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OPERATIONAL CHARACTERISTICS OF GERMANIUM DETECTORS AT HIGHER TEMPERATURES*

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SUMMARY

Several important areas for the use of germanium spectrometers would be opened if these detectors could be successfully operated at temperatures considerably in excess of 77°K. Precise measurements on a series of detectors made from different high-purity germanium crystals and on one lithium drifted germanium detector indicate that the resolution does not degrade significantly until nearly 150°K is reached. Similar-sized detectors, including the lithium-drifted device, exhibited essentially identical temperature-resolution relationships.

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INTRODUCTION

In recent years considerable interest has been expressed concerning the operating characteristics of germanium detectors at temperatures warmer than liquid nitrogen. Questions come mainly from three different areas of detector use: (1) Satellite related experiments, including possible planetary probes, (2) Medical applications, (3) Charged-particle detection in scattering chambers at accelerators. In response to a request of a Los Alamos group, and with their financial support, we have recently carried out a series of experiments to provide the information that would answer these questions.

Two previous studies concerned with the operation of germanium detectors at elevated temperatures should be mentioned here. Nakano and Imhof measured the performance of three single open-ended coaxial detectors at elevated temperatures, and demonstrated the feasibility of operating fairly large (≈ 30 cm^3) lithium-drifted germanium detectors with good resolution at temperatures up to 130° to 140°K.[1] Since the current-voltage characteristics of these detectors differed considerably from one another the question of the practical use of germanium detectors at elevated temperatures remained open.

More recently Armantrout has claimed that the operation of large germanium detectors at temperatures in excess of 200°K is theoretically feasible although he presents no data to indicate that such a result is attainable.[2] He also implies that high-purity germanium detectors can be operated at higher temperatures than can lithium-drifted devices.

Measurements on a series of both high-purity and lithium-drifted germanium detectors fabricated from the wide variety of crystals that are available to us will, hopefully, provide the practical information the detector user needs. The purpose of the present paper is to report this information.

EXPERIMENTAL ARRANGEMENT

The temperature of the detector was controlled by varying the power dissipated in two Zener diodes mounted in two thin-walled stainless steel tubes that support the Al plate on which the detector rests. The stainless steel tubes provide the thermal resistance between a liquid nitrogen-filled tube and the Zener diodes.

This thermal resistance could be easily changed by varying the exposed length of stainless steel tube to permit coverage of a wide temperature range, but such changes were unnecessary for the temperature range covered in the experiments reported here. The minimum temperature used here was 90°K. An Al enclosure, whose temperature was essentially identical to that of the detector, completely surrounded the detector in all experiments. This thermal shield was necessary to prevent infrared light emitted from the room temperature walls of the outer Al cap of the cryostat from reaching the detector. If no thermal shield was used, measurements of leakage currents less than 10^{-10}A would be meaningless insofar as this study is concerned since the measured current would arise mainly from infrared generation. Lack of a thermal shield caused the high currents Armantrout measured at low temperatures.[2,3]

The temperature of the detector was monitored by a carefully calibrated thermocouple attached to the Al plate on which the detector rests. Temperature measurements were accurate to about ± 1°.

The leakage current was measured between detector and ground using a Keithly Electrometer Model 601. The voltage drop across this meter was kept below 100 mV to reduce any leakage currents across insulators or connectors to a very low value. Since transients on the bias, radio frequency interference, etc., produce dc components due to the nonlinear V-I characteristics of a detector, the current path was shielded and ground loops were avoided.

RESULTS AND DISCUSSION

Some of the parameters of the detectors studied are listed in Table I. These detectors were selected to represent a wide variety of different types of crystals, including detectors fabricated from the very best crystals to the very worst insofar as charge trapping is concerned. The ^{60}Co gamma-ray resolutions presented in this table were obtained in standard cryostats that maintain the detector temperature at approximately 85°K.

TABLE I. GERMANIUM DETECTOR PARAMETERS

Detector	Type	Diameter (cm)	Thickness (cm)	Depletion Voltage (V)	Maximum Voltage (V)	^{60}Co 1.17 MeV γ-ray FWHM Resolution (keV)	Comments
172-7.0	P skin - N core	3.2	1.0	400	2000	1.7	Very symmetric peaks.
195-3.2	P	3.0	1.0	400	2200	1.6	Very symmetric peaks.
158-4.0	N, but small dislocation-free areas near center that are P	2.7	1.0	250	1500	1.7	Slightly asymmetric peaks.
214-6.0	P skin - small N core	2.8	1.0	100	1500	1.6	Very symmetric peaks.
155-1.0	P	1.0	0.5	250	600	1.6	Guard-ring configuration, groove cut through Li contact.
155-1.8	P	1.0	0.5	250	500	1.6	Guard-ring configuration, groove cut through Li contact.
102-3.0	Li-drifted	2.3	0.9	—	3500	1.7	Very symmetric peaks.
215-5.0	P homogeneous	3.4	0.225	50	400	—	Made especially to evaluate the Li-diffused contact contribution to the leakage current.
133-9.0	P homogeneous	2.5	0.4	400	1000	No observable peak	Crystal grown in N_2, this results in detectors having extreme charge trapping.
217-5.0	P homogeneous	1.8	0.8	400	1200	—	Guard-ring configuration, groove cut through Li contact.

Reverse current vs bias data were obtained for each detector at a series of temperatures. At each temperature, ^{60}Co spectra were recorded, usually at several bias voltages. All current and resolution measurements were made only after the detector had reached thermal equilibrium, and after bias had been applied for a sufficiently long time that the leakage current remained stable. Figure 1 presents the V-I characteristics for detector 214-6.0. The general pattern shown here is typical of every detector studied. Although this detector was depleted when 100 Volts were applied, the leakage current continued to increase with increasing bias at approximately the same rate as prior to depletion when the temperature was slightly elevated (>110°K). This characteristic was observed for every detector indicating that the dominant leakage-current source is not the bulk of the detector. Since the leakage current is closely proportional to $\sqrt{V}$, and prior to depletion the volume is proportional to $\sqrt{V}$, one would be tempted to explain the current increase on the bias of a volume increase if the depletion voltage had not been independently determined. In view of this behavior, the $I \propto \sqrt{V}$ relationship, even below full depletion, is probably due to sources other than bulk current.

If band-to-band transistions were dominant, the generated current would be given by[4]

$$I \cong 10^3 \, T \exp(-E_g/kT) \tag{1}$$

and a slope of about 0.7 eV would be expected when log I against 1/T is plotted.

Figure 2 presents such a plot for detector 214-6.0. The data plotted were obtained with 100 Volt bias. Since the shape of the V-I curves are similar above 100°K the log I vs 1/T slope is essentially independent of the bias chosen. The measured slope of about 0.35 eV is typical of every detector studied, strongly indicating that band-to-band generated current is not dominant. Furthermore, the calculated band-to-band current in this temperature range is many orders of magnitude less than we experimentally obtain.

Below about 120°K the measured leakage current invariably was greater than a straight extension of the log I vs 1/T line from higher temperatures would provide. Since measurement of these very low currents is difficult the divergence can possibly be explained by measurement errors, although additional current generated by the detector may be responsible. Background radiation also causes current amounting to about 5 x 10^{-14}A for detectors of this size.

Leakage current measurements were made on detector 195-3.2 up to 288°K to see if the band-to-band generation current became dominant at the higher temperatures. A plot of log I vs 1/T over this extended temperature range is shown in Figure 3. The data plotted were obtained with 500 V bias. Although the higher temperature points diverge slightly from the straight line drawn through the lower temperature points this divergence can be explained by the effect of the additional T dependence that should be included if a straight line is desired, and by self-heating of the detector. Calculations based on Eq. (1) show that a much higher temperature region must be reached before band-to-band current would be expected to become dominant.

A plot of log I vs 1/T for the lithium-drifted detector 102-3.0 is shown in Fig. 4. The data plotted were obtained with 500 Volt bias. Both the slope and the magnitude of the leakage current are similar to that obtained from high-purity detectors.

Since band-to-band transitions are not the dominant source of leakage current one must resort to either current generation via traps in the bulk or via surface states of the detector. There are other possible current sources, such as injection at the contacts, but these currents should be relatively negligible in properly fabricated detectors. The "pancake" detector, 215-5.0, was fabricated in an attempt to determine if the contacts, especially the lithium-diffused contact, were causing unexpectedly large currents. As can be noted by comparing the current values listed in Table II, detector 215-5.0 exhibits a fairly typical leakage-current characteristic.

After studying the leakage current relationships tabulated in Table II several pertinent comments can be made.

(1) As mentioned previously the log I vs 1/T slopes for all the detectors are very similar, possibly identical within the accuracy of the measurements. As the slope value is nearly $E_g/2$ the effective trap must lie near the center of the band gap. Although the possibility exists, the probability that so many different crystals, grown under widely varying conditions over a period of several years, and including a doped crystal, would all contain the same chemical impurity is small. The odds are likewise against structural defects in all the crystals leading to identical effective

traps. Furthermore, one should remember that this list encompasses both detectors that exhibit no measurable charge trapping when irradiated with 5 MeV gamma-rays and also a detector, 133-9.0, fabricated from a crystal grown in a non-reducing atmosphere, that traps charge so severely that no peaks are observable when irradiated.

(2) The current/volume and current/area ratios are equally constant, and consequently no claim that bulk-generated current is dominant is justified on the basis of the constancy of the current/cm^3.

(3) Two detectors, 155-1.0 and 133-9.0, exhibited significantly lower currents than the others. 155-1.0 was operated in a guard-ring configuration, and consequently it is more difficult to evaluate the surface contribution. 133-9.0 was fabricated from a crystal grown in nitrogen which invariably results in severe charge trapping. Although the high concentration of charge traps would usually be considered as correlated with an increased bulk leakage current via these traps, the measured total leakage current is comparatively very small in this detector, at least in the temperature range from 120° to 170°K.

(4) Although the two small guard-ring detectors, 155-1.0 and 155-1.8, were fabricated from adjacent slices of the same crystal, and were of identical size, the leakage current measured in 155-1.8 was five times larger than in 155-1.0. If bulk leakage current were dominant such a large difference would not be expected. Despite the large difference in current the slope of log I vs 1/T for these two detectors was the same.

TABLE II. GERMANIUM DETECTOR LEAKAGE-CURRENT RELATIONSHIPS

Detector	Volume (cm^3)	Surface Area (cm^2)	T = 143°K Current (A)	Current/Volume (A/cm^3)	Current/Surface Area (A/cm^2)	Slope (eV)
172-7.0	8.0	10.0	1.8×10^{-9}	2.3×10^{-10}	1.8×10^{-10}	0.32
195-3.2	7.0	9.4	1.0×10^{-9}	1.4×10^{-10}	1.0×10^{-10}	0.36
158-4.0	5.7	8.2	1.0×10^{-9}	1.8×10^{-10}	1.2×10^{-10}	0.36
214-6.0	6.1	8.8	1.0×10^{-9}	1.6×10^{-10}	1.1×10^{-10}	0.35
155-1.0	0.4	guard ring	8.0×10^{-12}	0.2×10^{-10}	—	0.32
155-1.8	0.4	guard ring	4.0×10^{-11}	1.0×10^{-10}	—	0.31
102-3.0	3.8	6.5	1.0×10^{-9}	2.6×10^{-10}	1.5×10^{-10}	0.33
215-5.0	2.0	2.4	2.0×10^{-10}	1.0×10^{-10}	0.8×10^{-10}	0.31
133-9.0	2.0	3.1	2.2×10^{-11}	1.1×10^{-10}	0.7×10^{-10}	0.34
217-5.0	2.0	guard ring	4.0×10^{-10}	2.0×10^{-10}	—	0.34

These comments all lean toward the position that the dominant current generation in all the detectors studied at elevated temperatures is via surface states. Although no definitive conclusion on this point can be reached at present, practical information concerning the use of germanium detectors at elevated temperatures is clear. Figure 5 shows the ^{60}Co 1.17 MeV gamma-ray resolution obtained with five of the detectors studied as a function of temperature. The pulser resolution measured when detector 172-7.0 was used is also included. Each of these detectors was approximately the same size, and the temperature-resolution relationship for each is remarkably similar. This is not surprising when one recognizes that the leakage current is the dominant factor in degrading the resolution at the higher temperatures, and that all the detectors had nearly identical current-temperature characteristics. When the leakage current exceeds about 4×10^{-9}A significant resolution degradation occurs.

For these detectors no resolution degradation is observed until 130°K has been reached, but above 150°K the degradation is extremely rapid. The break in the curve is so sharp that general conclusions are valid even though different detectors may show a measurably different curve. For example, detector 214-6.0 clearly could be operated several degrees warmer than any of the other detectors shown here, but the data points for this detector still fit well on Fig. 5.

Note that there is no significant difference between the temperature-resolution relationship of the lithium-drifted detector, 102-3.0, and the high-purity detectors. The apparent discrepancy between these measurements and the conclusions of Armantrout[2] can be explained by the fact Armantrout compared relatively large lithium-drifted detectors with a very small high-purity detector. From the I-V and temperature-resolution curves of Nakano and Imhof[1] one observes that significant resolution degradation also occurred when the leakage current exceeded about 4×10^{-9}A for their 30 cm^3 lithium-drifted detector. Furthermore, our analysis of their data indicates that the log I vs 1/T slope of their detector was also approximately 0.35 eV.

To draw general conclusions from measurements performed with very small detectors can often lead one astray, and such is the case with temperature-resolution measurements. Figure 6 shows the ^{60}Co 1.17 MeV gamma-ray resolution of a 0.2 cm^3 high-purity germanium detector as a function of temperature. Although no significant resolution degradation occurred until nearly 180°K had been reached, one is not justified in implying that high-purity germanium detectors can be used at this high a temperature. The data presented in Fig. 6 were obtained with an amplifier peaking time of 2.25 μsec, as were all our measurements. If a shorter time constant were used to minimize the effects of the leakage-current noise even higher temperatures could be reached before the resolution becomes poor. However, this tactic can only be employed if the detector is thin since the charge mobility decreases rapidly as the temperature is raised. Consequently, the fluctuation in the detector signal rise time due to long collection times may cause resolution degradation at higher temperatures if the time constant is shortened. Although this effect depends on the type of shaping network used, only a small increase in the maximum operating temperature would be expected from the optimum shaping network.

CONCLUSIONS

Detectors fabricated from a wide variety of crystals exhibited remarkably similar performance at elevated temperatures. Unless extremely small detectors can be tolerated, one is limited to about 150°K operation. Since band-to-band bulk generation is not the dominant current source some hope remains that the operating temperature can be increased. A better understanding of the dominant source of leakage current might enable one to find ways to reduce it, thus increasing the temperature limit.

When properly fabricated from good germanium crystals no significant difference between the temperature-resolution relationship of similar-sized lithium-drifted detectors and high-purity detectors exists.

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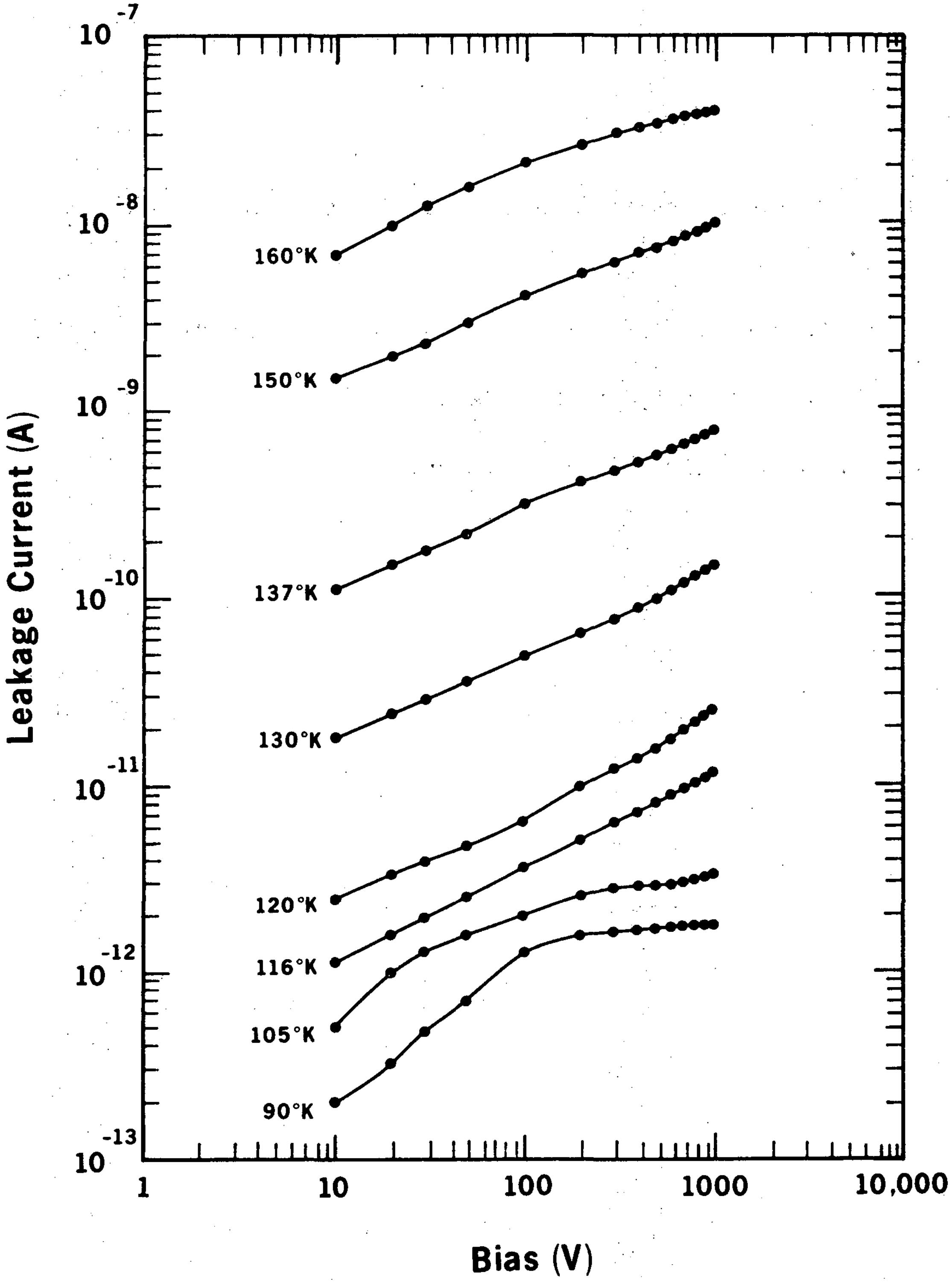
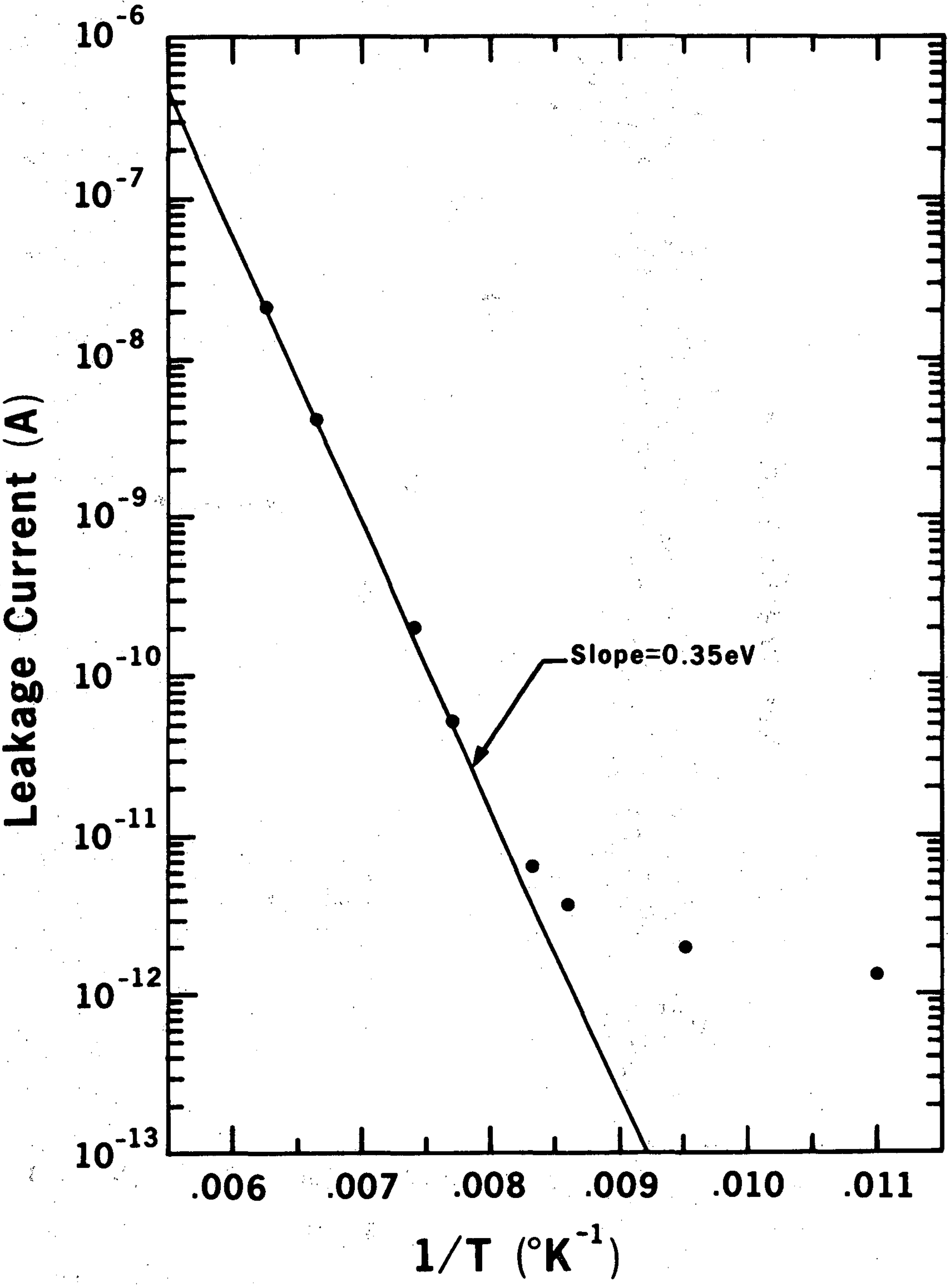
4. T. C. McGill, private communication.



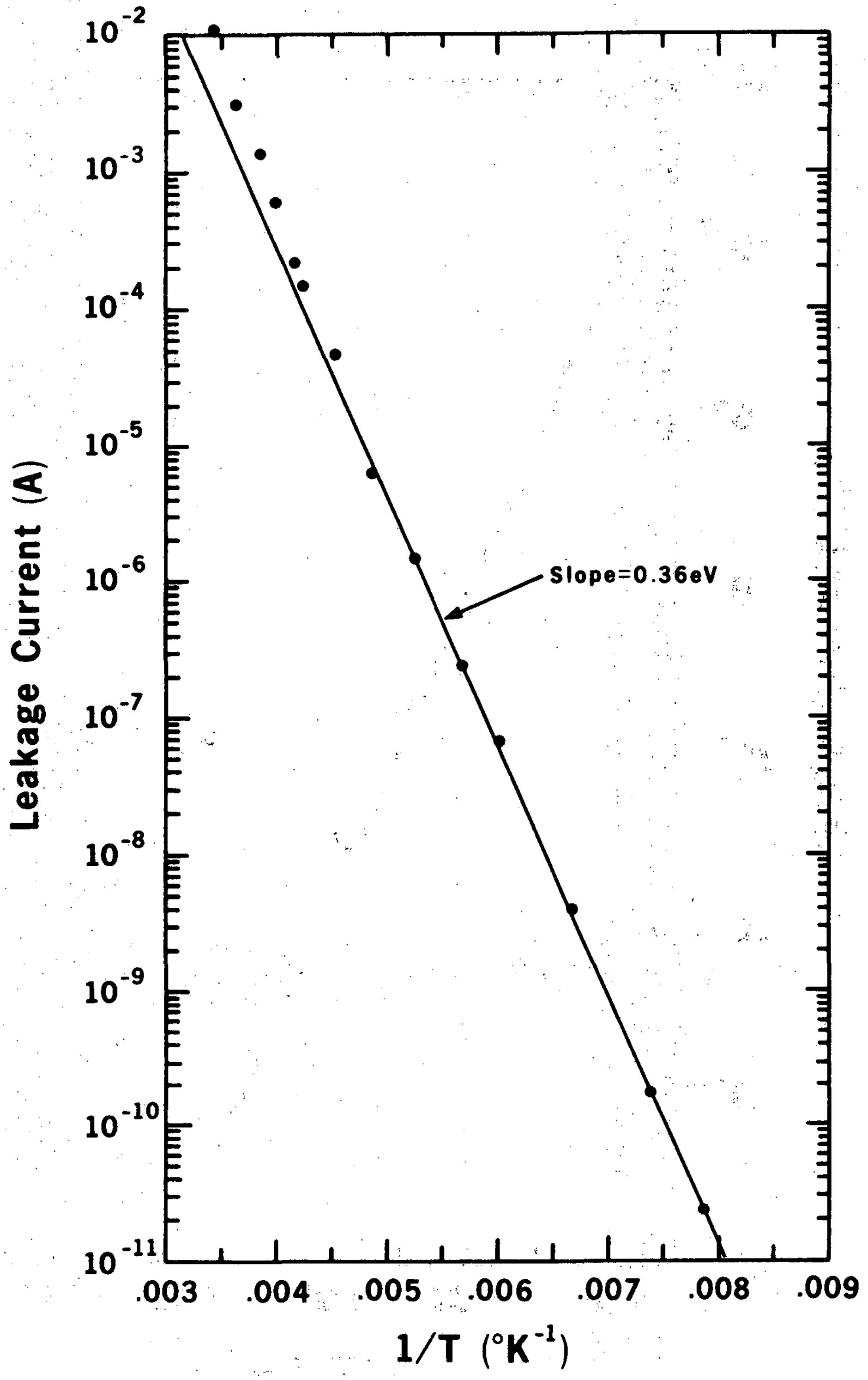
XBL 7211-7465

Fig. 1. Voltage-current characteristics as a function of temperature for detector 214-6.0.



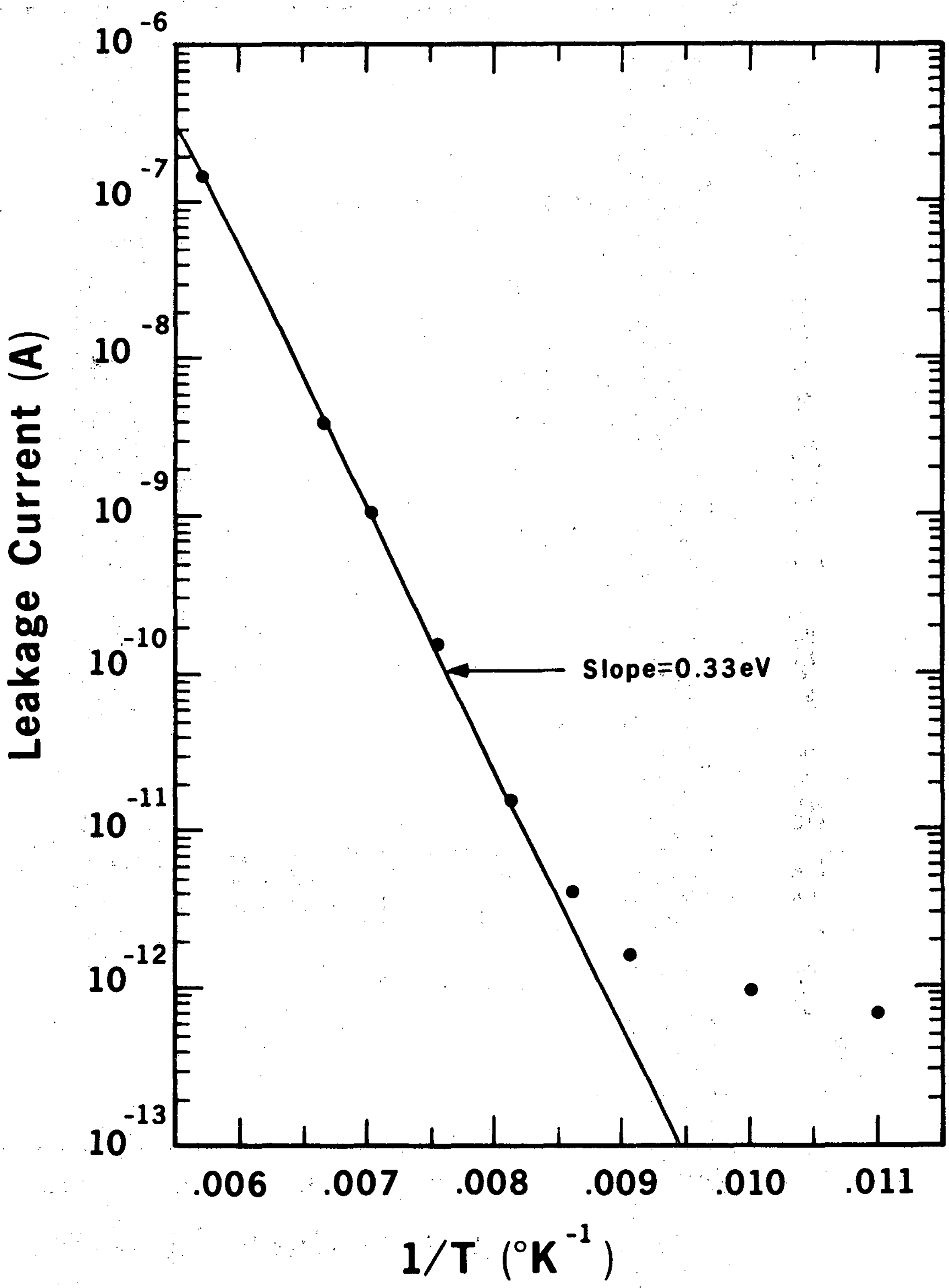
XBL 7211-7462

Fig. 2. Leakage current as a function of 1/T for detector 214-6.0. The data plotted were obtained with 100 Volt bias, but since the shape of the V-I curves are similar above 110°K the slope is essentially independent of the bias chosen.



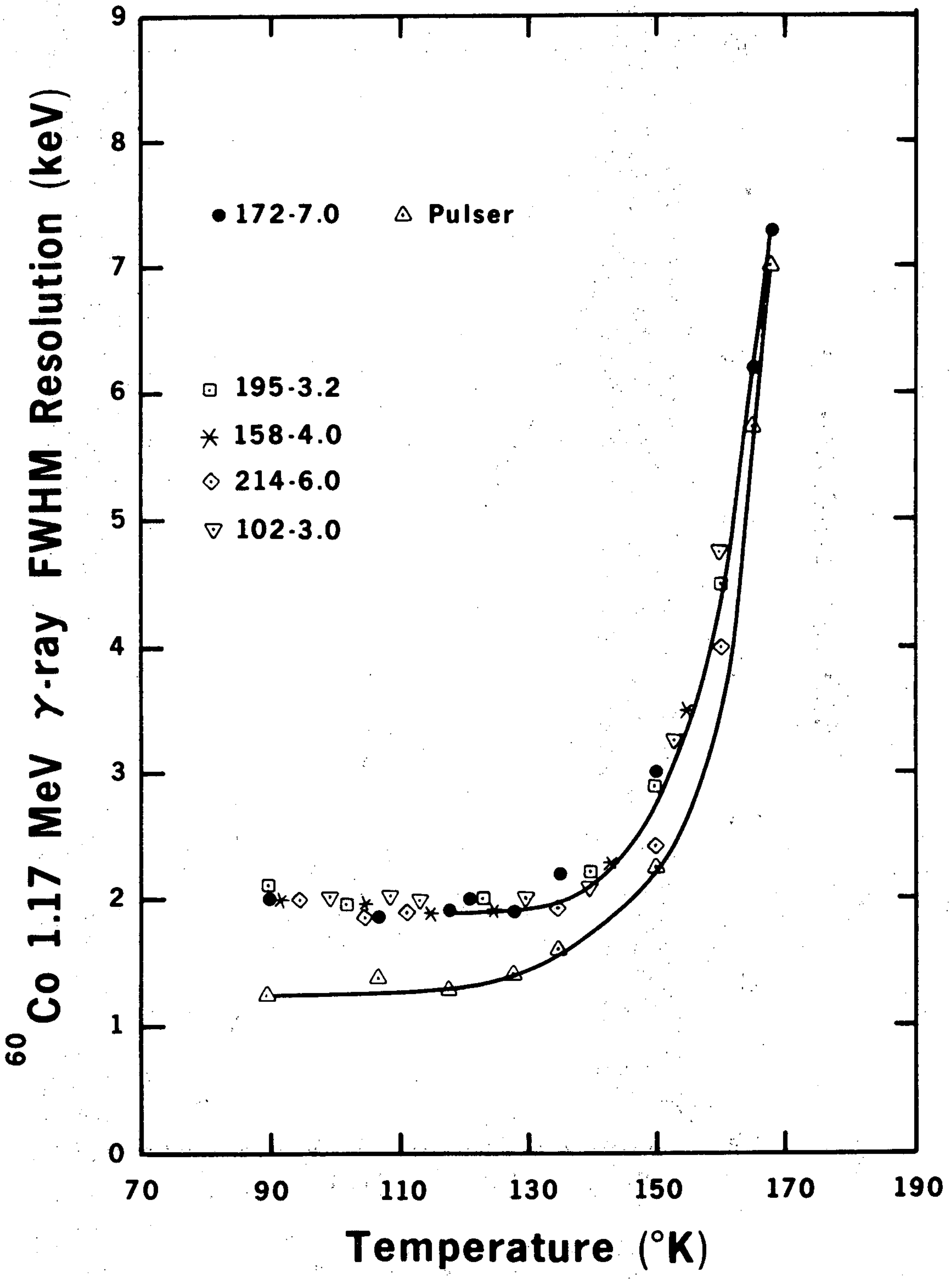
XBL 7211-7464

Fig. 3. Leakage current as a function of 1/T for detector 195-3.2. The data plotted were obtained with 500 Volt bias.



XBL 7211-7461

Fig. 4. Leakage current as a function of 1/T for lithium-drifted detector 102-3.0. The data plotted were obtained with 500 V bias.



XBL 7211-7460

Fig. 5. Resolution of the ^{60}Co 1.17 MeV gamma-ray obtained with five of the detectors as a function of temperature. The pulser resolution when detector 172-7.0 was used is also shown.

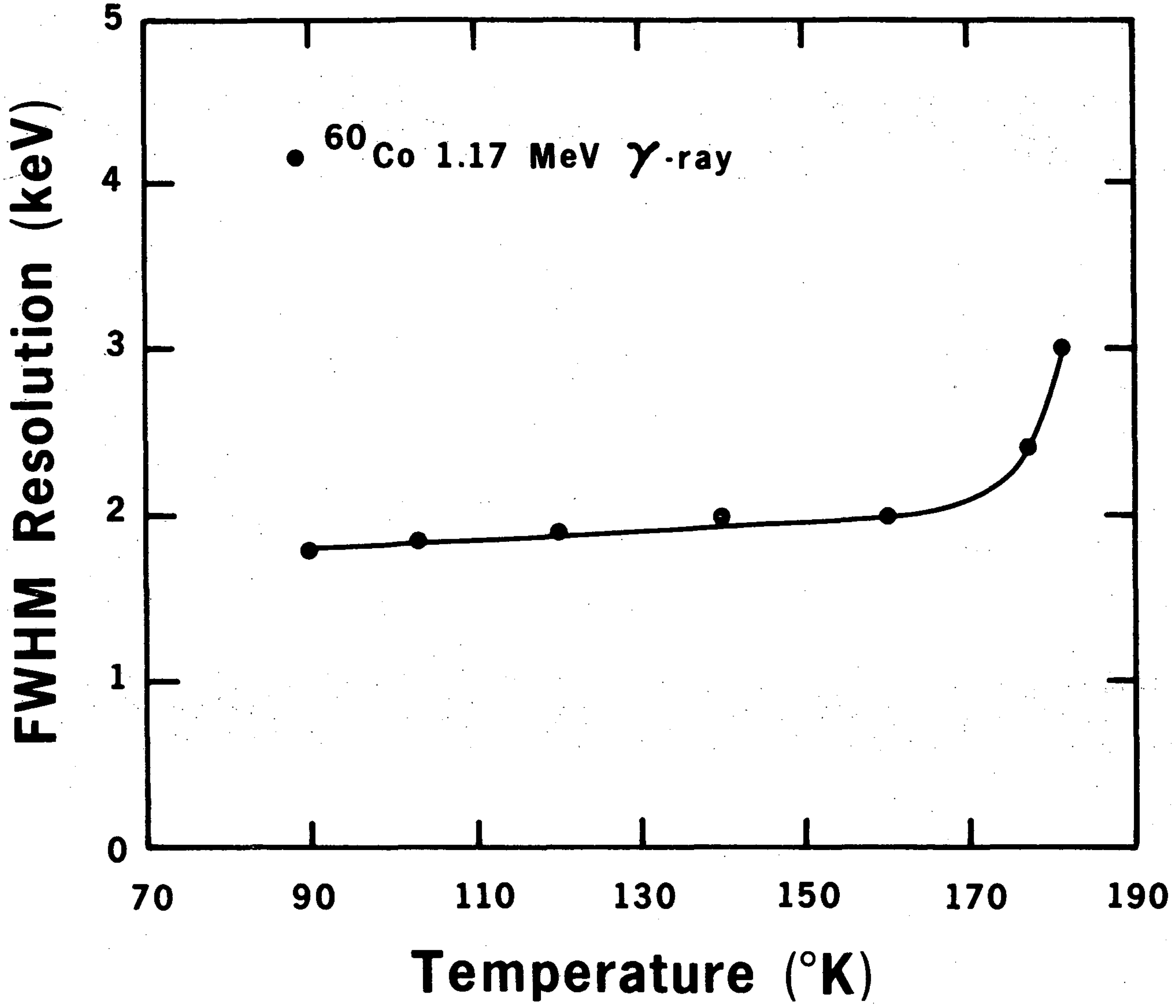


Fig. 6. Resolution of the ^{60}Co 1.17 MeV gamma-ray obtained with a very small, 0.2 cm^3, detector as a function of temperature.

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