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RESOLUTION FOR X-RAYS IN GAS PROPORTIONAL CHAMBERS***

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PHOTOELECTRON RANGE LIMITATIONS TO THE SPATIAL RESOLUTION FOR X-RAYS IN GAS PROPORTIONAL CHAMBERS*

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Abstract

Measurements have been made, for x-ray energies from a few keV to 18 keV, of the limiting spatial resolution caused by the finite range of the photoelectron, or electrons, created when an x-ray is absorbed in the gas of a proportional chamber. In hydrocarbon gases such as methane and ethane, where the photoelectron receives the bulk of the x-ray energy, the limiting spatial resolution is found to vary as a power law of x-ray energy. In argon and xenon, at an x-ray energy approximately twice that of the A_K edge and the X_{e1} edge respectively, the measured limiting resolution is better than expected from an equivalent power law behavior.

1. Introduction

There are at least four physical phenomena which, by virtue of their dispersive nature, limit the x-ray spatial resolution attainable in gas proportional chambers. These are the finite range (and number) of the electrons from the initial x-ray interaction in the gas, centroid fluctuation of the secondary ionization cloud due to diffusion, fluctuation of the avalanche along the anode wire, and the electronic noise of the position readout electronics. Further points to consider in a practical measurement of spatial resolution are instrumental uncertainties, such as finite x-ray beam width and parallax errors due to misalignment of the detector. These spatial resolution limitations are important for x-ray position-sensitive detectors employed in a variety of research fields using synchrotron radiation, and in other areas, such as x-ray astronomy.

2. Ionization Distribution Following X-ray Absorption

For all common counter gases, x-rays below 20 keV are absorbed almost entirely by the photoelectric effect. This is a complex process which, depending upon the x-ray energy and the atomic number of the absorbing atom, can result in the emission of photoelectrons, fluorescent x-rays and Auger electrons. The process may involve several individual atoms, but the energy in each succeeding interaction rapidly diminishes. For the purposes of the present simple analysis, we consider only the radiation emitted from the initial atom. A photoelectron is first ejected from one of the inner electron shells with kinetic energy $E_K - E_B$, where E_K is the x-ray energy and E_B is the binding energy of the electron shell. The atom then de-excites and the majority of its energy is dissipated by either emission of an Auger electron or emission of a fluorescent x-ray. For the gases with which we will be concerned, fluorescent emission has a low probability (< 15%) and normally the bulk of the x-ray energy is either taken by the photoelectron or distributed between the photoelectron and the Auger electron.

The centroid of the ionization created by the emitted electrons determines the measured position of the true x-ray absorption point. The centroid of ionization from one electron will be influenced by the

initial trajectory of the electron, its path length, and the distribution of ionization created along its path. Scattering of the electron during its thermalization process should cause the centroid of the ionization to lie somewhere along the practical range, R_p , of the electron. R_p is the range obtained by extrapolating to zero transmission the linear portion of electron transmission vs absorber thickness curves for gases¹ or metals.²

A few measurements of electron ranges in gases have been made by Williams.¹ In recent work the effect of electron range on spatial resolution in gas chambers, e.g., Bateman *et al.*³ and Sauli⁴, has been assessed by extrapolating electron ranges in solid absorbers^{2,5} to equivalent ranges in the gas under consideration. It is difficult to determine the limiting spatial resolution from a knowledge of electron range alone unless certain simplifying assumptions are made. For example, in the model of Gilvin *et al.*,⁶ ionization created by an electron is assumed, on average, to be uniformly distributed along a radius of length, R_p , and the angular distribution of photoelectrons is assumed isotropic, so that the centroids of ionization from many events are distributed on a sphere of radius $R_p/2$; projection of a spherical surface in one dimension is a rectangular distribution, in this case with width R_p .

Since the exact effect of electron range on x-ray spatial resolution is not easy to assess, and there exists little experimental work on this subject, we have made x-ray position measurements where the resolution was dominated by electron range. The x-ray energy range of a few keV to 18 keV was investigated

3. Apparatus

Measurements were performed using a collimated x-ray beam incident normally on a flat, one-dimensional, multi-anode, position-sensitive proportional counter. The direction of the anode wires determined the position sensing axis. The experimental arrangement was configured so that the limit to spatial resolution from diffusion, electronic noise and instrumental effects (as determined by either measurement or calculation) was small compared to that of electron range. All measurements were carried out at anode charge levels (measured in 1 μ sec) of 0.4 pC or less, to ensure that avalanche spread along the anode wire did not cause significant fluctuation of the avalanche centroid; for resolutions $\leq 200 \mu$ m, anode charge did not exceed ~ 0.1 pC. Optimized position readout was, therefore, essential. As a general rule, the detector depth needed to be ≥ 10 times the measured resolution, otherwise wall effects caused distortion to both spatial and energy resolutions.

With all of these constraints in mind, we were capable of measuring electron range limited spatial resolution of several mm down to 65μ m FWHM using three different detectors:

i) For resolutions ≥ 1 mm, a variable depth detector was used with position encoding, by charge division, from a cathode constructed as an RC line. This was a slightly modified form of the detector described by Rappaport *et al.*⁷

ii) A high resolution delay line detector with a total depth of 6.6 mm, as described by Boie *et al.*,⁸

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was used for resolutions ~ 1 mm down to ~ 200 μ m.

iii) For accurate measurements of resolution below 200 μ m, a special detector has been constructed, shown schematically in Fig. 1. In order that the photoelectron range be the dominant contributor to spatial resolution, it is instructive to illustrate, with reference to this third detector, the way in which the other limitations are minimized. These are:

Fig. 1. Schematic, exploded view of high spatial resolution detector for measurement of electron range limited resolutions below 200 μ m. Position sensing axis is along anode wires. Description of centroid finding electronics is given by Radeka and Boie.⁹

(a) Electronic Noise

The cathode of the detector is constructed in the form of strips running at right angles to the anode wire direction and a thin window contains the gas in a small volume whose depth, $2d$, is 1.6 mm; anode wire diameter is 10 μ m and the sensitive area is 15 mm x 15 mm. An anode avalanche gives rise to induced charge on several cathode strips which is encoded by an accurate centroid finding method (Radeka and Boie⁹). This is a continuously sensitive position readout that reduces the effect of electronic noise on position resolution by subdivision of the sensing axis. Instead of reading out every strip, we have reduced the number of channels required in this case, without compromising position resolution, by reading only every other strip and allowing charge from the intermediate, floating strips to be capacitively coupled to its neighbor.¹⁰ In order to do this without degrading nonlinearity, the capacitance to ground of the intermediate strips must be kept very small in relation to the strip-to-strip capacitance. The charge from each readout strip is collected by a charge-sensitive preamplifier; all of the preamplifier output signals are analyzed by the centroid finding electronics. The whole cathode is covered with a thin evaporated layer of chromium to keep the intermediate strips at a fixed μ C potential, but the strip-to-strip resistance is high enough (>20 M Ω) not to contribute significantly to preamplifier noise. The strip pitch, w_s , is 0.5 mm, with readout strips at 1 mm intervals. The noise from the preamplifiers then corresponds to ~ 20 μ m (FWHM) at an anode charge level of 0.1 pC.

This noise figure is, of course, inversely proportional to anode charge.

b) Diffusion

Effects of diffusion were generally very small compared to the limiting spatial resolution being measured, because of the small mean drift length in this detector (≤ 1 mm) and the large number of secondary electrons (> 200) produced by x-rays with energy greater than 5 keV. The gases under investigation were CH_4 , C_2H_6 , A/10% CH_4 , Xe/10% CO_2 and an approximate value of the fluctuation in anode avalanche centroid due to lateral diffusion of electrons can be obtained from the expression quoted by Gilvin *et al.*⁶ By far the greatest fluctuation occurs in A/10% CH_4 where calculation indicates diffusion effects are nearly 40 μ m FWHM at 5.41 keV, but they are a factor ≤ 0.5 smaller in CH_4 and Xe/10% CO_2 .

c) X-ray Beam

Measurements with the third detector were performed using an x-ray beam collimated to ~ 20 μ m width, and ~ 500 μ m height. In most other measurements, the collimation conditions were relaxed to ~ 32 μ m width and 1.3 mm height.

d) Detector Alignment

The detector was aligned with its window normal to the x-ray beam by using, to advantage, a result of angular localization of the anode avalanche.^{11,12} With reference to Fig. 1, if a narrow beam of x-rays is incident on the detector from directly above one of the anode wires, x-rays are absorbed both above and below this wire. The induced charge seen by, say, the window for events initiating an avalanche on top of the anode wire is slightly different in time development from that for events from below an anode wire; this physical difference is translated into a difference of cross-over time when the charge signal from the window is filtered by a suitable differentiating/integrating network.¹³ The window signals (from a charge sensitive amplifier followed by 0.5 μ sec Gaussian filtering) are shown by the upper trace in Fig. 2; long cross-over signals correspond to x-ray events absorbed in the upper half of the chamber, above an anode wire, and short cross-over signals correspond to events in the lower half of the chamber. If a stop signal is generated

Fig. 2. Signal waveforms used for "electronic alignment" of detector with respect to incoming photon beam.

from one or other of these two cross-over points, and an appropriately delayed start signal is derived from a prompt anode signal, two well-defined pulse height

distributions can be generated from a time-to-amplitude converter (TAC), as shown by the middle trace of Fig. 2. The TAC output provides the input to a single channel analyzer (SCA) where a suitable window allows one or other of the pulse height distributions to create a gating signal for the pulse height analyzer, or other input device, which analyzes the position signal from the detector. By alternate analysis of position signals from each half of the detector, the respective position peaks can be co-aligned by physical adjustment to the detector. This electronic technique allows the incident beam to be aligned to much better than 0.1 degree with the normal to the window, which translates into a parallax error of much less than 10 μm for this detector.

4. Results

Measurements were made with three main x-ray lines, $\text{CrK}\alpha$, $\text{CuK}\alpha$, and $\text{MoK}\alpha$; these are 5.41, 8.04, and (a mean of) 17.8 keV, respectively. Other energies were selected, less efficiently, by operating with an energy window on the continuum from the x-ray source. Figure 3 shows the spatial resolutions measured in the different gas mixtures.

Fig. 3. Photoelectron (and Auger electron) limited spatial resolutions for various energy x-rays in CH_4 ($\square$), C_2H_6 (Δ), A/10% CH_4 ($\bullet$), and Xe/10% CO_2 ($\circ$). Data points with circles around them are limiting spatial resolutions of escape peak events in the appropriate gas. All measurements are at atmospheric pressure and are uncorrected for the small contributions of other dispersive effects.

1) Hydrocarbon Gases

The data for methane and ethane fit a relation of the form:

$$\Delta p = \frac{k E_x^a}{\rho}$$

where Δp = FWHM(mm), E_x = x-ray energy (keV), ρ = gas density (gm l^{-1}), k and a are constants given in Table I. The limiting resolution for a given x-ray energy is approximately inversely proportional to gas density.

In these hydrocarbon gases, carbon is the dominant absorbing atom; its K shell binding energy is 0.28 keV. The kinetic energy, of the photoelectron, emitted after x-ray absorption, is ($E_x - 0.28$ keV), so nearly all of the x-ray energy is transferred into kinetic energy of one electron: Fig. 4a shows photoelectron energy as a function of x-ray energy for x-ray absorption by a carbon atom. The power law relationship of spatial resolution with x-ray energy is very similar to that of electron range with electron energy in metal absorbers.²

Most of these resolution measurements were of the order of a millimeter or greater and, as such, were the least difficult to ensure that position resolution was determined by electron range alone. However, they were also the most sensitive to the requirement that detector thickness be an order of magnitude larger than the measured resolution. Gross distortion of the position spectra occurred when this condition was not satisfied.

Figure 5 shows position spectra for $\text{CuK}\alpha$ x-rays in ethane: while these spectra are some way from being perfectly rectangular, the distribution predicted by the model outlined in Section 2, their shape is typical of all the results with FWHM ≥ 1 mm.

11) Argon/10% Methane

X-ray interactions occur primarily in the argon K shell; the fluorescence yield of this shell, w_K , is $\sim 13\%$.¹⁴ The anode pulse height spectrum from the detector contains, besides the main x-ray photopeak, a small escape peak which is formed when the fluorescent K shell photon ($E_x \sim 3$ keV, absorption depth in A/10% $\text{CH}_4 \sim 3.5$ cm) escapes from the detector. The two points for A/10% CH_4 in Fig. 3 with circles around them, are resolution measurements of the escape peak events from 5.41 and 8.04 keV x-ray interactions (performed with the aid of an appropriate gating signal from the anode energy spectrum). These two measurements, and those of the photopeak events at 12.5 and 17.8 keV, lie approximately on a (dashed) straight line. The 5.41 and 8.04 keV x-ray photopeak data deviate considerably, to better spatial resolution, from this line.

In all the x-ray photopeak events, the main components are a photoelectron and an Auger electron, energy ~ 2.7 keV, created by a radiationless transition in the x-ray absorbing argon atom to the K shell; Fig. 4b shows these two electron energies as a function of x-ray energy. (The residual energy of the excited argon atom, ~ 0.5 keV, is dissipated mainly by emission of other Auger electrons whose energy and range are negligible compared to those of the first Auger electron.) In photopeak events from x-rays with energy ≥ 12 keV, the photoelectron takes the bulk of the energy. In the two cases of escape peak measurements, the bulk of the escape peak energy is taken by the photoelectron. Thus the points on the dashed straight line for A/10% CH_4 are those in which only one electron has taken the majority of the energy, thereby resulting in a power law relationship of resolution with x-ray energy similar to the hydrocarbon gases.

In the 5.41 and 8.04 keV x-ray photopeak events, the x-ray energy is more evenly shared between two electrons: at 5.41 keV, Fig. 4b shows that the photoelectron and Auger electron energies are almost identical. Assuming that the emission distributions of both electrons are independent of each other, the centroid of ionization created by them will exhibit less positional variation than from one electron with energy equal to

Fig. 4. Photoelectron and Auger electron energies, as a function of x-ray energy, for x-ray absorption by a) carbon atoms, b) argon atoms, and c) xenon atoms.

iii) Xe/10% CO₂

Xenon gas mixtures are probably the most important for many experiments involving detection of x-rays. For the energy range used here nearly all x-ray interactions occur in the xenon L shell, giving rise mainly to a photoelectron, and an Auger electron (average energy ~ 3.6 keV) produced by a radiationless transition of the excited xenon atom to the L shell. Figure 4c shows the way in which energy is distributed between these two electrons as a function of x-ray energy. The residual energy of the excited atom, ~ 1.5 keV, is dissipated, in a similar manner to the excited argon atom, mainly by emission of further Auger electrons with negligible energy and range compared to the first Auger electron. For $E_x = 17.8$ keV, the photoelectron takes a major part of the x-ray energy. For $E_x = 8.04$ keV, the two electrons almost equally share most of the x-ray energy, and for $E_x = 5.41$ keV, the Auger electron receives the bulk of the x-ray energy. The measurements in Fig. 3 for Xe/10% CO₂ show that a minimum spatial resolution occurs at $E_x = 8$ to 9 keV, where the two electrons have about equal energy. The minimum experimentally measured resolution, for $E_x = 8.04$ keV, is $65 \mu\text{m}$ FWHM ($\sim 125 \mu\text{m}$ FWTM): the position spectra for this result are shown in Fig. 6.

Fig. 5. Position spectra for $\text{Cu}_{K\alpha}$ x-rays (8.04 keV) in C_2H_6 (linear vertical scale). FWHM = 1.1 mm.

that of their combined energy. Applying the ionization model for a single electron from Section 2 to a system of two electrons where one of the electron energies remains constant, it can be shown that the position variation is a minimum when both electron energies are equal.¹⁵ The (extrapolated) dotted line for argon in Fig. 3 shows how resolution will probably behave for 5.41 keV x-rays down to the energy of the A_K edge, 3.2 keV. Gradual degradation occurs because the Auger electron (whose energy is fixed) takes a progressively larger fraction of the x-ray energy.

The resolution discussion has ignored the small percentage of photopeak events in which the initial x-ray interaction has been followed by fluorescence in which the emitted photon has been absorbed in the detector gas. Because of the large absorption depth of this x-ray, the ionization centroids for such events will form a very low, extended background around the main position peak.

Fig. 6. Position spectra for $\text{Cu}_{K\alpha}$ x-rays (8.04 keV) in Xe/10% CO₂ (log vertical scale). FWHM = $65 \mu\text{m}$, FWTM $\sim 125 \mu\text{m}$.

The fluorescence yield of the xenon L shell, w_L , is very similar¹⁴ to w_K for argon, but the L fluorescent x-ray ($E_x \sim 4.4$ keV) has an absorption depth just under 6 mm in Xe/10% CO₂. Therefore only the thin, high resolution detector (2d = 1.6 mm) exhibited a prominent escape peak in its energy spectrum and it was only practical to perform a resolution measurement on the escape peak from 8.04 keV x-ray interactions, shown by the xenon point in Fig. 3 with a circle around it. This measurement (in which only the photoelectron takes the major part of the energy), and that for the 17.8 keV x-ray photopeak illustrate that single electron dominated resolution in xenon is lower than that in argon probably by a little more than the factor ρ_A/ρ_{Xe} . However, no quantitative assessment can be made without a wider energy range of x-ray measurements.

The most important point to emerge is that the best electron range limited resolution (for $E_x >$ energy of the Xe_L edge) appears to occur for $E_x = 8$ to 9 keV. The rate of degradation of resolution a few keV either side of this optimum energy region is small, but it is interesting to note that many biological and crystal diffraction experiments utilize the x-ray energy which provides minimum spatial resolution: the Cu_{K α} line at 8.04 keV.

5. Discussion

We have compared the experimental resolution measurements with electron ranges in the gas inferred from the generalized, semi-empirical electron range formula of Tabata *et al.*¹⁶ (which represents a best fit to many independent range measurements in solid absorbers). For methane the electron range curve lies almost parallel to the methane spatial resolution curve in Fig. 3, but is on average about a factor 1.2 higher, and for A/10% CH₄ the corresponding electron range curve is about a factor 1.5 higher than the dashed line for A/10% CH₄. Therefore the range of an electron in a gas that is deduced from range data for solid absorbers appears to be slightly larger than the limiting effect of such an electron on spatial resolution. For situations in which two electrons share the bulk of the x-ray energy, the limiting spatial resolution is considerably better than that expected from the power law behavior of single electron dominated resolution.

The next step in the experimental program is to increase the gas pressure so that electron range is reduced. For 8 keV radiation and with 3 to 4 atm. of Xe/10% CO₂, the 1.6 mm deep detector, outlined in Section 3, would produce an extremely high resolution detector with high efficiency and low parallax errors, which would be useful for several x-ray diffraction experiments using Cu_{K α} radiation. The results of photoelectron range on the spatial resolution at pressures greater than 1 atm. will be presented in a separate report.

TABLE I

Gas	k	a
CH ₄	$3.5 \cdot 10^{-2}$	1.78
C ₂ H ₆	$3.6 \cdot 10^{-2}$	1.77

for assistance with the high resolution detector and its electronics.

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