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Abstract

A novel low-noise preamplifier for use with semiconductor radiation detectors is described. The preamplifier utilizes the low-noise characteristics of a liquid-helium-cooled germanium junction field-effect transistor (JFET). The new germanium device is compared with the currently used silicon JFET's.

Pulse generator resolution of the preamplifier for zero external capacitance is 0.28 keV FWHM (Ge) with a slope of 0.018 keV/pF. Typical resolution obtained with silicon and germanium detectors for low-energy x rays is less than 0.4 keV.

Introduction

The development of semiconductor detectors triggered a continuous search for ever lower-noise preamplifiers to take full advantage of the excellent resolution of these detectors. During the last 3 years considerable progress has been made. In early 1965 the standard preamplifier was the vacuum tube preamplifier. The resolution of the best units was in the vicinity of 2 keV, and to keep it at that level the tubes had to be carefully selected, and be replaced nearly every 6 months.

In 1965 the technological progress in fabrication of junction field-effect transitors, JFET's (for which principles had been laid out by Shockley[1] in 1952), focused the attention of the designers on this device. The attractiveness of FET's for low-noise amplifiers stems from their being majority carrier active devices. As their main source of noise is thermal, optimal performance is obtained below the ambient temperature. Several preamplifiers based on cooled FET's were built, the most recent ones utilizing well-optimized n-channel silicon devices having high values of g_m/C_g.[2-4] These preamplifiers had signal-to-noise ratios between 0.35 and 0.4 keV FWHM (Ge) with a slope of 0.035 to 0.040 keV/pF.

This paper describes a liquid-helium-cooled germanium FET preamplifier, which has signal-to-noise ratio of 0.28 keV FWHM (Ge) with a slope of 0.018 keV/pF. Silicon and germanium JFET's and preamplifiers are briefly compared.

Germanium versus Silicon JFET's

Junction field-effect transistors operate through modulation of a current path by a depletion region of a reverse-biased p-n junction. Their principles of operation and characteristics are described in most books on semiconductor devices.[5]

An important parameter of a JFET is its transconductance, g_m. Maximum transconductance occurs at zero gate voltage, and

$$g_m(\max) = g_0, \quad (1)$$

where g_0 is the conductance of the metallurgical channel. For an n-channel FET,

$$g_m = S \cdot q \cdot \mu_e \cdot n, \quad (2)$$

where S is a geometrical factor, q is the charge of an electron, μ_e is the electron mobility, and n is the density of free electrons.

The particular temperature dependence of the mobility causes the transconductance to peak at the edge of the deionization region.[6] In germanium, which has lower ionization energies, the transconductance peaks at much lower temperature than in silicon. Thus, because of the higher mobility in germanium, the maximum transconductance of Ge FET's is higher, and is attained at lower temperature. This feature of germanium FET's ensures their lower noise, as the noise voltage is proportional[7] to

$$V_{noise} \propto \left(\frac{T}{g_m}\right)^{1/2}. \quad (3)$$

The temperature behavior of transconductance of typical silicon and germaium FET's is displayed in Figs. 1 and 2. The n-channel silicon FET's used in low-noise amplifiers include 2N3823, 2N4416, and 2N5105. The g_m of these devices at room temperature is between 3.5 and 5 millimhos, increasing to 7 to 9 millimhos at the optimum temperature, which ranges from 100 to 140°K. Below the optimum temperature the g_m decreases sharply (Fig. 1). The input capacitance of the FET's mentioned is approximately 5 pF.

At present there is only one type of germanium JFET manufactured commercially. This is the p-channel TIXM301 and its plastic-encapsulated version TIXM12. The input capacitance of the TIXM12 is 15 pF. Its transconductance at cryogenic temperatures is given in Fig. 2. (Maximum transconductance of the TIXM12 is 18 millimhos, attained at 10 to 20°K.)

We see that the optimum g_m of the germanium FET's is twice that of the silicon devices, and it is obtained at much lower temperatures.

FET Preamplifiers

Two commonly used preamplifier configurations are the charge-sensitive and the voltage-sensitive circuits. The gain of the charge-sensitive configuration does not depend on detectors' capacitance, and therefore this configuration is preferred for large-volume detectors. The voltage-sensitive circuit has a higher signal-to-noise ratio, and therefore it is used with low-capacitance detectors in high-resolution systems.

Silicon FET Preamplifiers

Typical input stage of a low-noise preamplifier using silicon JFET is shown in Fig. 3. This is a charge-sensitive circuit, but if we remove the 1-pF capacitor we get a voltage-sensitive stage. Also, variations of this basic stage are used.[8] The detector is insulated from ground to reduce parasitic noise sources.[4,9] The FET is operated at 120°K.

Pulse-generator resolution of the preamplifier, when the described input stage is used, for zero external capacitance is 0.4 keV FWHM (Ge) with a slope of 0.038 keV. To obtain the resolution quoted the FET's have to be selected at the operating temperature. The yield of low-noise units is about 30%.[4] Sensitivity to capacitance is reduced by paralleling FET's;[3] this method is usually employed in systems with high-capacitance detectors.

Germanium FET Preamplifier

To demonstrate the low-noise properties of the germanium JFET's, the following preamplifier was built. The input stage of the preamplifier is shown in Fig. 4. It consists of two TIXM301 (or TIXM12) units in cascode.

Voltage-sensitive configuration is used, also dc coupling between the detector and the input stage. The FET's are operated at liquid helium temperature with zero gate-to-source bias and V_{ds} = -2.5 V. The FET's are actually in the liquid, and the electrical connections to the rest of the stage, which is in a vacuum chamber, are made through low-capacitance feedthroughs.[10] The power dissipated in the channel (25 to 35 mW) brings the temperature of the FET's into the optimum region. The low V_{ds} voltage prevents a large component of avalanche-type noise, but also causes relatively large junction capacitances. The high gate-to-drain capacitance (≈ 5 pF) of the FET's forces us to use the cascode connection. Except for the input stage, the rest of the preamplifier is a conventional type of amplifier using bipolar transistors, which has been described elsewhere.[4]

Pulse generator resolution of the preamplifier for zero external capacitance is 0.28 keV FWHM (Ge) with a slope of 0.018 keV/pF. This result is obtained with low-current FET's (≈ 5 mA at 300°K) previously untested for low-noise operation. The very low sensitivity to external capacitance is a result of the relatively high input capacitance of the FET's, which, on the other hand, prevents the achievement of higher signal-to-noise ratios.

Experimental Results

The germanium FET preamplifier described was used with lithium-drifted silicon and germanium detectors. Low-capacitance (2 pF) LRL-Berkeley-type detectors were used. The pulse-shaping time constants of the main amplifier were 5 μsec integration and differentiation.

The silicon detector was operated at 110°K with a bias voltage of 1 kV. Low-energy spectra, namely ^{55}Mn and ^{241}Am, were used to check the resolution of the spectrometer. The pulse-height-analyzer spectra are shown in Figs. 5 and 6. The K_α and K_β lines of ^{55}Mn (Fig. 5), only 0.6 keV apart, are resolved and measured with 0.37 keV resolution. The spectrum of ^{241}Am (Fig. 6) shows the fine structure of this source with some of the very weak lines (L_{η}, L_{β_6}, and L_{γ_4}) resolved from the background noise. For comparison, a spectrum of ^{241}Am taken with the same detector, but with a silicon FET preamplifier, is shown in Fig. 7.

The germanium detector was operated at 77°K with a bias voltage of 600 V. The resolution obtained is generally not so good as with the silicon detector. The ^{55}Mn x rays are measured with 0.45 keV FWHM and the Am L_{α} line with 0.51 keV FWHM. Improved resolution is obtained with the detector operated at 25°K and with bias voltage of 1000 V.[10] The resolution for ^{55}Mn x rays is 0.405 keV, and for ^{241}Am, 0.42 keV. For the 122-keV ^{57}Co γ rays the resolution is 0.75 keV; it is limited mainly by statistical fluctuations.

Conclusions

A low-noise preamplifier, utilizing liquid-helium-cooled germanium JFET's, for use with semiconductor radiation detectors is described. This preamplifier has a higher signal-to-noise ratio than any silicon FET preamplifier described in the literature. Its sensitivity to capacitance is about half that of silicon FET amplifiers. These results were obtained in spite of the low breakdown voltage and high input capacitance of the only available type of FET's. Therefore further improvements of resolution are expected with the technological progress in fabrication of germanium FET's; n-channel devices may offer additional advantages.

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Footnote and References

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Figure Legends

Fig. 1. Transconductance of a silicon JFET (2N3823) at cryogenic temperatures.

Fig. 2. Transconductance of a germanium JFET (TIXM12) at cryogenic temperatures (1, low-current device; 2, medium-current; 3, high-current).

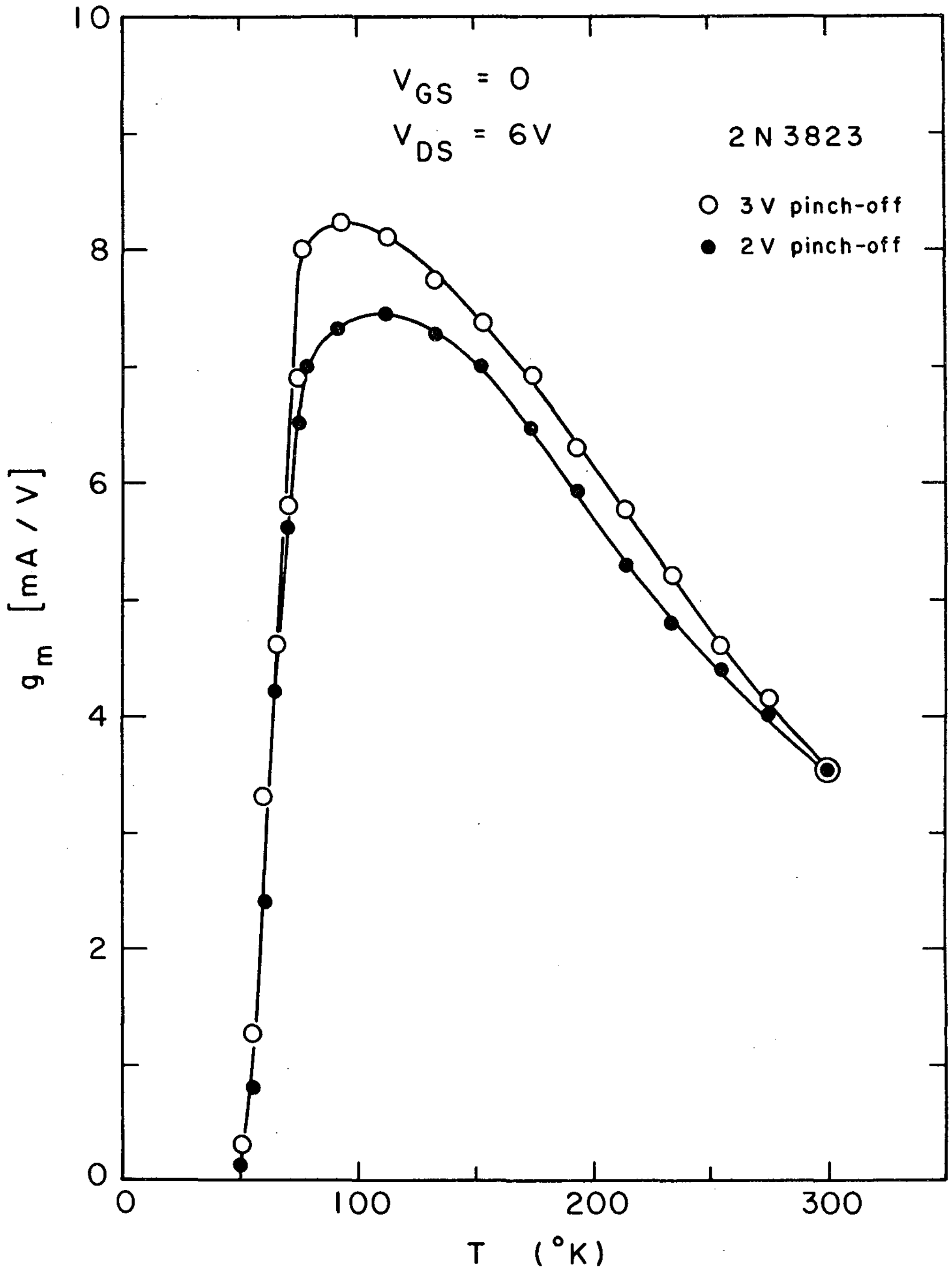
Fig. 3. Typical input stage using a silicon FET.

Fig. 4. The input stage of a germanium FET preamplifier.

Fig. 5. Spectrum of ^{55}Mn x rays. Energy in keV.

Fig. 6. Spectrum of ^{241}Am x rays. Energy in keV.

Fig. 7. Spectrum of ^{241}Am x rays taken with a silicon FET preamplifier.



XBL679-5285

Fig. 1

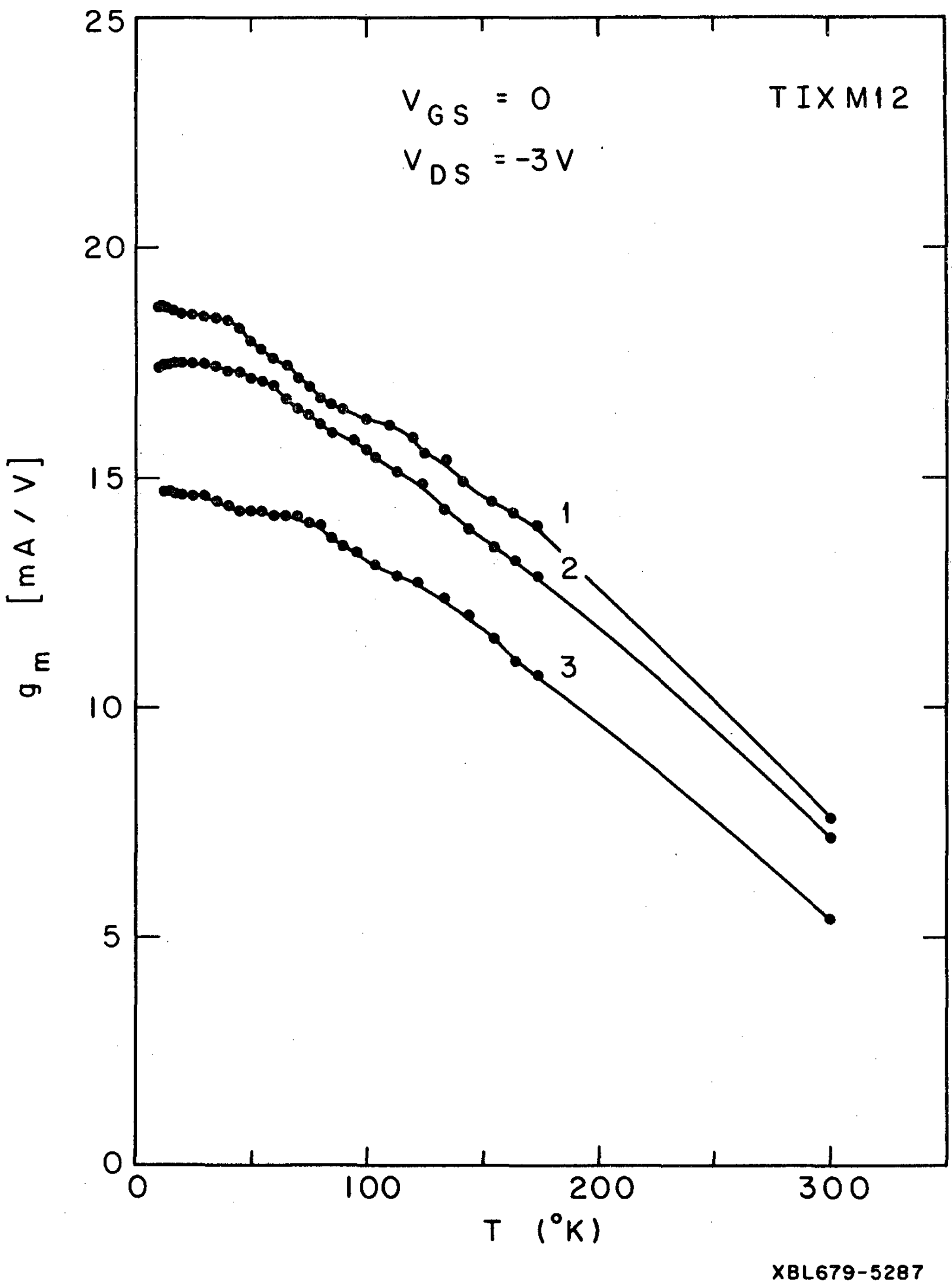
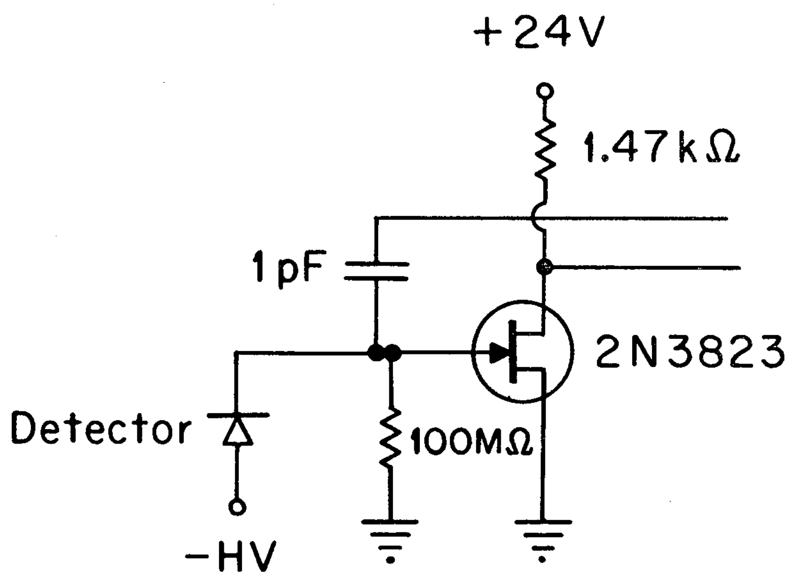

25
20
15
10
5
0
0
100
200
300
T (°K)
g m [mA / V]
V GS = 0
V DS = -3 V
TIXM12
1
2
3
XBL679-5287

Fig. 2



MUB-13078

Fig. 3

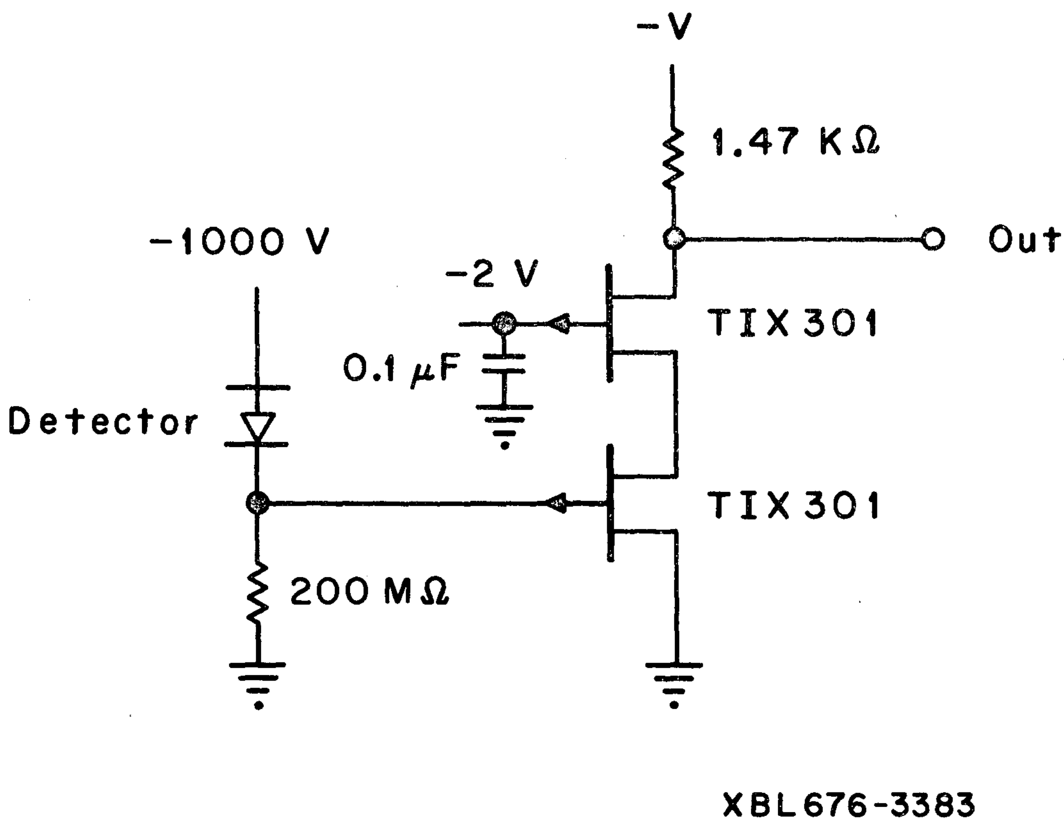

-V
1.47 KΩ
Out
-1000 V
-2 V
TIX 301
0.1 μF
Detector
TIX 301
200 MΩ
XBL676-3383

Fig. 4

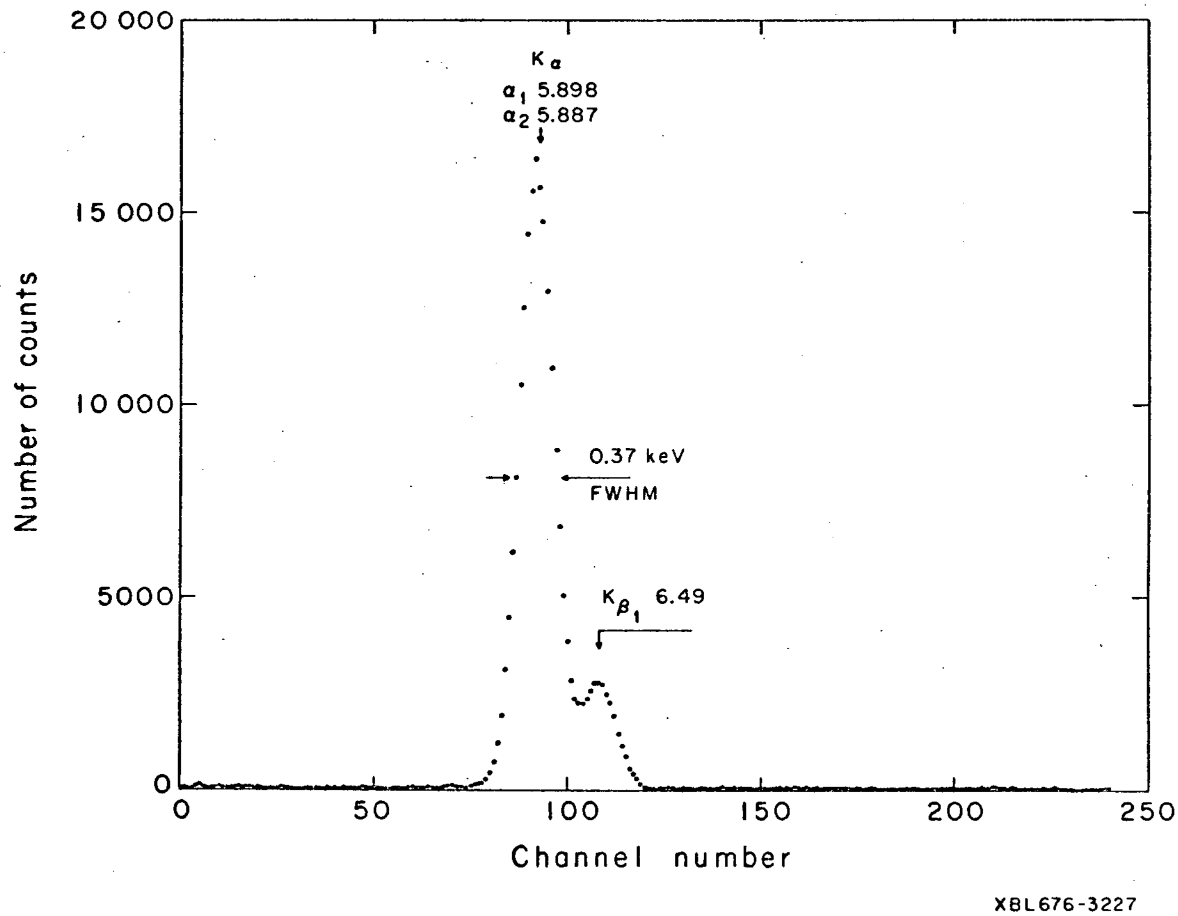

20 000
15 000
10 000
5000
0
Number of counts
K α
α1 5.898
α2 5.887
0.37 keV
FWHM
K β1 6.49
0
50
100
150
200
250
Channel number
XBL676-3227

Fig. 5

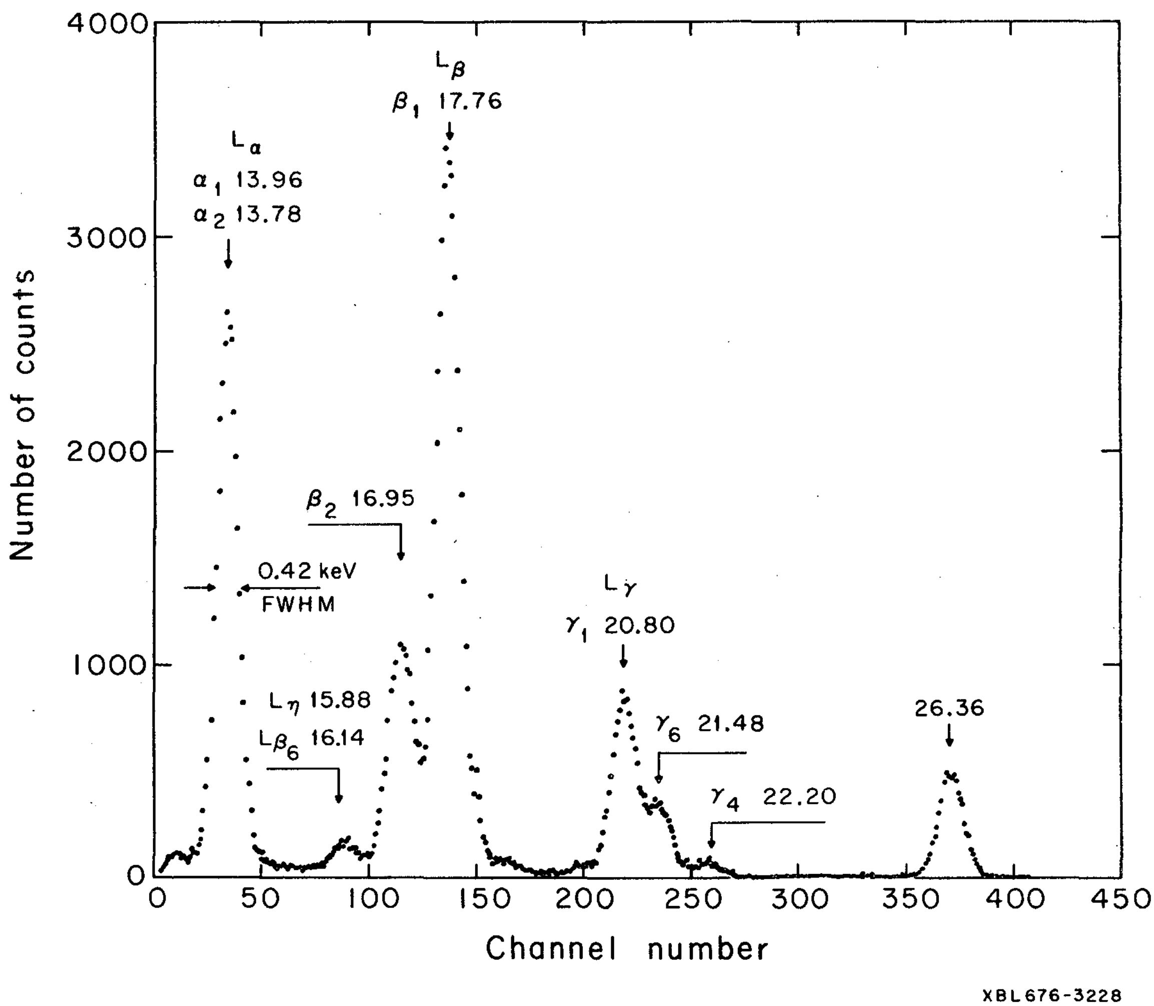

4000
3000
2000
1000
0
Number of counts
L α
α 1 13.96
α 2 13.78
L β
β 1 17.76
β 2 16.95
0.42 keV
FWHM
L η 15.88
L β 6 16.14
L γ
γ 1 20.80
γ 6 21.48
γ 4 22.20
26.36
0 50 100 150 200 250 300 350 400 450
Channel number
XBL676-3228

Fig. 6

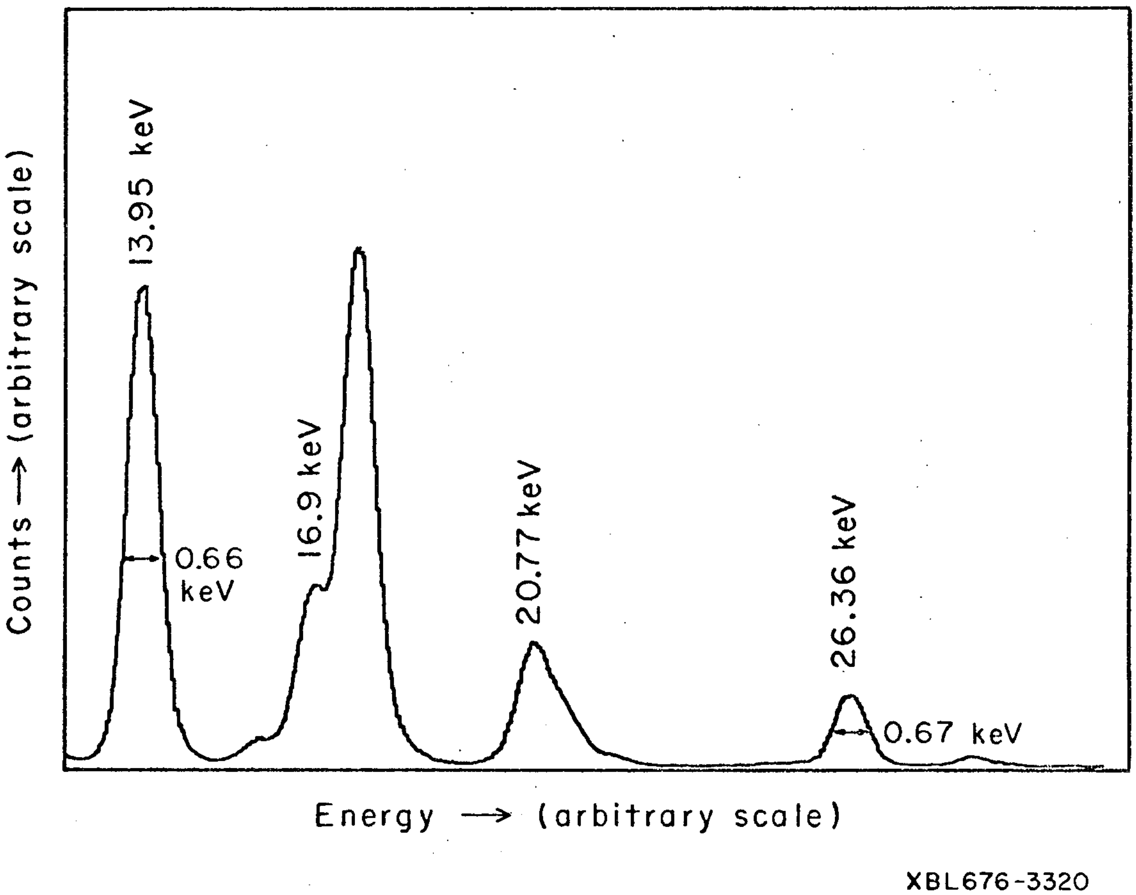

Counts ⟶ (arbitrary scale)
13.95 keV
0.66 keV
16.9 keV
20.77 keV
26.36 keV
0.67 keV
Energy ⟶ (arbitrary scale)
XBL676-3320

Fig. 7