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A STUDY OF LOW NOISE PREAMPLIFIER SYSTEMS FOR USE WITH ROOM TEMPERATURE MERCURIC IODIDE (HgI_2) X-RAY DETECTORS

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Abstract

An analysis of different preamplification systems for use with room temperature mercuric iodide x-ray detectors has been performed. Resistor-, drain-, and light-feedback preamplifiers have been studied. Energy resolution of 295 eV (FWHM) for Fe-55 source (5.9 keV) and 225 eV (FWHM) for the pulser have been obtained with both the detector and the input FET at room temperature using the pulsed-light feedback preamplifier. It has been shown that cooling the input FET using a small Peltier element allows the energy resolution to be improved up to 25%.

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INTRODUCTION

The significance of the development of mercuric iodide (HgI_2) x-ray spectrometers is that for the first time it has become possible to eliminate cryogenic cooling and at the same time achieve a high degree of x-ray energy resolution.[1-3] By eliminating the bulky dewar and cryostat required for the coolant material, it is possible to achieve an extreme degree of miniaturization of the entire x-ray spectrometer.

When we started the design, construction and testing of an optimum performance room temperature system we found the main limitation of the energy resolution is not the HgI_2 detector itself, but rather the noise associated with the electronics. The best commercially available preamplifiers at the time (e.g. the Tennelec Model 161D) had noise linewidths of more than 500 eV, referred to HgI_2. For large cooled Ge(Li) gamma-ray detectors or room temperature si charged-particle detectors, preamplifiers having noise linewidths on the order of 350 eV for Ge (500 eV referred to HgI_2) were sufficient. With the development of CdTe (and later HgI_2) room temperature detectors, however, it was necessary to lower electronic noise.[4] We decided therefore to first develop an all room temperature system with the lowest possible overall noise for use with HgI_2 detectors.

Ultra low noise electronic preamplification systems designed for cryogenically cooled Ge or Si x-ray detectors also used the coolant to lower the temperature of the FET to its optimum operating point. In order to design the room temperature system, it was necessary to consider the major sources of noise and to optimize the system, first by choosing an appropriate preamplifier design and second by selecting and placing components so that the system capability was preserved. The next steps were to consider the possibilities of cooling the input FET with a Peltier element and then to select the optimum temperature for the HgI_2 detector.

ROOM TEMPERATURE HgI_2 X-RAY SYSTEM

The most important single parameter determining the energy resolution of a solid state spectrometer, apart from the detecor itself, is the noise performance of the first stage of signal amplification.[5] It has been found that the electronic noise related to the preamplifier input circuit is due to four main sources: 1) "white" noise in series, 2) "white" noise in parallel, 3) so-called "1/f" noise, and 4) generation-recombination noise caused by traps present in the gate depletion region of the field-effect transistor. The noise linewidth is therefore given by:[6]

$$\Delta E_n = 2.35\,\frac{\bar{\varepsilon}}{q}\left\{\left(qI_L + \frac{2kT}{R_p}\right)\left[N_s^2\right] + 2kTR_s'C_{in}^2\left[N_p^2\right] + A_f\left[N_{1/f}^2\right] + BC_{in}^2\left[N_{gr}^2\right]\right\}^{1/2} \quad (1)$$

Where

ΔEn =	is the FWHM (full-width-at-half maximum) due to the electronic noise, eV
$\bar{\varepsilon}$	is the mean energy required to create one electron-hole pair in the detector, eV
q	is the electron charge, 1.6×10^{-19} coulombs
I_L	is the sum of the absolute values of the shunt leakage current in the input circuit
k	is Boltzmann's constant, 8.63×10^{-5} eV/°K
T	is absolute temperature, °K
R_p	is the parallel input circuit resistance, ohms
$[N_s]$, $[N_p]$	are the step and delta coefficients which are functions of the pulse shaping used in the system
R_s'	is the equivalent series resistance, ohms
C_{in}	is the total input capacitance, pF
A_f	is a constant expressed in (Volts)^2
$[N_{1/f}]$	is the coefficient dependent on the pulse-shaping network
B	is a constant
N_{gr}	is a coefficient dependent on the pulse-shaping network

As can be seen from this equation, the noise level of the system is due to input components at the input stage of the preamplifier and their configuration and also to the amplifier pulse-shaping network. Regarding later stages of amplification (the "main amplifier"), commercial types which employ pseudo-Gaussian pulse-shaping networks have been used in this work. Our efforts centered on minimizing electrical noise in the input preamplification stage.

We started with a commercially available resistor-feedback preamplifier (Tennelec Model 161D). Initially we focused on the input FET and the feedback resistor. It is well-known that the packaging of a commercial field effect transistor results in a very "noisy" FET.[6] To reduce this source of noise we used two different approaches. In the first approach we de-encapsulated a number of commercially produced FET's, and selected the least noisy chips for remounting. In the second approach we took unmounted FET chips obtained from Texas Instruments and mounted them on ceramic substrates.

Intensive experimentation with different types of feedback resistors had shown that besides the input FET, the feedback resistor is the major source of the preamplifier noise. The noise produced is not only the thermal noise generated by the resistor, but also the predominating excess noise due to the construction of the resistor, its methods of fabrication, the materials used, and nonuniformity of the resistance film.

During the selection of resistors it was found that differences in noise ranged over an order of magnitude for the same value resistors made by different techniques. This led to revision of the original concept of the amplification system for a room temperature spectrometer. The possibility of eliminating the feedback resistor was analyzed.

In operation, the feedback resistor functions as a drain path for the detector leakage current. In the liquid nitrogen cooled systems for Ge and Si detectors, several different systems are currently used. Drain feedback, pulsed and DC light-coupled feedback are employed in various applications. These systems utilize circuit configurations in which the leakage current is drained through the FET gate-drain junction. Since the leakage current in the liquid nitrogen-cooled Ge or Si detectors is inherently very small (10^{-13} A, or less), the detector current noise introduced is negligible compared with other noises present in the system. From the standpoint of energy resolution, the feedback technique selected for use in the preamplification system for cooled detectors is not as critical as for room temperature HgI_2 detectors, in which the leakage current is at least one order of magnitude higher. In drain feedback and DC light-coupled preamplifiers, the leakage current is continuously drained through the gate-drain junction during preamplifier operation. However, the current fluctuations at the input of the FET do increase the noise level and hence, the noise of the system.[7] In pulsed light-feedback preamplifiers, the leadage current of the detector charges the input capacitance to a predetermined value when it is then discharged by the triggered light-emitting diode. Since the discharge current flow occurs when the preamplifier is blocked, it does not introduce additional noise to the system. An additional advantage of pulsed-light feedback versus drain feedback is that the operating point of the input FET can be set to produce a minimum noise level. Of various possible techniques considered, the one appearing to have the most promising features of interest was found to be pulsed-light feedback preamplification. It was decided to try to adapt a pulsed-light feedback system to operation with an HgI_2 detector at room temperature. One condition necessary for operation of such a system is detector leakage current must be higher than the FET gate current. However, the difference between these two currents must be small enough such that it would not drastically increase the switching rate of the reset pulses and increase the dead time of the system.

At normal operating conditions (drain potential of 5 V), selected and de-encapsulated Texas Instruments 2N4416 FETs were found to have a leakage current in the range of approximately 0.2 pA. Similarly the HgI_2 detectors selected at room temperature were found to exhibit a current of approximately 1.0 pA. The difference between these two currents makes it possible to design a practical preamplifier having a reset rate of about 100 Hz.

For one particular detector, and with the same input FET operating at the same working point, we compared the noise in two operational modes: 1) using resistor feedback, and 2) using pulsed light feedback. The capacitance of the HgI_2 detector was 0.75 pF and the leakage current 1.0 pA. The results are presented in Figure 1, which shows the noise linewidth (FWHM in eV) versus the peakage time (in μs) of the pulses. The peaking time is selected by setting the shaping times in the main amplifier. The

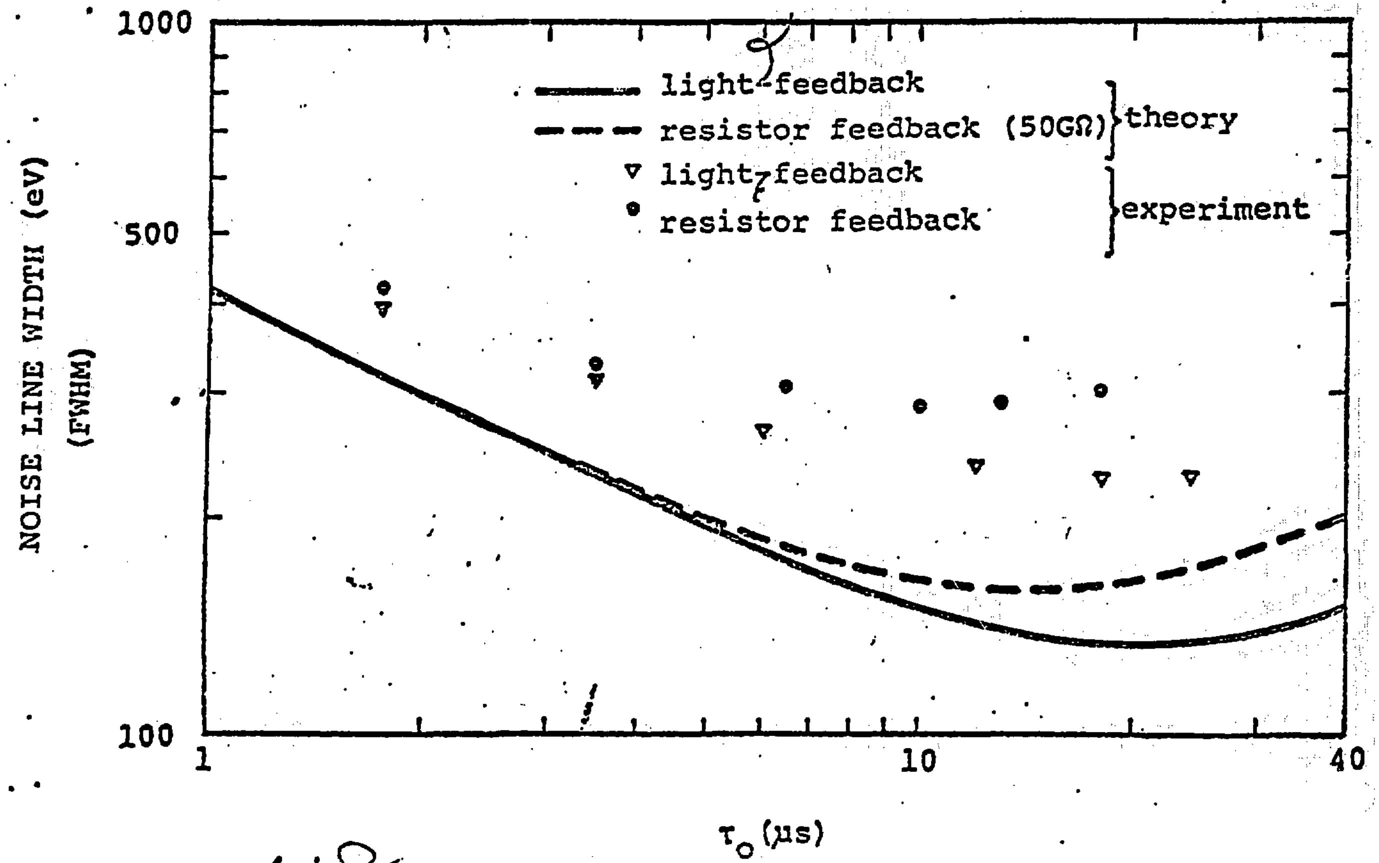

Figure 1 ~~[illegible]~~ Comparison of ~~[illegible]~~ noise linewidth for resistor feedback and pulsed light feedback systems theoretical curves given in Figure 1 were calculated using Eq. (1). The theoretical noise linewidth has minimum values of 135 eV (FWHM) and 160 eV (FWHM) at the optimal peaking times for the light-feedback and resistor-feedback (50 GΩ) systems, respectively. The corresponding experimental values are 225 eV (FWHM) for the pulsed-light feedback system and 280 eV (FWHM) for the resistor-feedback system. Comparison of the light-feedback and resistor-feedback systems makes it possible to estimate the excess noise contribution due to the feedback resistor. The minimum excess noise contribution was found to be 170 eV (FWHM) for selected resistors.

For short peaking times the predominant noise contribution is the series resistance equivalent noise. The theoretical calculation does not take any detector contact resistance into account, so that the discrepancy between the experimental points and the calculated curve may be attributed to this source. In this way the equivalent series resistance of the detector contacts was estimated from the equation[8]

$$Rs' = Rs + Rsd \left(\frac{cd}{C_{in}}\right)^2 \text{ ohms} \qquad (2)$$

where

Rs = equivalent series resistance of the FET, ohms

Rsd = equivalent series resistance of the detector, ohms

Cd = detector capacitance, pF

C_{in} = total input capacitance, pF

The values of Rs' arrived at using Eq. 2 were around 5 kΩ for several detectors. Figure 2 shows the x-ray spectrum from an Fe-55 source using a pulsed-light feedback preamplifier with both detector and input FET at room temperature. The energy resolution obtained was 295 eV (FWHM) for the 5.9 keV line of the Fe-55 source, and 225 eV (FWHM) for the pulser line. Figure 3 presents an ultra low-energy x-ray spectrum of the 1.5 keV K_α line from Al, again taken with the same room temperature system using pulsed-light feedback. The resolution was 250 eV (FWHM) in this case. These results clearly show that in the ultra low-energy region the energy resolution for an HgI_2 detector dystem at room temperature is still limited

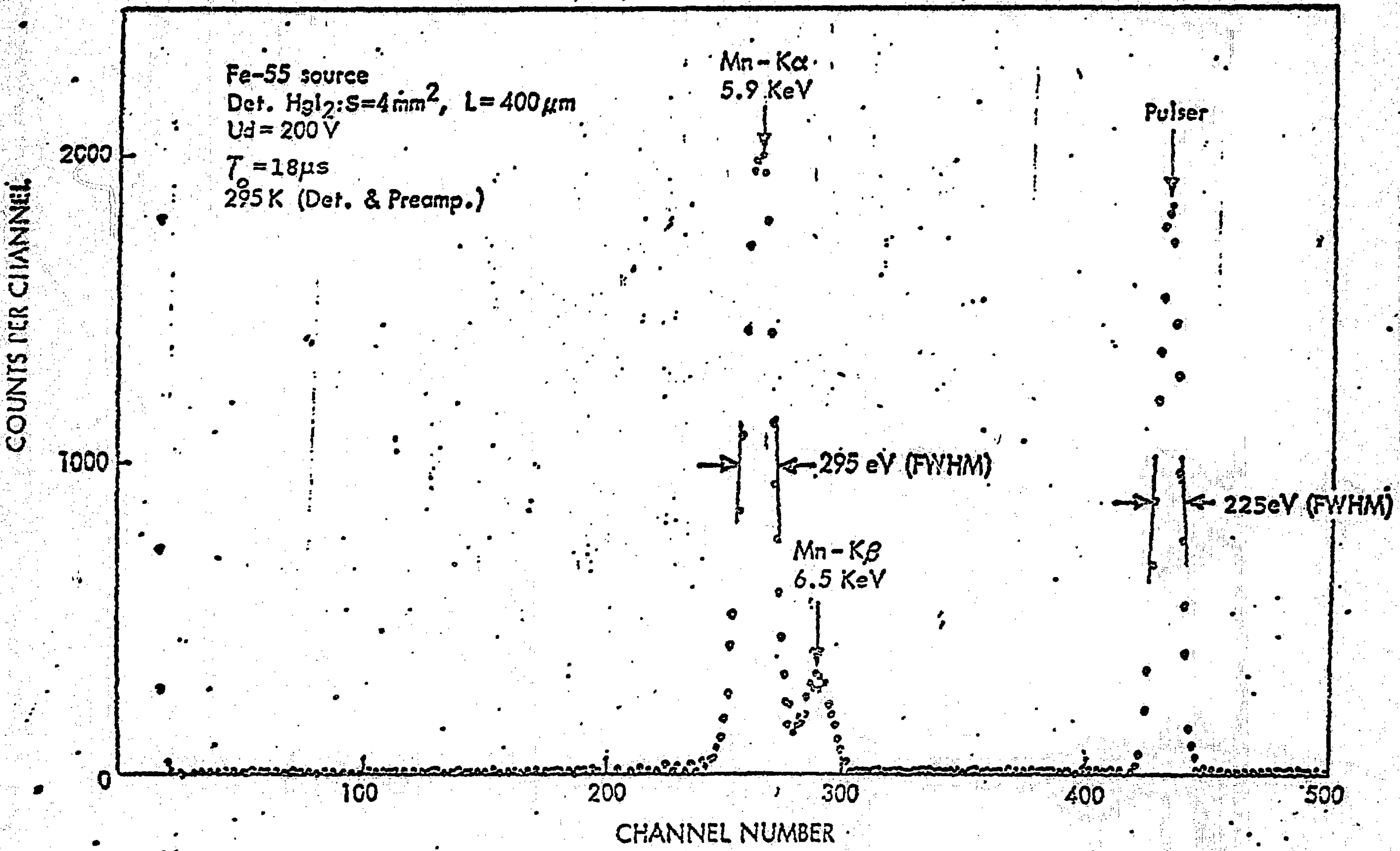

Fig. 2 Fe-55 spectrum measured by HgI_2 room temperature spectrometer (with room temperature pulsed-light-feedback preamplifier).

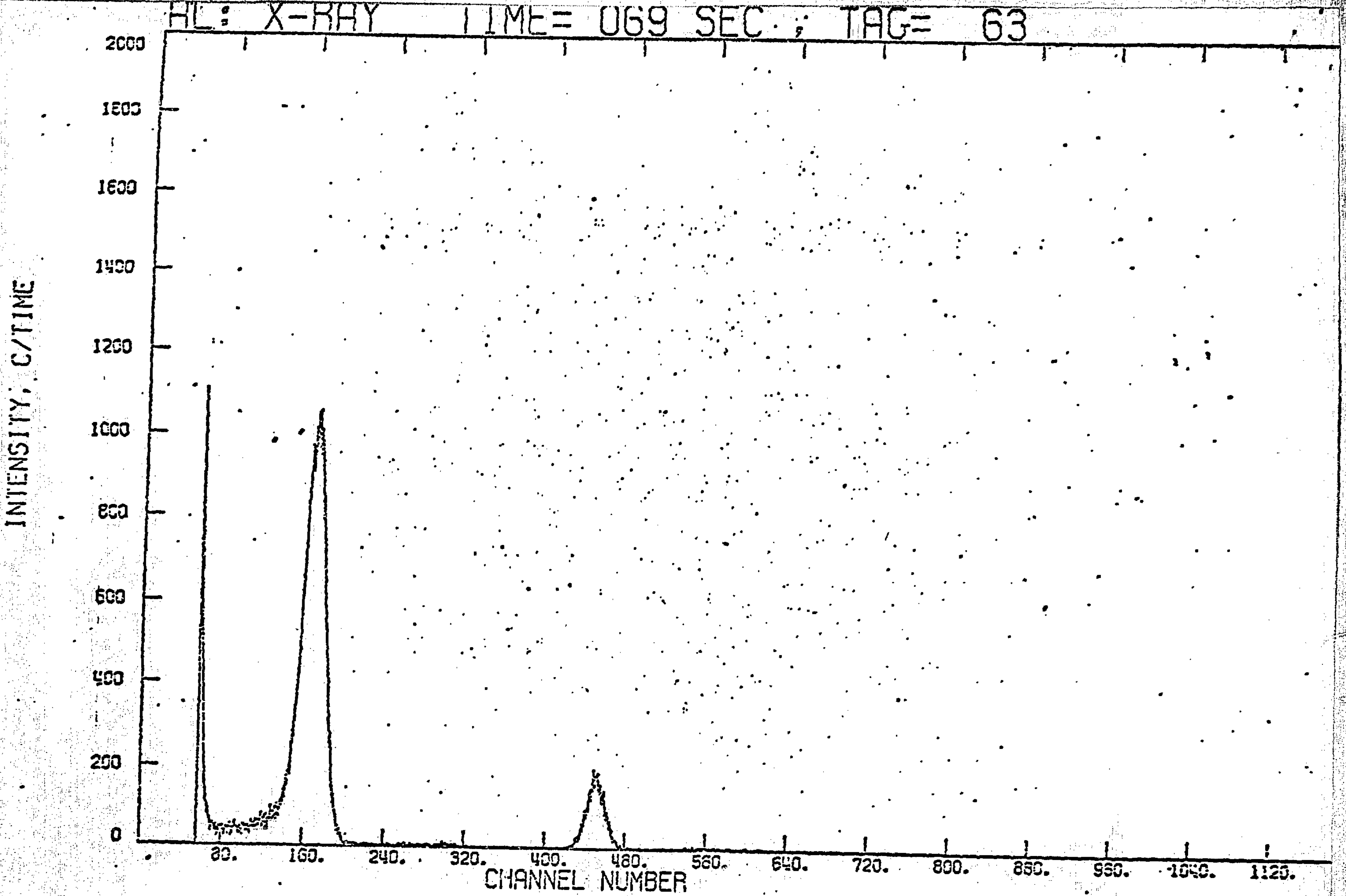

Figure 3 The 1.5 keV Al K X-ray line using an HgI2 detector with carbon front contact.

by the preamplifier noise. The next step in improving the energy resolution at low energies is to use Peltier cooling of the input FET.

PELTIER COOLED FET HgI_2 X-RAY SYSTEM

We intend to use a Peltier junction element to cool the input FET of the pulsed-light feedback preamplifier to about -50°C. We expect the energy resolution will be improved by an additional 25% as described below.

The electronic noise associated with a preamplifier input circuit is given by Eq. 1. According to the second term of the equation, lowering the temperature of the FET reduces the noise because of the explicit dependence of this term on T and also because the transconductance of the FET increases with decreasing temperature. The transconductance (g_m) is related to the equivalent series resistance of the FET (R_s) in the following manner:

$$R_s = \frac{0.7}{g_m} \tag{3}$$

We can expect an additional decrease in noise because in the first term of the equation, lowering the temperature decreases the gate current of the FET. The third term of the equation also decreases because of a reduction in A_f. However, the fourth term of the equation (generation and recombination noise) may increase with the decrease in temperature because of the presence of traps in the gate depletion layer. But as is known, this effect can be minimized by selecting an FET which has a low concentration of deep trapping levels in the gate depletion layer.

Preliminary experiments with Peltier cooling of the input FET using a resistor-feedback preamplifier confirms the expected improvement of energy resolution. A pulsed-light feedback system with Peltier cooling of the FET is being designed and built.

SUMMARY AND CONCLUSIONS

To fully exploit the possibilities of HgI_2 x-ray detectors in the low-energy region, it is necessary to develop ultra low-noise preamplification systems which operate at room temperature. Existing low-noise preamplifiers which utilize a liquid N_2-cooled first stage were analyzed and redesigned for operation at room temperature. Resistor-, drain-, and light-feedback preamplifiers were studied and optimized for operation with HgI_2 detectors. Pulsed-light feedback seems to offer some advantages over the other types: 1) lower noise and 2) higher counting rates. In addition, it appears that the pulsed-light feedback system can be miniaturized.

Resistor-feedback and pulsed-light feedback preamplifier room temperature resolution performances were compared. The theoretical noise linewidth has a minimum of 135 eV (FWHM) and 160 eV (FWHM) at the optimal peaking times for the light-feedback and resistor-feedback (50 GΩ) systems, respectively. The corresponding experimental values are 225 eV (FWHM) for the pulsed-light feedback system and 280 eV (FWHM) for the resistor feedback system. By comparing the light feedback and resistor feedback systems it was possible to estimate the excess noise contribution due to the feedback resistor. This analysis was carried out for several resistor types and values. The minimum excess noise contribution was found to be 170 eV (FWHM) for selected resistors. By eliminating the feedback resistor and its associated noise, HgI_2 spectrometers built with pulsed-light feedback show the lowest noise. Using the pulsed-light feedback room temperature preamplifier system we obtained an energy resolution (for the 5.9 keV Fe-55 x-ray) of 295 eV with HgI_2.

Acknowledgements

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