are in high energy physics and in medical imaging. In the former, thousands of 20 cm long BGO crystals would be used to detect electromagnetic showers in magnetic fields^{2,3)}. Our research interest is in the latter, where thousands of BGO crystals, much smaller than available phototubes, would be used for the high-resolution, dynamic, 3-D tomographic imaging of positron-labeled tracers in the human body. In this scheme, the BGO crystals would be coupled in groups to phototubes for coincidence timing information and coupled individually to solid state photosensors for crystal identification^{4,5)}. The annihilation photons produce a 511 keV photopeak that corresponds to a signal level of about 2000 electron charge carriers in the photodiode. Most photodiodes have zero bias capacitances of several hundred pF, which results in a charge amplifier noise level greater than the signal level. A reverse bias voltage greatly reduces this capacitance, but the resulting dark current is typically tens of nA, which produces a shot noise that is also greater than the signal level.

The first report of photodiode readout of BGO for the detection of individual charged particles estimated an energy resolution of 2-3 MeV FWHM²⁾. More recently, a new class of low-capacitance, low dark current silicon photodiodes has been developed by the Hamamatsu TV Co. of Japan in collaboration with Dr. Groom of the University of Utah³⁾. Using the Hamamatsu S1723, which has a 10 mm x 10 mm active area and a reverse-biased capacitance of 70 pF, Drs. Groom and Cavalli at the Stanford Linear Accelerator Center have detected pulses from ⁶⁰Co irradiation (1173 and 1332 keV γ -rays) on bismuth germanate, with an estimated energy resolution of 750 keV FWHM³⁾. Key factors in this development were the use of high resistivity silicon, which permitted nearly full depletion without breakdown, and diode contacts having low series resistance.

Using a 3 mm x 10 mm HgI₂ crystal as a photodetector for a 3 mm x 10 mm x 2 mm deep BGO crystal, Iwanczyk and co-workers have measured a 511 keV photopeak FWHM of 19%⁶⁾. Important features of their photodetector are its thickness, which results in a low capacitance, and the fact that HgI₂ is an insulator (band gap 2.13 V), which results in a room temperature dark current below 0.1 nA.

Using BGO scintillators and HgI₂ photodetectors, Barton and co-workers made the first measurement of coincident timing resolution of a pair of scintillators coupled to solid state photodetectors. They measured a resolution of 105 nsec FWHM for annihilation photon pairs, and estimate that the timing resolution could be improved to 50 nsec FWHM by decreasing the charge amplifier noise and by increasing light collection⁵⁾.

2. Materials and Methods

Throughout this work we used the Hamamatsu S1722-01 silicon photodiode, which has an active area 4 mm in diameter and a reverse-biased capacitance of 12 pF. All BGO crystals were polished, coated with MgO powder in water suspension, and allowed to dry. For our first tests, we selected a BGO crystal measuring 3 mm x 3 mm x 10 mm deep that had a 662 keV photopeak resolution of 14% FWHM when used with a Hamamatsu R1306 phototube. After this crystal was cemented to the photodiode, we measured photopeak resolutions of 12% and 10% FWHM at -75°C and -150°C, respectively, using an amplifier peaking time of 10 μ sec. As these resolution widths were significantly larger than the combined effect of carrier statistics, shot noise, and amplifier noise, we suspected that variations in light collection were a significant factor. Additional selection from a sample of 150 crystals (supplied by Harshaw Chemical Co., Solon, Ohio) provided a 3 x 3 x 3 mm³ BGO crystal that had a 662 keV photopeak resolution of 12% FWHM when using the R1306 phototube.

The selected 3 x 3 x 3 mm³ BGO crystal was cemented with RTV 3140 (Dow Corning Corp., Midland, Michigan) to a S1722-01 silicon photodiode (Figure 1a). The charge amplifier used a 2N4393 FET, which has a rated capacitance of 15 pF and a transconductance of 20 mA/V. (Figure 1b). For a lower capacitance photodiode, the 2N4416 FET would provide lower noise. The BGO crystal, the FET and the feedback components were kept at the same temperature as they were cooled. In this work we used equal RC integration and differentiation time

constants τ , which for a very narrow ($\ll \tau$) calibration pulse produces a response with the time dependence $(t/\tau) \cdot \text{EXP}(-t/\tau)$. This function peaks at $t=\tau$ and falls to 10% of the peak value at $t=4.9\tau$. The BGO photopeak pulses have a longer duration (especially at low temperature), and their pulse peaking times are longer (Table 1). The pulse height analyzer digitizes the maximum amplitude of each pulse and ignores the subsequent exponential decay.

Table 1. Observed time for calibration and photopeak pulses to reach peak amplitude

Nominal amplifier peaking time (μsec)	0.5	1	2	5	10
Calibration pulses (μsec)	0.4	0.7	1.5	3.5	7
Photopeak pulses at +25°C (μsec)	0.6	1.1	1.8	4	7
Photopeak pulses at -25°C (μsec)	0.7	1.3	2.3	4.5	7
Photopeak pulses at -75°C (μsec)	0.8	1.7	2.8	5.5	8
Photopeak pulses at -125°C (μsec)	0.8	2.0	3.5	6	10
Photopeak pulses at -190°C (μsec)	-	-	4	8	13

3. Results

3.1 Characteristics of Photodiode and Charge Amplifier

Figure 2a shows the measured capacitance and dark current as a function of reverse bias voltage at +20°C. The device is fully depleted at 10 V and there is no advantage in operating at a larger bias voltage. Figure 2b shows the measured dark current as a function of temperature at a reverse bias of 10V. A Keithley model 410 micro-micro ammeter was used, which has a most sensitive full range of 0.3 pA. Moderate cooling greatly reduces the dark current and cooling below -60°C reduces the dark current below our limit of measurement (0.1 pA).

Table 2 presents the electronic noise present in our charge amplifier for various temperatures and peaking times when connected to the silicon photodiode at a reverse bias of 10V. Figures in parentheses are for the charge amplifier without an input load (i.e. disconnected from the photodiode). The two predominant sources of charge amplifier noise are Johnson (thermal) noise in the FET, and shot noise, due to statistical fluctuations in the number of charge carriers in the bias current⁷). The Johnson noise is proportional to $C\sqrt{T(R_S + 1/g_m)}$, where C is the total capacitance (photodiode + FET + parasitic), T is temperature in degrees Kelvin, R_S is the photodiode series resistance, and g_m is the FET transconductance. In addition, longer pulse peaking times τ reduce the effect of Johnson noise, but the dependence seems to be more complex than $\sqrt{1/\tau}$. The shot noise is proportional to $\sqrt{\tau}$ and is greatly reduced by cooling, through the reduction in photodiode dark current.

Figure 2: Measurements of the silicon photodiode used in this work.
 (a) Capacitance and dark current as a function of reverse bias at +20°C.
 (b) Dark current as a function of temperature at a reverse bias of 10V.

At +20°C and at a 10V reverse bias, the dark current is 2.6 nA and the capacitance is 12 pF. At this temperature, shot noise due to dark current in the photodiode dominates at longer peaking times and Johnson noise in the FET dominates at shorter peaking times. The amplifier noise has a minimum value of 660 e⁻ FWHM at a pulse peaking time of 2 μsec. As the temperature is lowered to 0°C, there is a reduction in amplifier noise due primarily to the reduction in dark current from 2.6 nA to 0.6 nA. Further cooling to -20°C reduces the dark current to 0.05 nA. Below -20°C amplifier noise appears to be dominated by Johnson noise and decreases approximately as the square root of the temperature in degrees Kelvin. At a temperature of -150°C (dark current < 0.1 pA), the best pulse peaking time is the longest provided by our amplifier, 10 μsec. Under these conditions, the noise level is 295 electrons FWHM.

3.2 Performance of a BGO crystal coupled to a silicon photodiode

Figure 3 shows measurements of the 662 keV photopeak amplitude in units of electron charge as a function of temperature from +20°C to -190°C and for 0.5, 1, 2, 5, and 10 μsec amplifier peaking times. The photopeak amplitude increases by a factor of 2.4 from +20°C to -100°C, in excellent agreement with previous measurements⁸). At the lowest temperatures, the BGO scintillation pulse becomes slower than the amplifier peaking time, and the photopeak amplitude decreases. Amplitude values were calibrated by applying 1 mV square-wave pulses through a 0.885 pF capacitor that was kept at room temperature. Both the voltage of the calibration pulse and the value of the capacitor are accurate to a few percent.

Table 2. Amplifier noise (FWHM electrons)

Temperature	Amplifier peaking time				
	0.5 μ sec	1 μ sec	2 μ sec	5 μ sec	10 μ sec
+20°C	850 ^a (470) ^b	700 (425)	660 (385)	685 (345)	850 (345)
0°C	780 (440)	695 (385)	560 (360)	510 (335)	520 (340)
-25°C	790 (410)	615 (400)	535 (345)	490 (315)	485 (325)
-50°C	730 (380)	595 (360)	475 (325)	420 (295)	390 (290)
-75°C	610 (360)	515 (345)	420 (295)	355 (260)	330 (270)
-100°C	630 (335)	505 (305)	420 (280)	360 (250)	345 (250)
-125°C	585 (325)	475 (305)	415 (255)	345 (225)	325 (225)
-150°C	560 (305)	455 (325)	365 (255)	320 (210)	295 (180)
-190°C	585 (415)	470 (325)	385 (255)	335 (215)	320 (205)

^aAmplifier connected to photodiode at reverse bias of 10V.^bAmplifier disconnected from photodiode

Table 3 presents the 662 keV photopeak width for various temperatures and peaking times. Note that the pulses actually reach their peak value after time τ (see Table 1). As shown in Figure 1, only the BGO crystal, photodiode, feedback resistor, and capacitor and FET were cooled. Figures at the 25-30% level have uncertainties of about 3% because the FWHM was estimated by doubling the right-hand half-width at half-maximum. Figures in the 10-20% range have uncertainties of about 0.5%. Figures below 10% have uncertainties of 0.3%.

Figure 4 shows the photopeak resolutions observed in this work (a) at room temperature where the best τ is 2 μ sec, (b) using $\tau = 1 \mu$ sec, where the best temperature is -75°C, and (c) at the combined optimal operating point $\tau = 10 \mu$ sec and -150°C, where the 662 keV photopeak contains 7800 e⁻ and has 7.2% FWHM. Under these conditions, the pulse amplitude and photopeak resolution were measured for several other gamma ray energies (Table 4).

XBL 834-148

Figure 3: Plot of 662 keV photopeak amplitude in units of electron charge as a function of temperature for various amplifier peaking times. See Table 1 for actual pulse peaking times.

Table 3. Measured 662 keV photopeak FWHM at 10V reverse bias

Temperature	0.5 μsec	1 μsec	2 μsec	5 μsec	10 μsec
+20 $^{\circ}\text{C}$	38%	29%	27%	27%	30%
0 $^{\circ}\text{C}$	33%	26%	20.7%	17.3%	19.3%
-25 $^{\circ}\text{C}$	28%	21.4%	16.4%	13.5%	14.9%
-50 $^{\circ}\text{C}$	28%	18.9%	13.4%	9.9%	9.7%
-75 $^{\circ}\text{C}$	30%	17.6%	11.8%	8.4%	8.2%
-100 $^{\circ}\text{C}$	27%	18.2%	11.3%	8.4%	7.7%
-125 $^{\circ}\text{C}$	30%	20%	12.4%	8.0%	7.5%
-150 $^{\circ}\text{C}$	32%	23%	13.2%	8.7%	7.2%
-190 $^{\circ}\text{C}$	no peak	26%	17.9%	8.7%	8.1%

Figure 4: Pulse height spectrum for 662 keV gamma rays using the set-up of Figure 1.

(a) best results for $+20^{\circ}\text{C}$, obtained at an amplifier peaking time of $\tau = 2 \mu\text{sec}$.
 (b) Best results for $\tau = 1 \mu\text{sec}$, obtained at a temperature of -75°C .
 (c) Best results in this work, obtained with $\tau = 10 \mu\text{sec}$, and at -150°C . See Table 1 for actual pulse peaking times.

XBL 834-151

3.3 Performance of a BGO crystal coupled both to a phototube and a silicon photodiode

To measure the response of a SPD and a phototube coupled to the same BGO crystal, the silicon photodiode was cemented to a 3 mm x 3 mm face of a 10 mm long BGO crystal, and a 14 mm diameter phototube was cemented to the opposite 3 mm x 3 mm face. A wire mesh at cathode potential was placed between the crystal and the front face of the phototube to prevent coupling of the phototube pulses to the very sensitive charge amplifier. If this precaution is not

Table 4. Photopeak response of $3 \times 3 \times 3 \text{ mm}^3$ BGO crystal and silicon photodiode at -150°C , $\tau=10 \text{ } \mu\text{sec}$, and 10V reverse bias

Source	γ -ray energy	Photopeak amplitude	Photopeak FWHM
^{133}Ba	80 keV	900 e^-	46%
^{57}Co	122 keV	1,300 e^-	38%
^{133}Ba	356 keV	4,100 e^-	13%
^{22}Na	511 keV	6,000 e^-	8.7%
^{137}Cs	662 keV	7,800 e^-	7.2%
^{22}Na	1275 keV	15,100 e^-	5.4%
^{60}Co	1332 keV	15,800 e^-	5.3%

taken, the charge amplifier detects artifact pulses whose amplitudes depend on the phototube voltage.

The SPD did not produce an observable 662 keV photopeak at $+20^\circ\text{C}$, but at -120°C the photopeak pulses had 2800 e^- and FWHM 27%. The phototube recorded a photopeak FWHM of 41% at $+20^\circ\text{C}$ and 34% at -125°C . Only photopeak silicon photodiode pulses were recorded when the output of the charge amplifier was gated by photopeak pulses from the phototube. This demonstrated that the silicon photodiode photopeak consisted of the same photopeak events seen by the phototube.

4. Discussion

In this work, cooling improved the pulse height resolution through four factors:

- 1) The dark current is reduced from several nA to below 0.1 pA, essentially eliminating shot noise in the photodiode (Figure 2b).
- 2) The reduced shot noise permits the use of longer pulse peaking times, which reduces the effect of the Johnson noise in the FET (Table 2).
- 3) The Johnson noise in the FET and feedback resistor are reduced by approximately the square root of the temperature in degrees Kelvin (Table 2).
- 4) The BGO light output increases, but the scintillation decay time also increases, so that the increased pulse height is only seen when using the longer pulse peaking times (Figure 3).

While factors 2) and 4) are most important for applications that permit longer pulse peaking times, cooling substantially improves the resolution at short peaking times through factors 1) and 3).

The best 662 keV photopeak resolution measured in this work (7.2% FWHM) is broader than what would be expected from the combination of amplifier noise (3.8% FWHM) and quantum statistics (2.7% FWHM). Assuming that these factors add in the square, the additional 5.5% FWHM may be due to other factors such as nonuniform light collection. Decreasing the SPD and FET capacitances by a factor of three would reduce the amplifier noise to below 1.5% FWHM, thus we expect that a very high quality BGO crystal could achieve a 662 keV photopeak resolution of 4% FWHM at low temperature.

The best room temperature 662 keV photopeak resolution measured in this work was 27% FWHM, limited by amplifier noise (18% FWHM) rather than charge statistics (4.5% FWHM). By using a SPD with much lower dark current, we expect that 10% FWHM could be achieved at room temperature. HgI_2 appears to be the only material whose dark current does not contribute significantly to amplifier noise at room temperature. If leakage current at the edge of the device is a factor, a separately grounded guard ring may be used to intercept this current and reduce shot noise⁹). Even if dark current is very low, Johnson noise can be a serious factor, and low capacitance will be important.

For applications requiring low deadtime, the silicon avalanche photodiode may permit very short peaking times by increasing the signal that enters the charge amplifier. A 25 mm diameter silicon avalanche photodiode with a quantum efficiency-gain uniformity of 7% and a photopeak resolution of 9.5% FWHM using 662 keV on NaI(Tl) has been reported¹⁰).

Other scintillators (such as BaF_2 , NaI(Tl) , CsI(Tl) , and CdWO_4), while not as efficient as BGO in detecting high energy γ -rays, are more luminous and when used with a SPD, may exhibit significantly narrower photopeaks than those shown here. Primary concerns are luminosity, a good match between the emitted wavelengths and the spectral response of the SPD, and that the number of photons entering the photodiode is independent of the position of interaction in the scintillation crystal. In addition, if the SPD has low capacitance (< 5 pF) and low dark current (< 0.1 nA), then photopeak resolutions of a few % FWHM may be possible with little or no cooling. The most luminous scintillator thus far reported is pure NaI at -196°C , which has about seven times the output of BGO at -125°C and twice the light output of NaI(Tl) at room temperature^{11,12}).

BaF_2 is especially important for time-of-flight positron tomography¹³) but the spatial resolution is presently limited by the size of high-quality phototubes necessary for sub-nanosecond timing. In this application a fast phototube with a UV window can be coupled to groups of BaF_2 crystals to detect the sub-nanosecond emission component at 220 nm, and UV sensitive photodiodes can be coupled individually to detect the slower 630 nsec component at 300 nm. The phototube timing resolution will be degraded, however, by the sharing of light with the photodiodes.

5. Conclusions

At room temperature, the dark current and small pulse height of BGO limit the 662 keV photopeak resolution to 27%, even at the optimal amplifier peaking time of $\tau = 2$ μsec . As the photodiode is cooled, dark current drops rapidly and the light output increases with an increase in scintillation decay time. The best photopeak resolution for $\tau = 1$ μsec was found to be 20% FWHM at -75°C . The best overall photopeak resolution was 7.2% FWHM at -150°C and $\tau = 10$ μsec .

Important factors for improvements in energy resolution are low dark current (which is strongly reduced by cooling), low capacitance (which is proportional to the ratio of photodiode area to thickness), and signal amplitude (which is increased by a factor of 2.4 for BGO on cooling from +20°C to -100°C). We conclude that by proper design, small BGO crystals can detect gamma rays with an unprecedented combination of detection efficiency, spatial resolution, and energy resolution.

When a SPD and phototube are coupled to the same BGO crystal, photopeak events seen by the phototube are also seen by the SPD as photopeak pulses. This shows the feasibility of using phototubes for timing groups of crystals and silicon photodiodes for the identification of individual crystals.

ACKNOWLEDGEMENTS

We thank T. Vuletich for invaluable technical assistance, B. Baringer and T. Ortiz for assistance in data taking, N. Servies and A. Kurahashi of Hamamatsu, Corp. for providing silicon photodiodes, and T. Budinger, M. Cavalli-Sforza, F. Goulding, D. Groom, R. Huesman, and D. Landis for helpful discussions. This work was supported in part by the Director, Office of Energy Research, Office of Health and Environmental Research of the U.S. Department of Energy, under Contract No. DE-AC03-76SF00098, and in part by the National Institutes of Health, National Heart, Lung, and Blood Institute under grant No. P01 HL25840.

REFERENCES

1. Farukhi MR: Radiation detectors for CT instrumentation. In Selected Topics in Image Science, O Nalcioglu and ZH Cho, eds, Springer Verlag, New York, 1983 (in press)
2. Blamar G, Dietl H, Dobbins J, et al: Photodiode readout for scintillating crystals of BGO and NaI(Tl). Nucl Instr Meth 203: 213-221, 1982
3. Groom DE: Silicon photodiode detection of bismuth germanate scintillation light. International Workshop on Bismuth Germanate, Coyne DG ed, Princeton University, Princeton, 1982, pp 256-265
4. Derenzo SE, Budinger TF, Huesman RH, and Cahoon JL: Dynamic positron emission tomography in man using small bismuth germanate crystals. Proceedings of the Sixth International Conference on Positron Annihilation, Coleman PG, Sharma SC, and Diana LM, eds. pp 935-945, North-Holland, New York, 1982
5. Barton JB, Hoffman EJ, Iwanczyk JS, et al: A high-resolution detection system for positron tomography. IEEE Trans Nucl Sci NS-30: No 1, 671-675, 1983
6. Iwanczyk JS, Barton JB, Dabrowski AJ, et al: A novel radiation detector consisting of an HgI_2 photodetector coupled to a scintillator. IEEE Trans Nucl Sci NS-30: No 1, 363-367, 1983
7. Goulding FS and Landis DA: Semiconductor detector spectrometer electronics. In Nuclear Spectroscopy and Reactions, part A, Academic Press, New York, 1974, pp 413-468
8. Piltingsrud HV: The low-temperature scintillation properties of bismuth germanate and its application to high-energy gamma radiation imaging devices. J Nucl Med 20: 1279-1285, 1979
9. Goulding FS and Hansen WL: Leakage current in semiconductor junction radiation detectors and its influence on energy-resolution characteristics. Nucl Instr Meth 12: 249-262, 1961
10. Entine E, Reiff G, Squillante M, et al: Scintillation detectors using large area silicon avalanche photodiodes. IEEE Trans Nucl Sci NS-30: No 1, 431-435, 1983
11. Van Sciver WJ and Bogart L: Fundamental studies of scintillation phenomena in NaI. IRE Trans Nucl Sci NS-5: No 3, 90-93, 1958
12. Persyk DE, Schardt MA, Moi TE, et al: Research on pure sodium iodide as a practical scintillator. IEEE Trans Nucl Sci NS-27: No 1, 168-171, 1980
13. Workshop on Time-of-Flight Tomography, May 17-19, 1982, St. Louis, IEEE Catalog No 82CH1719-3

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720