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DEVELOPMENT OF A PRESSURIZED XENON WIRE CHAMBER GAMMA CAMERA FOR MEDICAL APPLICATIONS

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Abstract

We describe the development and performance evaluation of a pressurized xenon wire chamber for applications in nuclear medicine. A chamber with an active imaging area of 25 x 25 cm^2 and an effective depth of 5.5 cm has been constructed which has operated at pressures of up to 6.5 atm with a xenon gas mixture. The chamber has been fitted with front end electronics for filtering, amplification and shaping of the signal. A purification system has been designed which allows long term operation of the system without degradation in performance. The performance characteristics of the chamber have been investigated using various sealed radioactive sources in the energy range 20 keV to 120 keV. Results obtained demonstrate a detection efficiency of 48% and a energy resolution of 10% (FWHM) at 60 keV with a maximum rate of over 20 KHz per wire being recorded. Optimal operating conditions and parameters have been chosen from the results of measurements. All studies were carried out with future clinical conditions and hospital requirements being considered. The work has demonstrated a very promising future for the detector in medical imaging.

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INTRODUCTION

The multi wire proportional counter (MWPC) was developed in the late sixties to satisfy the requirements in experimental particle physics.[1]. Since then the MWPC technology has developed rapidly enabling it to have applications in medicine and biology as well as high energy physics [2]. Properties of such detectors offer advantages over the conventional gamma cameras used in nuclear medicine today which are based on scintillation crystal technology. Such advantages include high data rate and improved spatial resolution, particularly for isotopes with photon energies below 100 keV.

The low absorption power of gamma rays in gaseous mediums has led to the necessity of working with high pressure xenon fillings. Some groups have been successful in developing MWPC single-photon imaging detectors which have demonstrated good resolution, simplicity of construction and good results for detection in the 20-80keV range [3] - [5]. One group in particular has developed a gamma camera operating at a pressure of 3 bar with a position accuracy of 3mm operating at nearly 1MHz. This camera has shown great potential in nuclear cardiology [6].

The studies reported here had the aim of using the know-how in the gaseous detectors acquired at CERN to develop a pressurized xenon wire chamber for applications in nuclear medicine with improved position accuracy, increased counting rate and high efficiency all accomplished with a minimum of gas filling operations and general maintenance.

DETECTOR CONSTRUCTION

The basic design of the wire chamber is shown schematically in Figure 1. The physical characteristics are summarized in Table 1. The detector structure consists of a drift region and an amplification zone. The ionization electrons liberated in the gas of the chamber drift to an asymmetrical amplification zone where the charge is amplified by avalanche. The amplification zone is made up of a wire anode plane between two planes of cathodes. A grid of cathode wires set at negative potential is separated by a distance of 3mm from a plane of anode wires at positive potential. The anode wire plane on which the avalanche multiplication occurs is separated by a distance of 1mm from a lower plane of strips which are operated at ground potential. These 1.1mm wide copper strips are printed on a 50μm kapton foil. The anode wire plane is oriented orthogonally to the cathode strips to enable bi-dimensional reading. The detector is enclosed in a rigid aluminium container with an aluminum entrance window.

The structure is capable of withholding a pressure of up to 6.5 bar.

The detector design has the advantage that the grid wires can be used to trigger the detector read-out. Other special features included in the design are the short distance between the cathode strips and the anode wires enabling a strong signal to be induced on the cathode strips by the motion of the ions created by the avalanches around the anode wires. This permits the readout of pulses and localization of the avalanches along the wires from the cathode strips as well as from the anode wires.

TABLE 1. DETECTOR	CHARACTERISTICS
Sensitive area	250 x 250 mm^2
Drift zone	52 mm
Anode to cathode grid gap	3.00 mm
Anode to cathode strips gap	1.00 mm
Anode wire spacing	1.27 mm
Cathode grid spacing	1.27 mm
Cathode strip separation	0.08 mm
Cathode strip width	1.10 mm
Anode wire diameter	20 μm
Entrance window	1.2 mm aluminum

GAS PURIFICATION AND RECIRCULATION

The schematic layout of the xenon purifier and recirculator is shown in Figure 2. The system has been constructed with standard metallic components including an oxisorb Grosspatrone [7] the role of which is to remove the electronegative impurities, mostly oxygen molecules from the xenon gas. Other components include Nupro valves and a magnetically driven recirculation pump [8]. The final vacuum obtained in the purifier was 10^{-6} mbar and demonstrated a very small outgassing of 10^{-9} mbar.l/cm^2.sec. Such a purifier is capable of producing xenon with a concentration of electronegative impurities of ppb [9]. All components in the system demonstrate an acceptable level of cleanliness.

The chamber underwent a helium leak test under vacuum and under helium pressure before it was filled. Only one gas handling system is required for preparing the gas and filling up the chamber. A small recirculating pump used to recirculate the gas within the chamber has been tested and demonstrated perfect reliability over a period of one month. The connections between the gas handling system and the detection chamber are shown in Figure 3.

Gas contamination is a well-known phenomenon in long-term sealed operation of MWPC detectors. Electronegative gas contaminants which can result from outgassing of detector interior structure cause loss of electrons produced by x-ray interactions. Such effects show up as instabilities in detector operation. With this system we have been able to maintain stable operation of the detector over a time period of several months. However if the recirculation was stopped it was found that the energy spectra began to shift in time as gas amplification deteriorated due to outgassing (Figure 4). It was concluded that the materials used in the construction of the chamber had not been optimized for low outgassing. Maintaining recirculation a degradation in the quality of the energy spectra was observed after a few months and the detector operation was stopped to allow the chamber to be opened up and the interior cleaned. After this procedure, the spectra returned to the same quality as before.

The optimal xenon gas mixture after trials with methane, ethane and isobutane was found to be xenon-ethane. Measurements of energy resloution at 22keV in identical experimental conditions for 95%-4% mixtures of xenon-methane, xenon-ethane and xenon isobutane gave FWHM values of 22%, 15% and 33% respectively. Figure 5 shows the pulse height spectra of Am-241 obtained for each of these gas mixtures. From these spectra it is evident that a xenon-ethane gas mixture provides the best quality spectrum. The poor quality of the spectra with isobutane was due to the oxisorb filter traping a larger quantity of isobutane than either ethane or methane and so reducing the percentage of isobutane to below 4%.

ELECTRONICS

Figure 6 displays the basic voltage supply and electronic signal processing circuitry for the chamber. As the complete electronic readout for the chamber is still under study, only a limited number of anode wires were equipped with electronic channels for signal processing purposes. The signal processing circuitry consisted of one section designed for filtering the signal and a second section designed for amplification (gain of 4mV/fC), integration (integrating time of 20μs) and shaping (shaping time of 2μs) of the signal. A gain of 50 was obtained on each wire with a xenon-ethane gas mixture at a pressure of 6 bar. The electronic noise was measured to be 1000 electrons which gives a very high signal to noise ratio. In addition to these electronic channels we used some additional electronics to further process the signal. These included an adder in order to add the output of several channels together, an amplifier in order to further amplify and integrate the signal. To analyze the energy response of the detector an ADC and a multi channel analyzer were used to generate an energy spectra and in order to analyze the counting rate of the detector, a discriminator, gate and counter were used. The parameters of these electronics could be modified throughout the measurements.

EXPERIMENTAL RESULTS

Using the experimental detector described previously, a series of measurements has been performed with four radionuclides Americium-241, Cadmium-109, Barium-133 and Cobalt-57. The gas mixture used for these tests was 96% xenon and 4% ethane at a total pressure of 6 atm. For the measurements reported here, the best settings were found to be a drift potential of -5500V, an anode potential of +2300V and a grid potential of -1200V. All spectra presented here were taken from the output of two anode wires added together.

A. Efficiency

Using a germanium detector of known efficency we were able to measure the number of photons per second entering into the detector volume. Then by recording the number of pulses recorded per second by the detector under analysis we were able to determine from the ratio of these quantities that the intrinsic efficiency of the detector at 60keV was 48%. When this result is compared with theoretical predictions for this value we conclude that it gives a satisfactory value of efficiency of the detector.

B. Energy Resolution

Imaging properties of gas proportional detectors depend on the emission spectra of radionuclides and on the interaction processes in the absorbing gas. Photoelectron range and fluorescence limit spatial resolution and produce complex energy spectra. When a gamma photon interacts with the xenon gas medium, one or more of the following courses is taken depending on the energy of the incident photon; photoelectric absorption by K or L shell electrons, Compton scattering or escape of the photon from the detector [10]. For energies less than the K shell excitation energy of xenon (35keV), L shell interactions take place and most of the incident photon energy is deposited entirely at the interaction site resulting in a full photopeak on the energy spectra. However for energies superior to 35 keV, K shell rearrangements occur and the excess energy above 35 keV is deposited at the interaction site with a 29 keV fluorescence photon being emitted 88% of the time (the remaining 12% of fluorescence emissions are internally converted, leading to total energy deposition at the interaction site).

To demonstrate the energy resolution characteristics of the detector, we present the energy spectra of Cd-109 and Am-241 in Figures 7 and 8. Am-241 emits a 60 keV photon which results in 25 keV deposited energy from a K-shell interaction and a 60 keV full deposited energy from a L-shell interaction. These are accompanied by a 29 keV fluorescence peak. The intrinsic energy resolution measured is 9% (FWHM) at the total incident energy 60 keV. Although this value

is favourably comparable with that obtained in crystal cameras the value is expected to be improved in the future with further developments in the electronic processing circuitry. Cd-109 emits dominantly 22 keV x-rays and a very low abundance (3%) 88 keV photon. From the energy spectrum the characteristic photopeaks of 88keV and 22keV can clearly be seen as well as peaks occurring at 29 keV and 53 keV which correspond to the escape peak and the K shell interaction respectively.

Other radionuclide spectra that were taken were Barium-133 and Cobalt- 57. These spectra are shown in Figures 9 and 10. What is interesting in the latter spectrum is that it shows that the detector can respond to energy values of 120 keV which offers the option of extending its applications to the use of radioisotopes with an energy in this range.

For each of the spectra mentioned above, the channel number corresponding to the position of the different energy peaks was recorded. These results were then used to investigate the linearity of the detectors energy response. The result is shown in Figure 11 where we can see that the detector response demonstrates a good linearity.

To evaluate the potential problem of an attenuating medium effecting the energy response of the detector, a water absorption medium was placed between the source and the detector. The resulting spectrum is shown in Figure 12. The evolution of attenuation of spectra with increasing level of water is obvious. However the spectra maintains its basic shape with no energy shifts and the increase in level of Compton scattering is not significant and is therefore not expected to be of any practical consequence in the future. Further detailed measurements with standard phantoms have been envisaged for the future.

C. Spatial Resolution

Another parameter important for the quality control assessment of a detector is its spatial resolution. We carried out a series of measurements where we irradiated the detector with a collimated Am-241 source at various points across its surface. By measuring the distribution of counts over the anode wires we were able to estimate the size of the radiation cluster. The cluster size was found to be 4 channels. However due to poor collimation of the source we were unable to conclude this to be an accurate estimation of the spatial resolution.

As a further investigation we made an estimation of the percentage of events that were being counted by two adjacent wires. This was accomplished by firstly measuring the count rate from each wire separately and then together. With a gas mixture of 96% xenon- 4% ethane we found that 28% of the events were common to two adjacent wires. However, when we increased the proportion of ethane in the gas mixture to 10% we found that the percentage of common events recorded on two adjacent wires was reduced to 2.5%. This improvement was attributed to the diffusion of the electrons being reduced by the presence of ethane and so the charge signal being less spread out over the wires. From this we conclude that the detector provides a spatial resolution of approximately 1.3mm over an energy range of 25 keV-85 keV.

D. Rate Performance

A maximum rate of 20 kHz per wire was measured from each wire when the detector is irradiated with a collimated Am-241 source. This rate was the maximum rate delivered from the source used in the measurement. This high count rate will eventually lead to a high quality image for low irradiation doses. The high rate did not lead to pulse pile up problems and distortion of the energy spectrum.

CONCLUSION

We have described the development of a wire chamber operating at a pressure of 6 bar with a xenon gas mixture. The chamber has maintained stable operation and demonstrated good reliability over a time period of several months.

The experimental measurements described in the present work have demonstrated the following performance characteristics:

- a detection efficiency of 48% at 60 keV. This value corresponded to theoretical efficiency values expected at this energy.
- a good linearity over the range 20keV to 120 keV. The pulse height output from the detector was proportional to the energy deposited.
- an energy resolution of 9% FWHM at 60 keV. This provides a good energy discrimination capability and from the spectra it is evident that the events are distinguishable from each other. This facilitates the design of energy selection windows to select the photopeaks.
- a rate of 20 kHz per wire which did not produce any smearing in the spectrum. We can expect a much higher rate capability when using a higher rate source.

The presence of an attenuation medium was found not to distort the energy spectrum. The practical significance of this is important as attenuation by biological tissue plays an important role in organ imaging.

As an investigation of spatial resolution we were able to conclude that a single event spread itself over a one wire pitch for 60 keV X-Rays.

The optimal gas mixture used during the course of the measurements was a mixture made up of 10% Ethane and 90% Xenon. This significantly limited electron diffusion thereby improving spatial resolution.

The results obtained during the course of these studies provides important information for the design of an adequate electronic circuitry. The high count rate and good resolution should lead to a promising future in clinical nuclear medicine applications where low energy radioisotopes are used.

In view of the promising results obtained up until now, we intend to continue our development studies of this detector. Further detailed measurements are envisaged and will be carried out in the months to follow. The possibility of exploiting the signals induced on the underside of the cathode strips will be fully investigated.

Acknowledgements:

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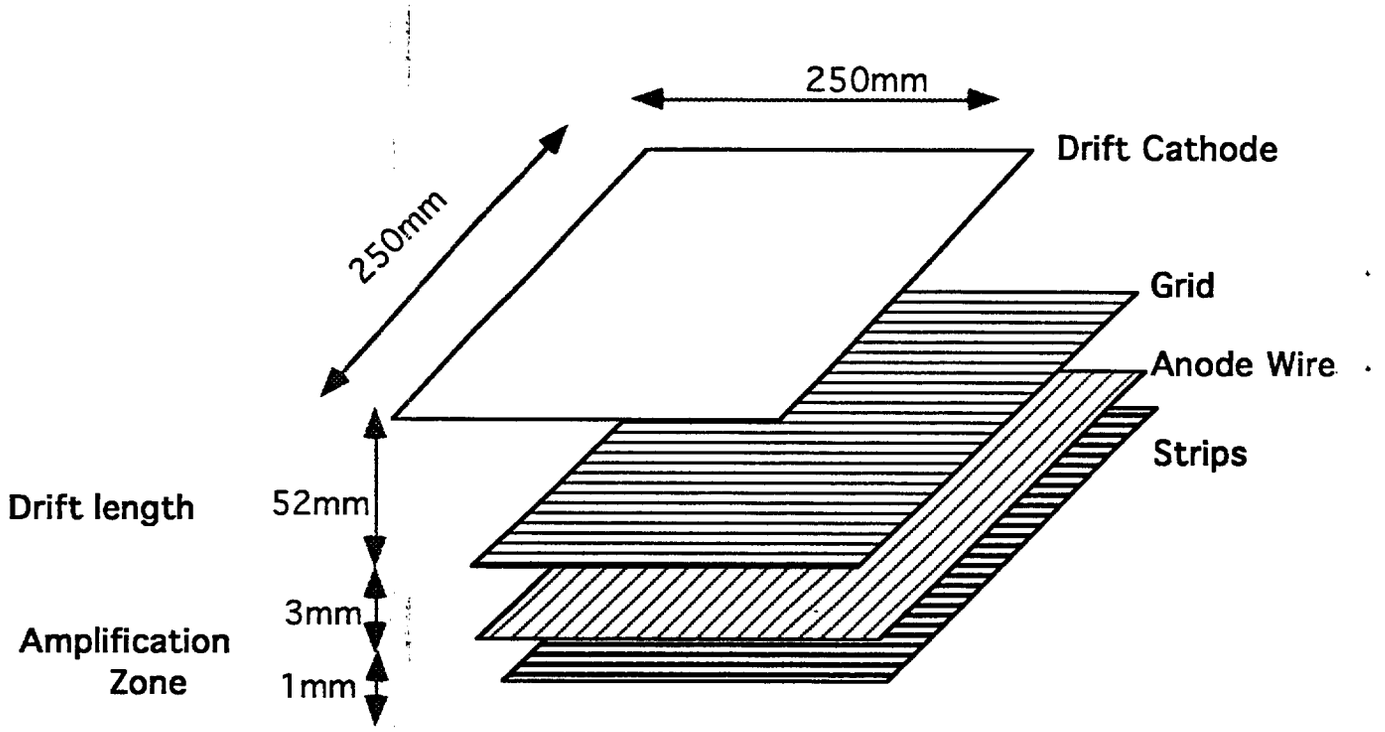


Figure 1: Basic Design of the detector

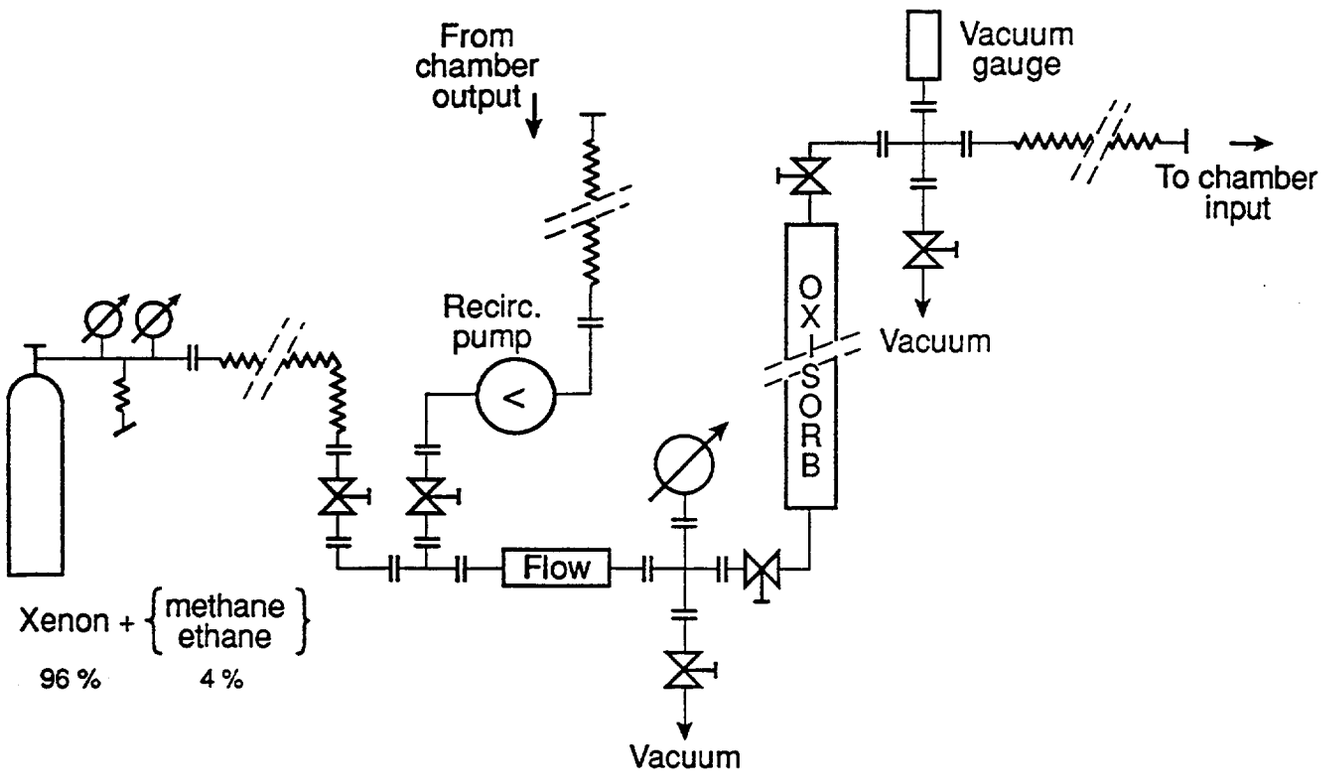


Figure 2 : Xenon purifier and recirculator

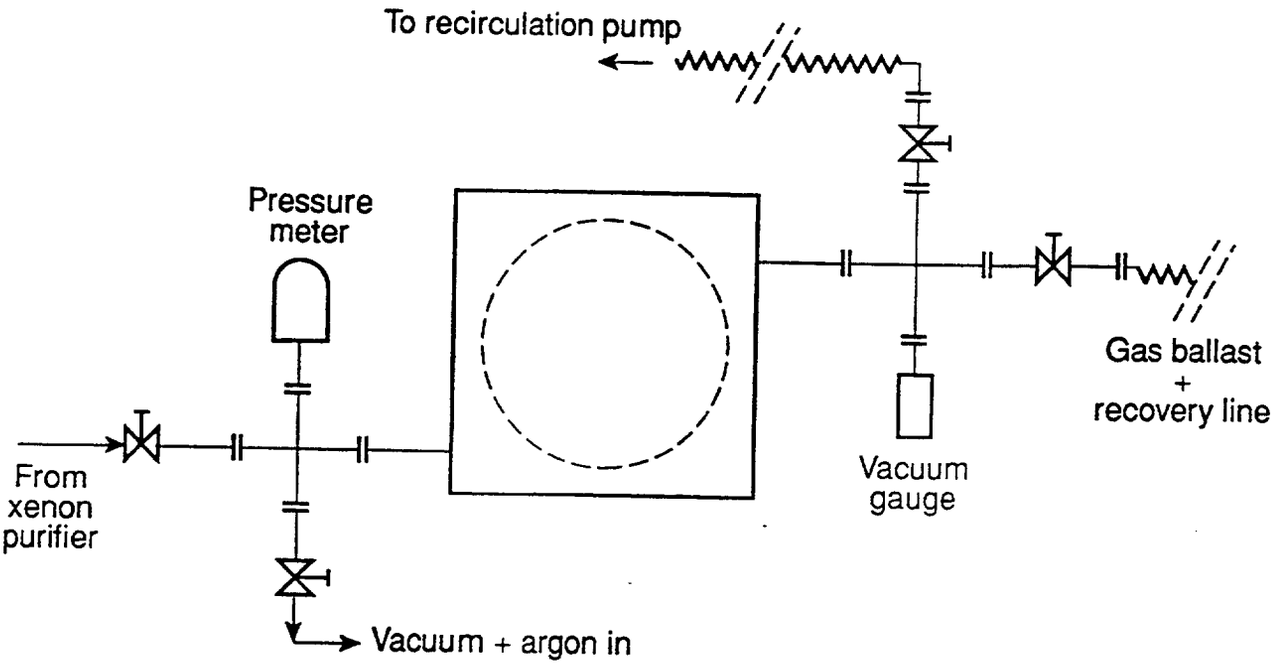


Figure 3 : Connections between chamber and gas system

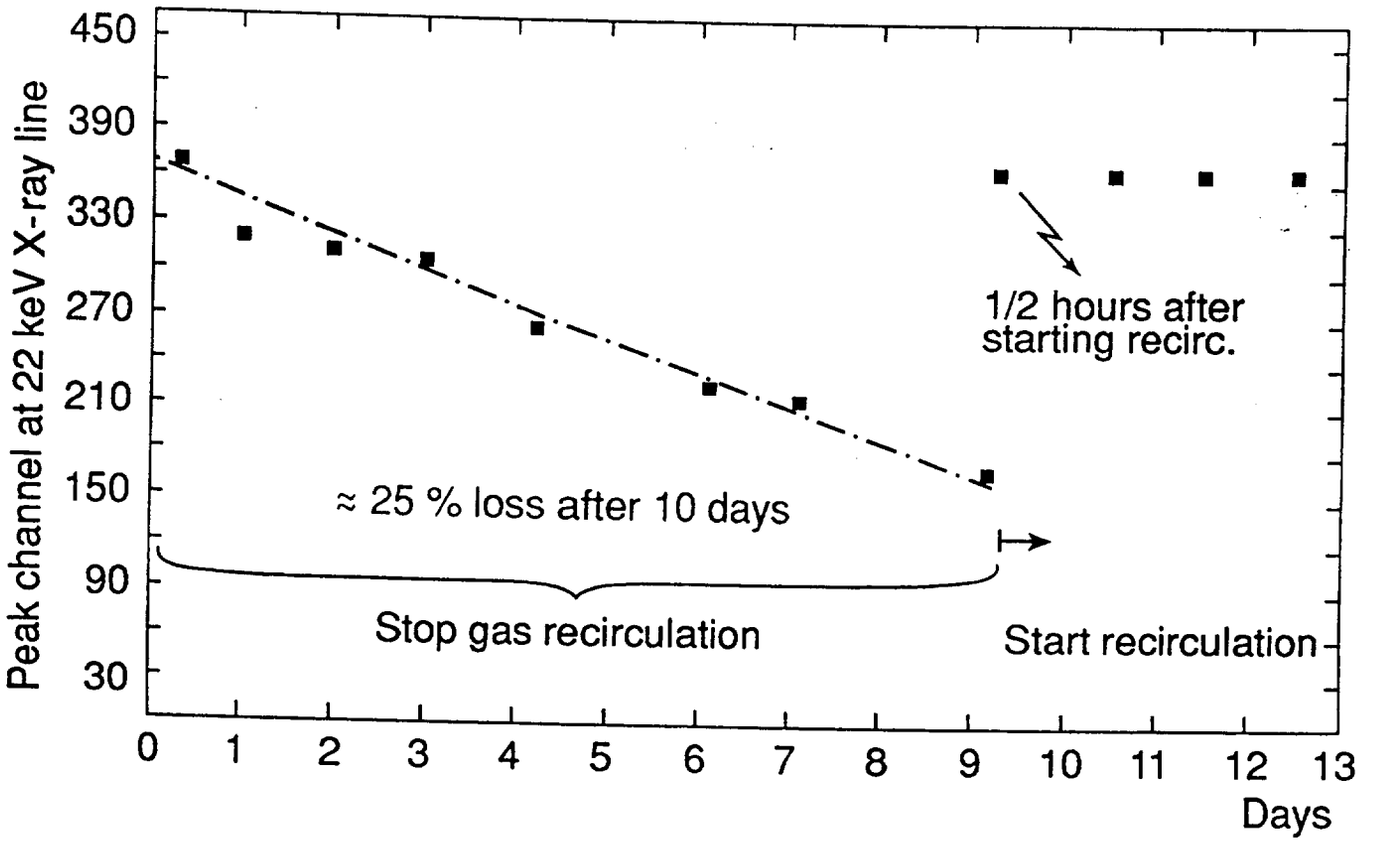


Figure 4 : Displacement of peak position with time

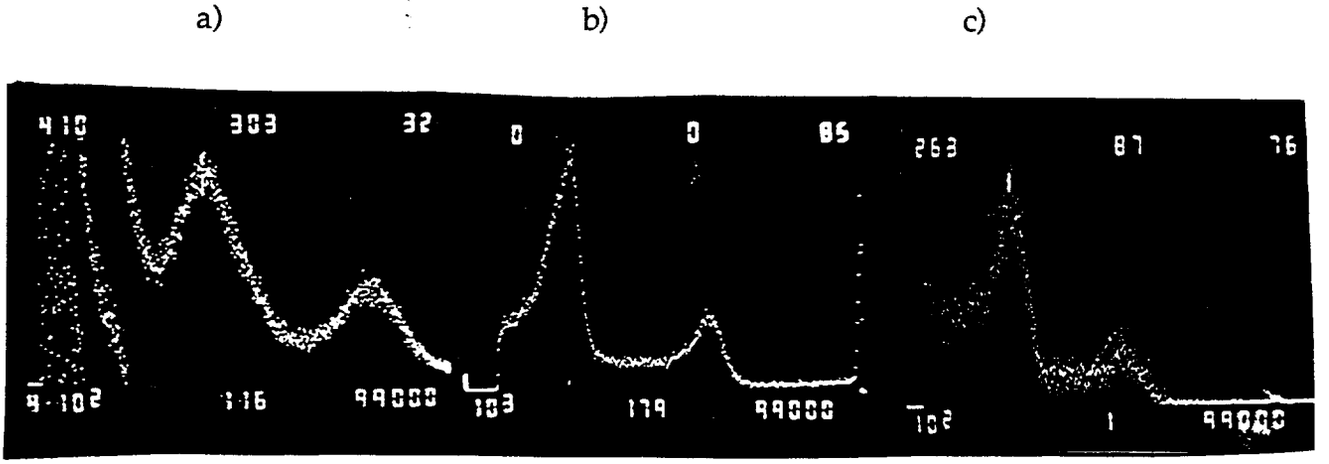


Figure 5 : Pulse height spectra of Am-241 source taken in gas compositions of: a)xenon-methane (96%-4%), b) xenon-ethane (96%-4%) and c) xenon-isobutane (96%-4%), the improvement in resolution obtained with a xenon-ethane gas mixture is obvious.

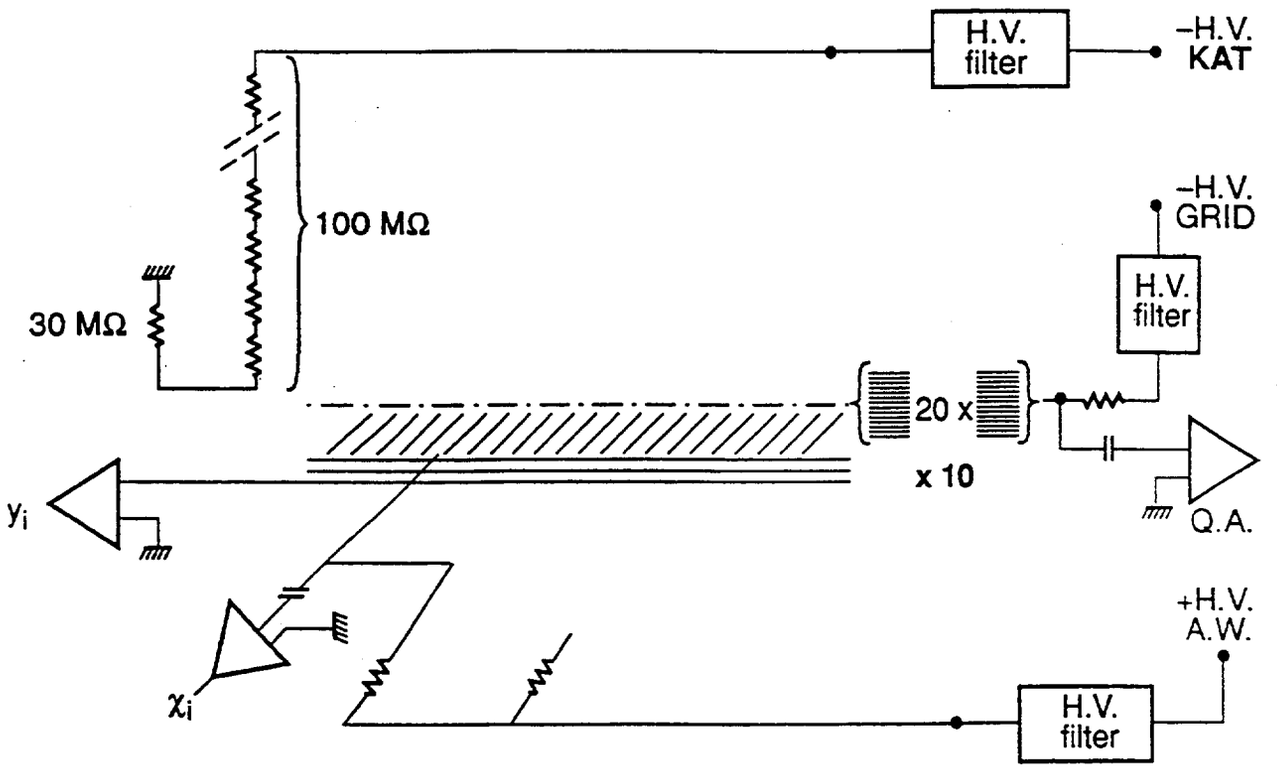


Figure 6 : Voltage supply and electronic circuitry

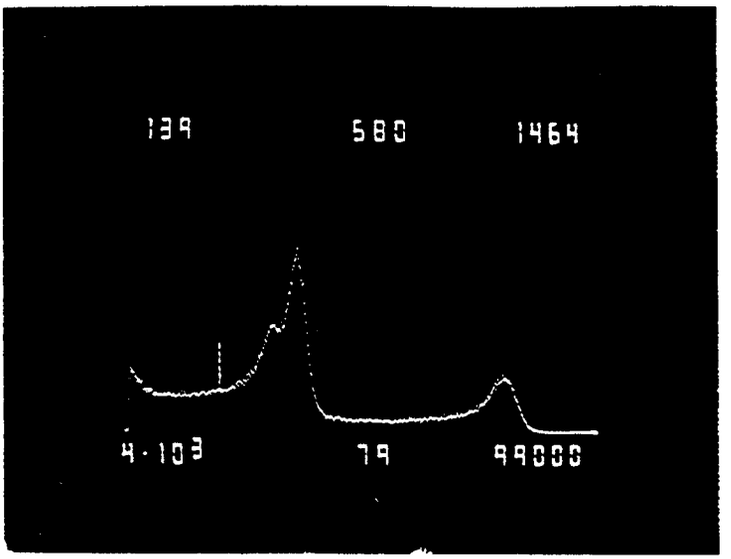


Figure 7 : Pulse height spectrum of Am-241 source The spectrum clearly displays the 60 keV photopeak characteristic of the source energy and the 25 keV photopeak resulting from the K-shell interaction. The 29 keV corresponding to the fluorescence can also be seen.

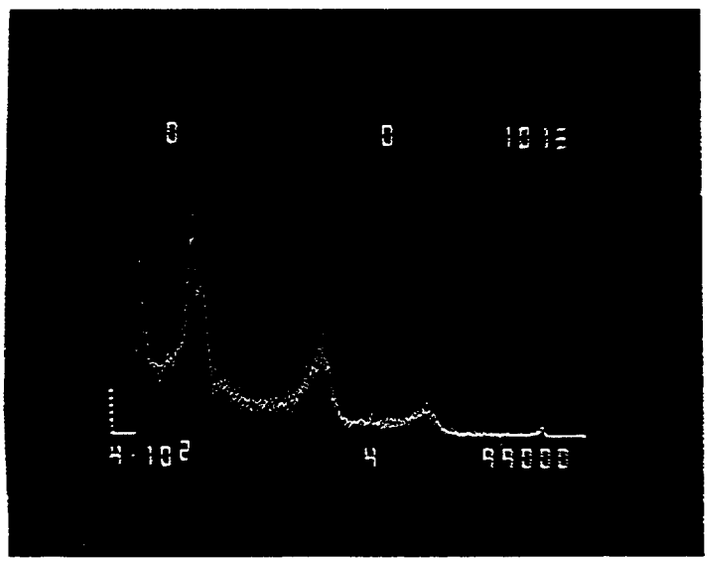


Figure 8 : Pulse height spectrum of Cd-109 source From this spectrum the position of the characteristic photopeaks of 88 keV and 22 keV can be clearly seen as well as peaks occurring at 29keV and 53 kev which correspond to fluorescence peaks and K-shell interactions respectively.

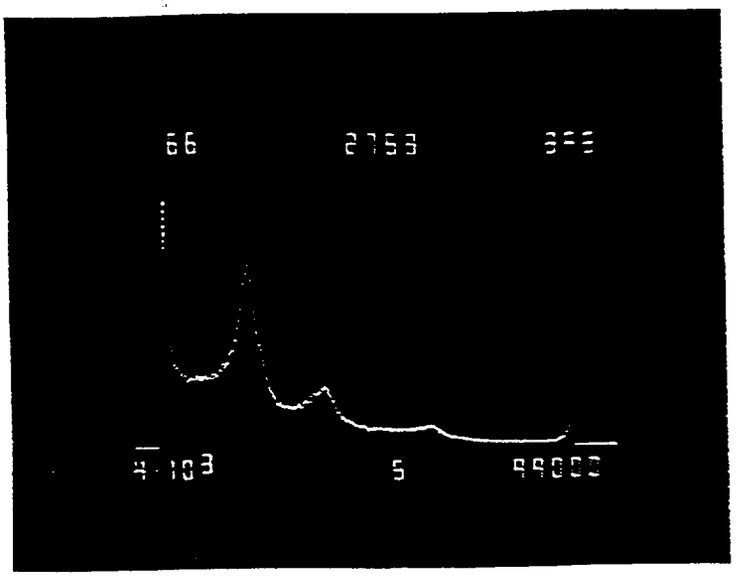


Figure 9 : Pulse height spectrum of Ba -133 source.The peaks in the spectrum correspond to the photopeak of 81 keV, a K -shell interaction of 46 keV and the fluorescence peak characteristic of xenon interactions at 29 keV.

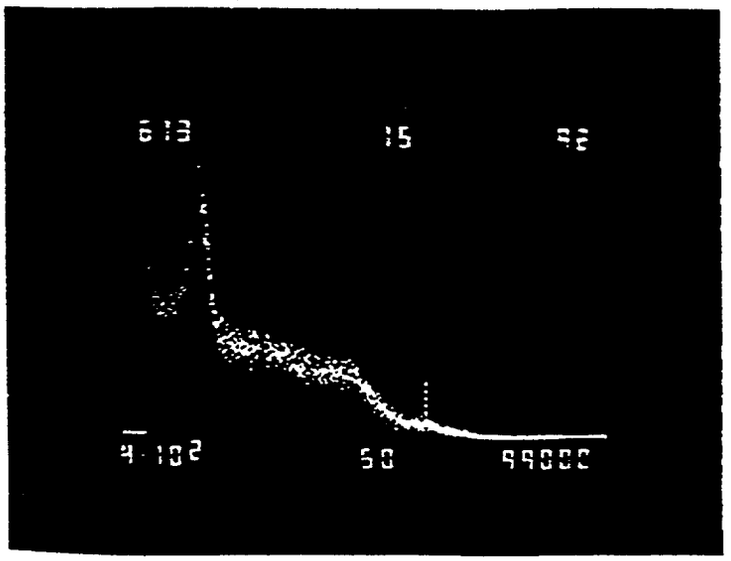


Figure 10 : Pulse height spectrum of Co-57 source.The peaks correspond to the photopeaks at 122 kev and the fluorescence of xenon at 29 kev. This spectrum demonstrates that at higher energies the Compton effect comes into play more significantly.

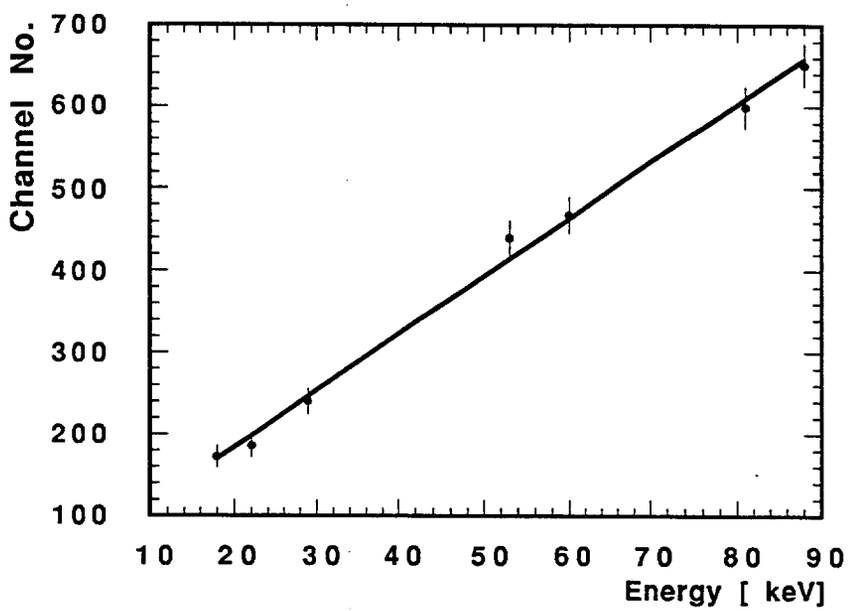
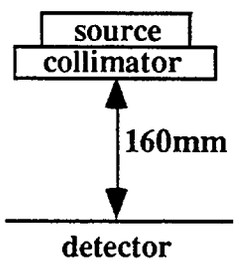
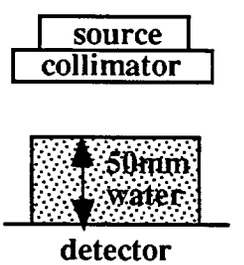
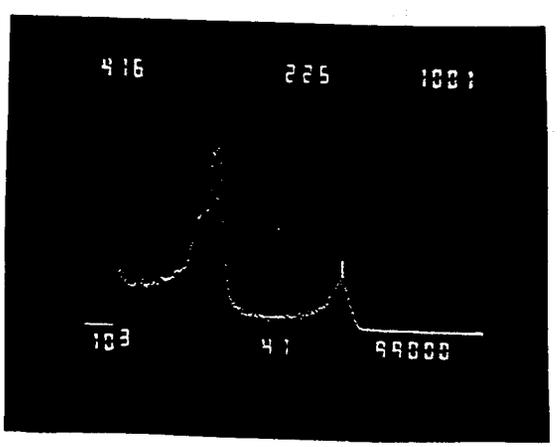


Figure 11 : Linearity of the energy response of the detector.







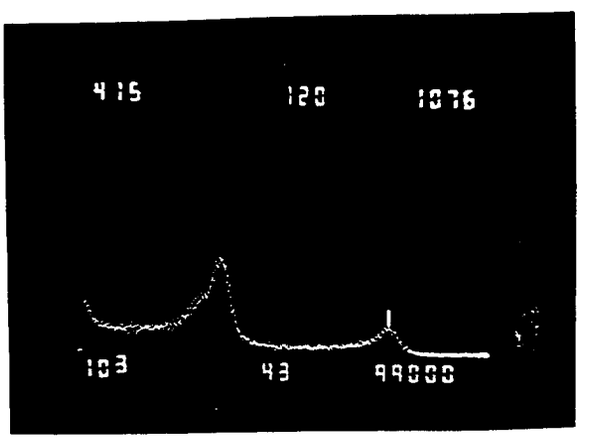


Figure 12 : Attenuation of spectrum with 5 cm water medium for a 60keV gamma ray.