CAM PIPS Detector Features and Characteristics

Figure 1 shows an exploded view of a CAM PIPS detector.

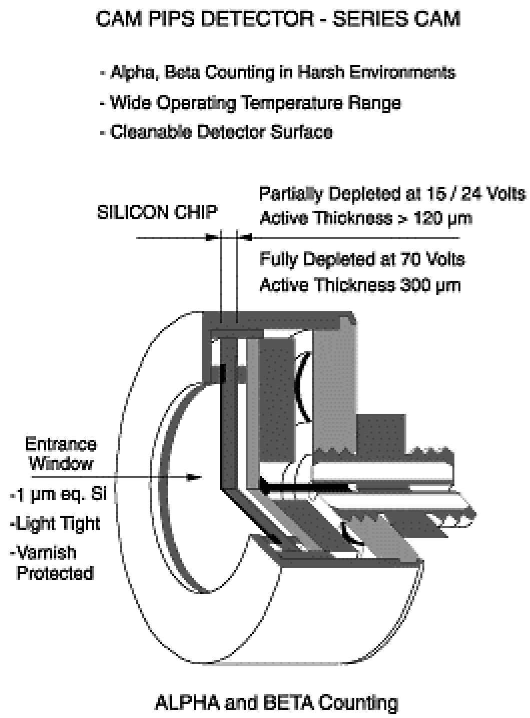

Figure 1
Exploded view of a CAM PIPS detector.

- Operable in light - to 5000 lumens
- Corrosion resistant - varnish coated
- Moisture resistant - passivated
- Low bias voltage
- Beta and alpha discriminated by energy
- Wide temperature range - low leakage current
- High beta sensitivity - 300 mm active thickness

General Characteristics of PIPS Detectors

Salient advantages of PIPS technology include the following:

- Buried ion-implanted junctions
- SiO_2 passivation
- Low leakage current
- Low noise
- Ruggedness (cleanable surface)
- Operational up to 50 °C
- Storage temperature up to 100 °C

The operating principle of a PIPS detector is as follows:

A particle stopped in the depletion region forms electron-hole pairs. The energy necessary to form a single electron-hole pair depends on the detector material, but is essentially independent of the energy of the incoming particle. The number of electron-hole pairs ultimately formed is thus directly proportional to the energy of the particle. The electric field in this region sweeps the electrons to one terminal and the holes to the other. The resultant charge pulse is integrated in a charge sensitive preamplifier to yield a voltage pulse.

The thickness of the depletion region depends on the applied bias voltage, so that higher voltages give a thicker region, capable of stopping more energetic particles. The capacitance of the detector is given by:

where:

A = surface area (cm^2)

W = thickness (cm)

A represents the surface of the junction. It is typically 20% higher than the active area of the detector. W represents the thickness of the detector and is given by:

where:

r = resistivity (Ohm□cm)

V = bias (volts)

Note that the maximum thickness is given by the dimensions of the Si wafer.

It is thus possible to operate partially depleted, fully depleted, or fully depleted with overvoltage as illustrated in Figure 2.

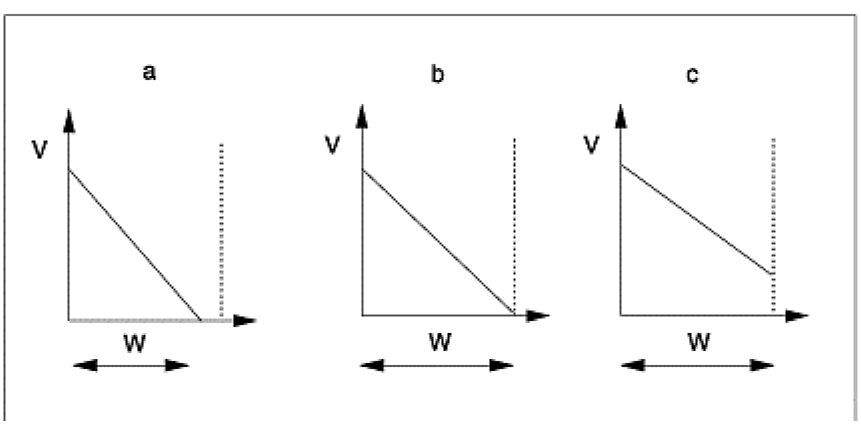

Figure 2
Thickness W of the depletion layer as a function of the applied bias

a: partially depleted

b: fully depleted

c: fully depleted with overvoltage

Figure 3 shows (for a CAM 450 detector) the variation of the capacitance as a function of the applied bias while Figure 4 gives the same information for a CAM1700 detector.

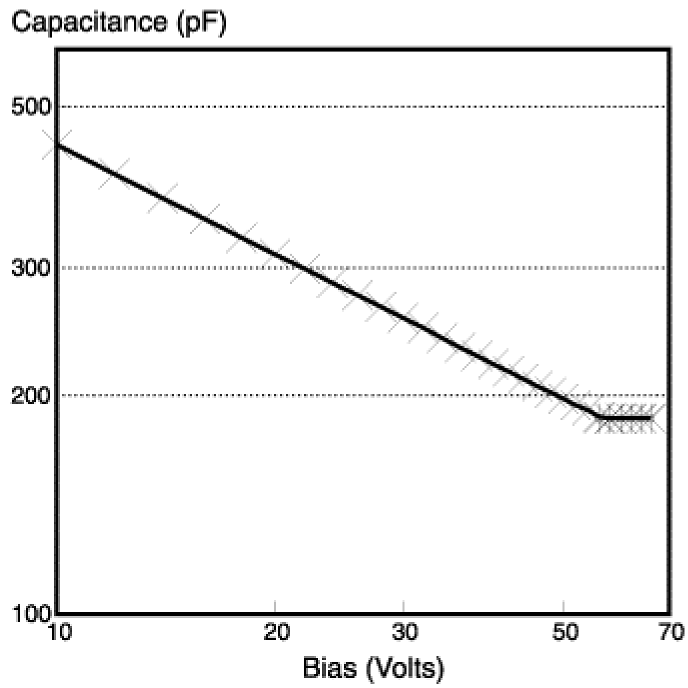

Figure 3

Capacitance of a typical CAM450 detector as a function of the applied bias. (Typical)

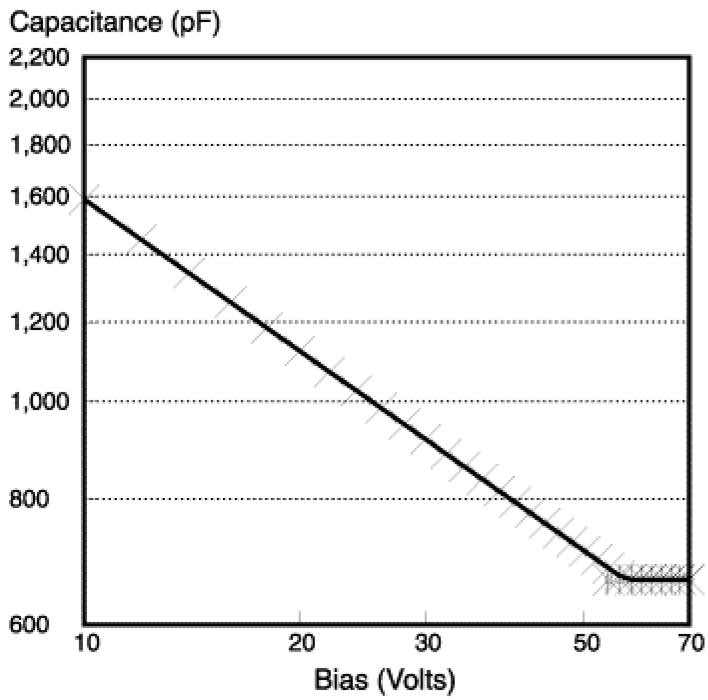

Figure 4

Capacitance of a typical CAM1700 detector as a function of the applied bias. (Typical)

The noise level at the preamplifier output is given by :

$N = N_o + D\,N_s \times C$

where:

N_o (eV) = Electronic noise with no capacitance or input

DN_s(eV/pF) = Incremental noise vs. capacitance

C (pF) = Detector capacitance

The detector capacitance is reduced at higher voltages, so that the lowest noise and best resolution are obtained at higher voltages within the recommended range.

Special Characteristics of CAM PIPS Detectors

Specially designed for continuous air monitoring, CAM PIPS detectors are light tight and resistant to harmful environments thanks to special aluminum and varnish coatings.

Light Tightness and Resistance to Harmful Environments

Silicon detectors are fundamentally light sensitive. For alpha and beta spectroscopy and counting, this fact can be generally ignored, as both the source and the detector are placed within the same (light tight) vacuum chamber. However in continuous air monitoring, the detector is not protected by a vacuum chamber and light may reach the detector in some cases. CAM PIPS detectors are made with a front surface coating of 0.5 µm thick aluminum, which blocks the light. Furthermore, due to the nature of continuous air monitoring, detectors are very often used in a harmful environment, such as a humid and/or dusty atmosphere charged with corrosive gases. In order to extend their usable life, CAM PIPS detectors are covered with a 1 µm varnish coating, providing mechanical and chemical resistance against abrasion, solvents and corrosion. This varnish corresponds to a supplementary absorption layer of about 0.6 µm silicon equivalent. The entrance window of a CAM detector is much thicker than that of an alpha or beta PIPS detector which causes roughly doubling of the alpha resolution in vacuum with respect to that of an alpha PIPS of similar size. However, one has to take into account the energy straggling and absorption of alpha particles in the air gap between filter and detector, as well as in the filter/source itself, which makes straggling in the entrance window of the detector relatively unimportant.

Figure 5 shows the range of alpha particles in air. Some loss in counting efficiency will occur in CAM measurements due to full absorption in the air gap, not to mention the source and window effects in degrading the alpha spectrum.

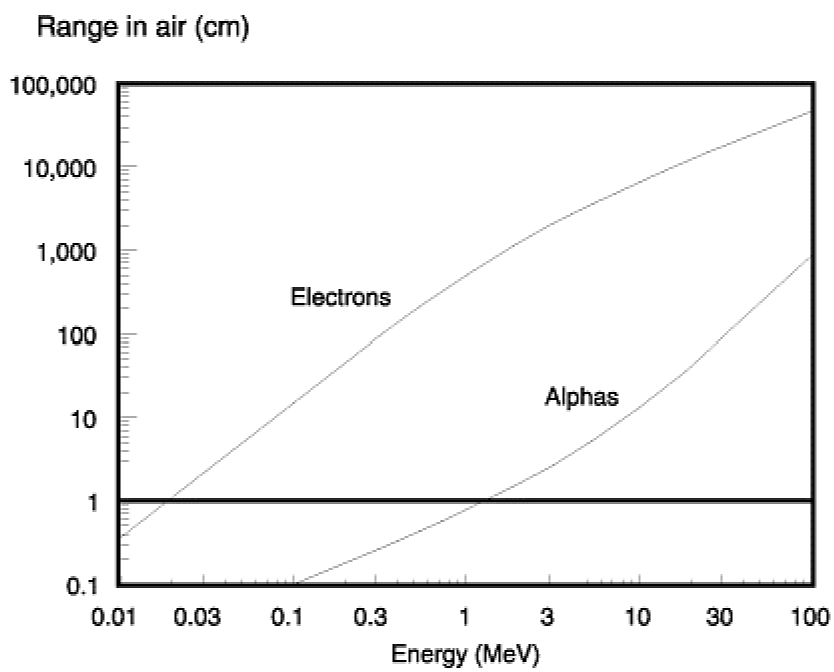

Figure 5
Range of electrons and alpha particles in air.

Figure 6 shows the resolution (FWHM) of CAM450 and CAM1700 detectors for the 5499.2 keV line of ^{238}Pu as a function of the source-detector distance.

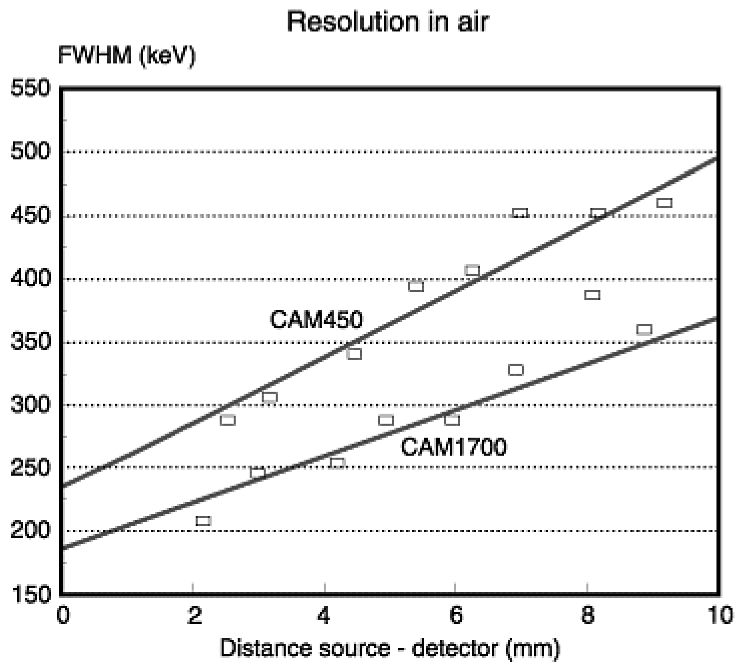

Figure 6

Variation of the resolution (FWHM) as function of the detection source distance in air.

Efficiency for Alpha Particles

From the preceding it should be clear that the efficiency for alpha particles is approximated by w/4p where w represents the solid angle under which the active area of the detector sees the source. Efficiencies for a 1700 and 450 mm^2 detector are shown in Figure 7 as a function of the source-detector distance. Source diameters are 42 mm and 24 mm respectively. Curves for other source diameter and detector diameter combinations can be calculated too.

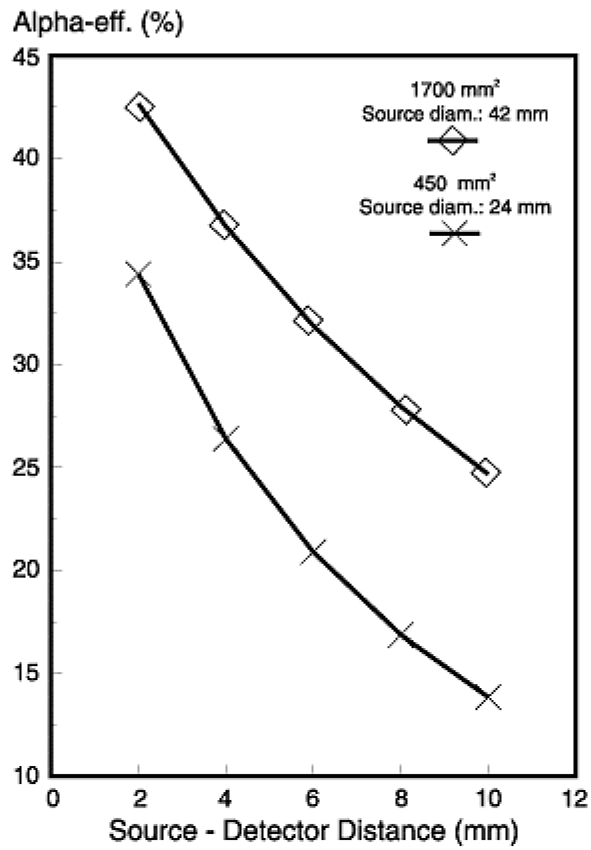

Figure 7

Geometrical efficiency for alpha counting as a function of the source-detector distance for various detectors and for various source diameters.

Figure 8 shows the geometrical efficiency of CAM detectors as a function of the source diameter for a source-detector distance of 5 mm. One sees immediately that the efficiency of the bigger detector is much greater, whatever source diameter is chosen. (The source diameter, however, should not exceed the diameter of the detector).

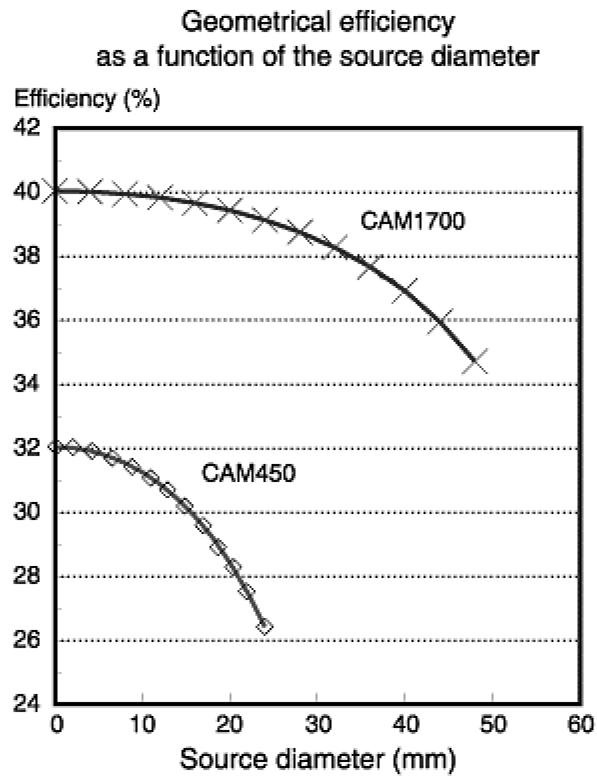

Figure 8

Geometrical efficiency of CAM detectors as a function of the source diameter with source detector distance of 5 mm.

The total number of counts is proportional to the geometrical efficiency and to the total activity deposited on the filter. The latter depends on the pumping speed which in turn is limited by the pressure drop through the filter. The pressure drop itself increases linearly with the pumping speed and decreases with the square of the filter diameter. A large detector thus allows the use of a larger filter and consequent higher air flow for the same pressure drop, so that larger total activities can be deposited on the filter in less time.

The Efficiency for Beta Counting

Estimating the efficiency of a CAM PIPS detector for betas is more complex. Additional factors have to be taken into account besides the geometrical efficiency as in the case of alpha counting.

Solid Angle

This is similar to the case of alpha counting. Note however that the detector mount of 0.5 mm of stainless steel and 0.5 mm of contact material is (partially) transparent for betas above a certain energy (1 MeV). The total efficiency is thus increased by an amount corresponding to the difference between the junction area and the active area (Table 1) corrected for the absorption in the mount. It can be shown, however, that using the nominal solid angle leads to small errors in comparison to backscatter and noise for most betas.

Backscatter

Backscattering of low energy electrons from the detector surface may cause significant loss of efficiency. Figure 9 shows the fraction of normally incident electrons backscattered from bulk silicon. On the other hand, if backscattering occurs in the source, it may increase the apparent number of beta particles. In order to minimize source backscatter effects, source backing material should be of low Z.

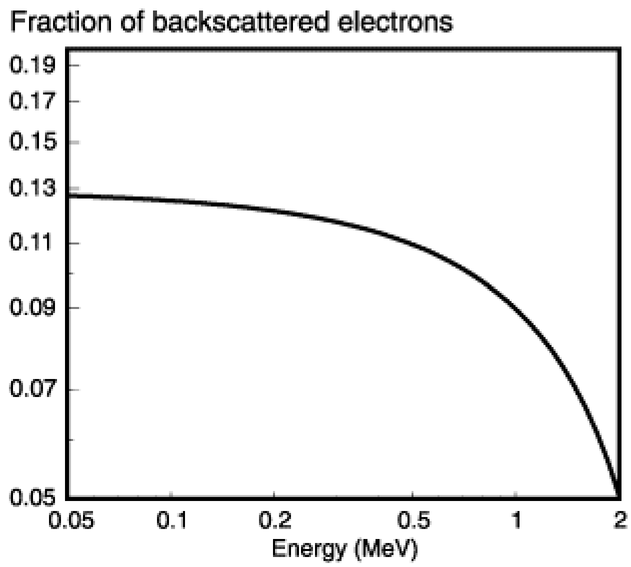

Figure 9

Fraction of normally incident electrons backscattered from bulk silicon.

Resolution/Noise

Beta particles are electrons emitted by a radioactive nucleus during the decay process. They share their energy with the almost massless neutrino, which leaves no trace in the detector. Beta particles have thus a continuous energy distribution ranging from zero energy to an end point energy which is given by the mass difference between the two neutral atoms involved in the nuclear decay. Typical beta spectra may be found in Reference 1.

Beta resolution (Table 1), approximated by the pulser width (FWHM) of the detection system, is limited by electronic noise. In order to eliminate this noise, a threshold of about three times the beta resolution has to be imposed. This means that some of the betas, whose distribution goes down to zero energy, will lie below the threshold. Thus, in spite of the fact that resolution is largely ignored in beta counting, low noise is of great importance for high counting efficiency.

TABLE 1 Main Characteristics of CAM PIPS Detectors

MODEL	CAM450	CAM600	CAM900	CAM1200	CAM1700
Active Area (mm2)	450	600	900	1200	1700

Junction Area (mm2)*	531	697	1046	1400	1900
Active Diameter (mm)	23.9	27.6	33.9	39.1	46.5
Thickness (min/max)	120/325 □m	120/325 □m	120/325 □m	120/325□m	120/325 □m
Bias (min/max)	+10/90 V	+10/90 V	+10/90 V	+10/90 V	+10/90 V
Bias (typical)	+24/70 V	+24/70 V	+24/70 V	+24/70 V	+24/70 V
Si-Resistivity (min)	3000	3000	3000	3000	3000
	Ohm□cm	Ohm□cm	Ohm□cm	Ohm□cm	Ohm□cm
Operation Temp. (min/max)	-30/+50 □C	-30/+50 □C	-30/+50 □C	-30/+50 □C	-30/+50 □C
Storage Temp. (max)	+100 □C	+100 □C	+100 □C	+100 □C	+100 □C
Alpha Resolution at 15-24V	38	42	45	55	70□
(FWHM - in keV)	□	□	□	□	□
Alpha Resolution at 70 V	34	37	39	45	55
□(FWHM - in keV)	□	□	□	□	□
Alpha Background (counts/day)		8	13	17	23
Beta Resolution at 70 V	17	20	22	25	30
(FWHM)	□	□	□	□	□
Beta Threshold at 70 V	51	60	66	75	90

* To be considered in the calculation of Beta and Gamma efficiencies.

Note: Alpha resolution is given for 241Am 5486 MeV Alphas in vacuum, using standard Canberra electronics
and 0.5 □s shaping time constant.

The total efficiency E is thus given by:

$E=NF_{th}$

Where N is the geometric efficiency and F_{th} is the fraction of counts above the threshold (discriminator energy level). The factor F_{th} may be estimated for a particular case. (See Reference 1 - Section 6). For the detection of low energy Betas, preference should be given to a small, low noise detector.

As an illustration, in Figure 10 the efficiency $E = NFth$ is shown as a function of the source-detector distance for the detection of ^{90}Sr with a 450 and 1700 mm^2 detector and a threshold of 100 keV.

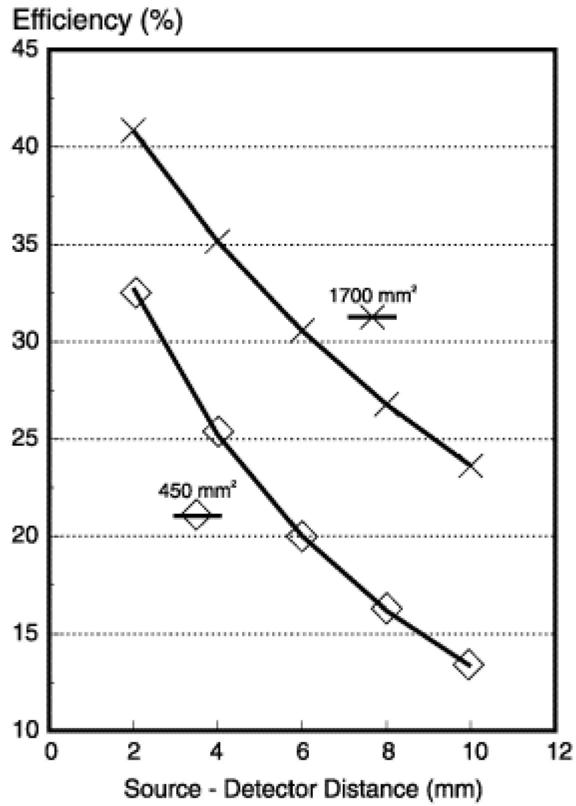

Figure 10

Efficiency E = NF_{th} as a function of source detector distance for the detection of ^{90}Sr with a 450 and a 1700 mm^2 detector and a threshold of 100 keV.

Source diameter: 24 mm for 450; 42 mm for 1700.

Channeling

Betas can "channel" between the crystal planes of the detector and lose energy at a lesser rate than if they cross planes. To minimize this effect, CAM PIPS detectors are made from silicon wafers that are cut off-axis. Some betas may randomly travel along the crystal planes however, leading to small errors in calculated efficiency.

To avoid errors in calibration due to these various effects, it is best to use calibration standards. This is true for both alphas and betas although alpha efficiency can be predicted or calculated with greater precision than that of betas. Also there is little if any energy dependence in alpha efficiency whereas beta efficiency is energy dependent and therefore isotope specific.

The Efficiency for Alpha and Beta Counting

When alpha and beta particles are counted together, it is important that alpha and beta events be completely separated. This condition is largely met when measuring in vacuum as seen in Figure 11. It shows the beta spectrum of ^{137}Cs [conversion electrons of 629 keV and two beta groups of respectively 1.176 MeV (6%) and 0.514 MeV (94%)] in the presence of an alpha source containing ^{239}Pu, ^{241}Am and ^{244}Cm showing alpha peaks at 5.155, 5.486 and 5.804 MeV. The spectrum was taken in vacuum with a CAM1700 detector. Figure 12 shows the same spectrum taken in air with a source-detector distance of 4.3 mm. No significant overlapping of alpha and beta events is observed.

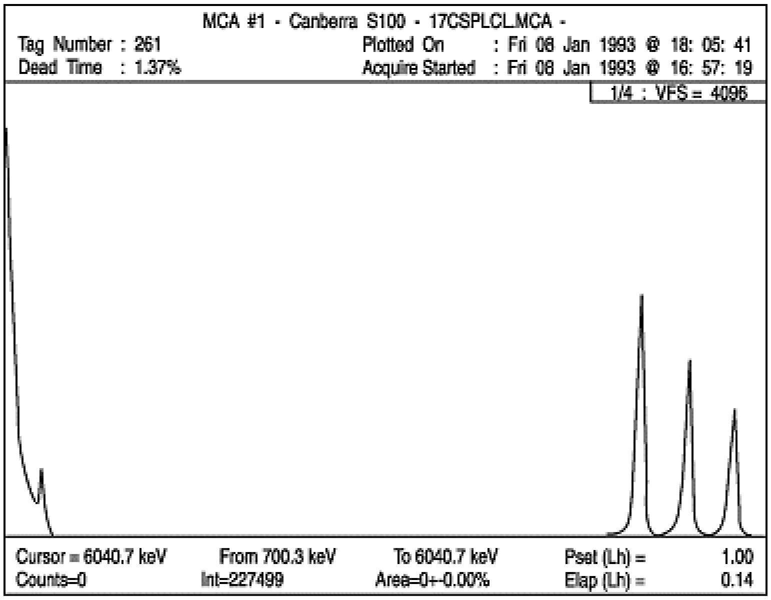

Figure 11

Beta spectrum of 137Cs in the presence of a mixed Alpha source of 239Pu, 241Am and 244Cm, taken in vacuum with a CAM1700 detector.

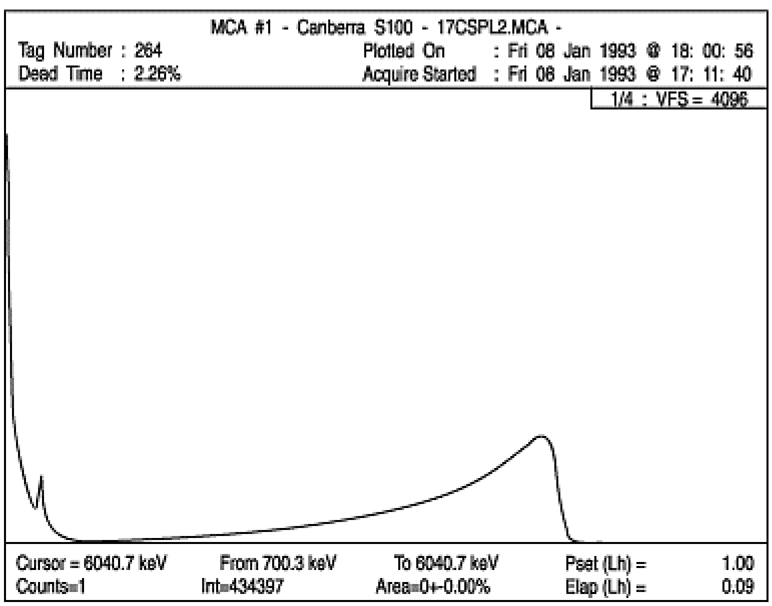

Figure 12

Beta spectrum of 137Cs in the pressure of a mixed Alpha source of 239Pu, 241Am and 244Cm, taken in air with a CAM1700 detector. The source-detector distance was 4.3 mm.

Beta Counting in the Presence of Gamma Background

If high bias voltage is applied to the detector, full depletion (Figures 2, 3 and 4) will be achieved leading to an active thickness of 300 □m. This is enough to fully absorb electrons of up to 290 keV as seen in Figure 13. As long as the detector absorbs enough energy from the beta to exceed the noise level, the beta is counted. Note, however, that at this thickness (0.07 g/cm^2 of Si) a certain gamma efficiency exists. Indeed the half-thickness of Si for the absorption of 100 keV gamma rays is 4 g/cm^2 and for 50 keV Gamma rays it is 2 g/cm^2 so that 1.2% and 2.4%, respectively, deposit energy in the detector. As long as beta particles and gamma rays are in coincidence, this will result in distortion of the spectrum but it will not change the counting efficiency. This will be generally the case if the gamma rays are emitted by the source as they are due to the de-excitation of (short lived) nuclear levels populated by beta decay. However, if betas and gammas are not coincident, pulses due to gamma rays will be registered separately contributing to a higher apparent count rate from the beta source.

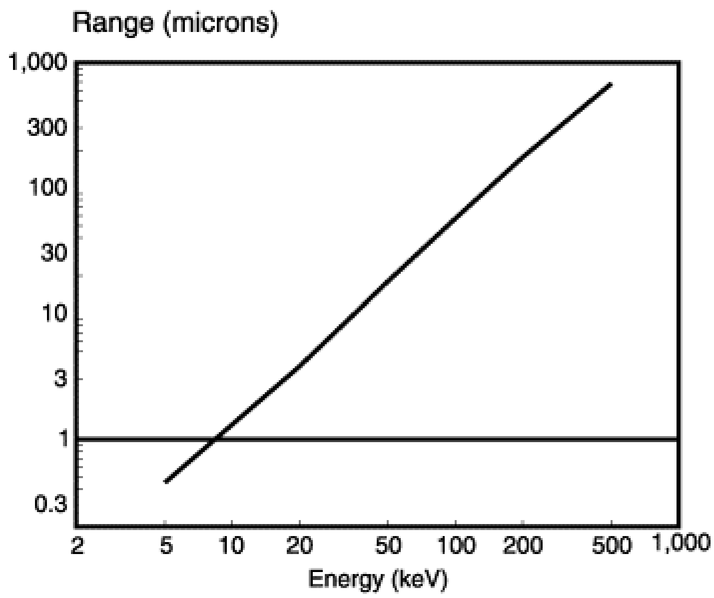

Figure 13
Range of Electrons in Silicon.

Note that conversion electrons are never in coincidence with the gamma rays. Furthermore they are seldom coincident with the betas as they are generally emitted by long lived isomeric levels. Thus source-specific effects have to be taken into account if exact Beta activities are to be determined.

Finally it has to be noted that gamma rays coming from an external source can only be in random coincidence with the betas. External background including cosmic radiation must be reduced by shielding or by guard detectors to achieve extremely low beta background. Indeed, the earth is continuously bombarded by high energy (50 MeV) ionizing particles (p, a, mesons...) of cosmic origin. In silicon these particles have a specific energy loss of about 1 keV/□m, so that, depending on the thickness of the detectors, 120 to 325 keV is deposited in the detector. Typical vertical fluxes at sea level are 10^{-2} particles/cm^2-steradian-sec distributed according to the cosq^2 law, q being the polar angle. For a horizontal CAM450 detector this leads to about 2400 background counts registered in eight hours or 1.3 cts/min-cm^2. One experiment registered 5400 cts or 2.1 cts/min-cm^2. As expected from the cosine^2 law, this number came down to 3780 (or 1.45 cts/min-cm^2) when the detector was oriented vertically.

This cosmic background can be reduced by installing a guard detector (e.g. a second CAM PIPS) working in anticoincidence mode with the primary detector, as cosmic particles have enough energy to leave a trace in both detectors.

The Minimum Detectable Activity

Following the development of L.A. Currie (Reference 2), the minimum detectable activity (MDA) is given by:

$$\text{MDA} = \frac{2.71 + 4.65 \times \sigma_B}{\varepsilon \times 0.5 \times \Delta t \times 3600}$$

where Dt is the pumping and measuring time expressed in hours, s_B the standard deviation of the background and e the fractional counting efficiency. The factor 0.5 in the denominator takes into account the fact that the activity measured over a certain time Dt corresponds to the mean activity accumulated on the filter measured over time Dt/2.

Besides the measuring time Dt, the most important parameter is the standard deviation of the background. Because the background is quite different in the alpha and beta regions, the MDA must be examined separately for alpha and beta emitters.

MDA for Alpha Emitters

The background is strongly influenced by the activity of the ^{222}Rn progeny accumulated on the filter, which can be much higher than the alpha activity of concern. Whether the air in the laboratory is filtered or not, radon levels of 4 to 40 Bq/m^3 can be regarded as quite normal, while DAC-values of 0.08 Bq/m^3 have to be detected for soluble ^{239}Pu. Furthermore, the concentration of the Rn progeny in air is not constant over time. The standard deviation s_B is thus not only given by the square-root of the number of counts during the time interval Dt, but must also take into account the concentration fluctuations. Indeed, all alpha lines due to ^{222}Rn lie above the alpha energies of ^{239}Pu, so that (due to tailing effects) these peaks contribute to the ^{239}Pu-peaks. Energy discrimination is thus needed in order to characterize the background beneath the Pu peaks. Furthermore, separation of pulses due to alpha and beta particles should be possible. Both these conditions are largely met by CAM PIPS detectors as seen in Figures 11 and 12, showing that this discrimination is possible, despite the tailing inherent in the CAM measurement.

Assuming a counting efficiency of 40%, a pumping speed of 1 m^3/hr and a constant background of 40 Bq/m^3, the required MDA of 0.08 Bq/m^3 can be obtained over eight hours. Up to four times better results can be obtained using background subtraction based on stripping methods; i.e. by subtracting the independently determined contribution of higher energy background peaks.

MDA for Beta Emitters

While ^{222}Rn progeny constitutes most of the background in the high energy (Alpha) region of the spectrum, the background in the beta region (2.1 cts/min-cm^2) is due largely to cosmic radiation. A simple calculation shows that in an eight hour run, MDA is of the order of 0.08 Bq/m^3 if a 450 mm^2 detector is used with high geometric efficiency. (See "Beta Counting in the Presence of Gamma Background" on page 6.) This background and the corresponding MDA can be drastically reduced by using inert and/or active shielding.

Detector Stability

Both temperature stability and long-term stability are important in detectors used for alpha and beta Spectroscopy because count times are often many hours or days and gain shifts during data accumulation lead to erroneous results.

Detector Leakage Current vs. Temperature

The leakage current of silicon diodes doubles for every 5.5 to 7.5 □C increase in ambient temperature. Since the preamp H.V. bias resistor is a noise contributor, it is necessarily of high value, typically 100 MW. With a detector having leakage current of 0.5 □A, the change in bias voltage at the detector for a 2 □C change in ambient temperature can be as much as 13 V. This is enough bias change to affect overall gain of the detector-preamplifier by a substantial amount.

The PIPS detector has a typical leakage current of about ^{1}/10 that of SSB or Diffused Junction detectors. Consequently voltage drop across the bias resistor in the preamplifier is much less, so that up to temperatures of 35 □C no significant peak shifts are observed. Figure 14 shows the experimental variation of the leakage current as a function of the temperature for several CAM450 and CAM1700 detectors. It shows maximum and minimum values for the two types of detectors.

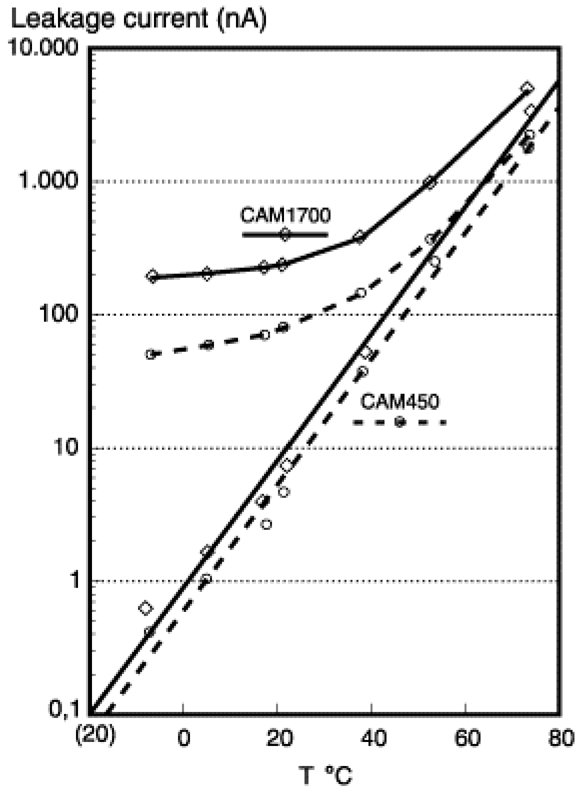

Figure 14
Minimum and maximum leakage current as a function of temperature for a CAM450 and a CAM1700.

Long Term Stability

The long-term stability is affected by the impact of the environment on detector junctions. The CAM PIPS detectors are specially designed to overcome the influence of harsh environments. This is demonstrated by long term stability tests. Figure 15 shows such a test carried out over a period of one year.

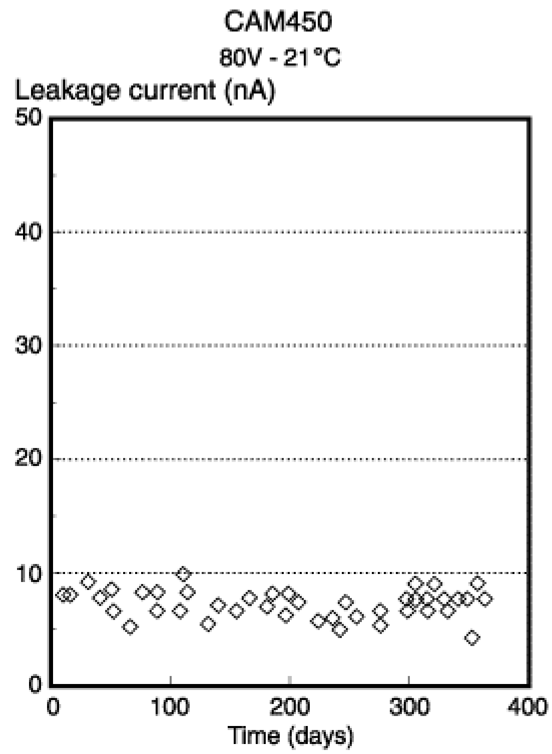

Figure 15
Leakage current of a CAM450 detector carried out over a period of one year.

Operation in Humid Environments

Obviously a CAM detector is subject to big variations in ambient humidity. The CAM PIPS detector is designed to operate in high humidity. Our QA procedures involve long term testing of sample detectors in a chamber containing standing water to simulate high humidity environments. CAM PIPS detectors tolerate this condition with little or no change in leakage current or noise.

References

1. Mantel, J. (1972). *Int. Appl. Rad. and Isot.* 23:407.
2. Currie, L.A. (1968). *Analytical Chemistry*. 40:587.