CERN LIBRARIES, GENEVA

CM-P00064257

CERN-PRE-77-153

ON SOME FACTORS CONTROLLING HIGH-ACCURACY MEASUREMENTS
OF X-RAY QUANTA POSITIONS WITH MULTIWIRED PROPORTIONAL CHAMBERS

G. Charpak and F. Sauli

CERN, Geneva, Switzerland

and

R. Kahn

Laboratoire d'Utilisation du Rayonnement Electromagnétique
(LURE), Orsay, France

Presented at the
International Conference on Synchrotron Radiation Instrumentation,
Orsay, France, Sept. 12-14, 1977
(Proceedings to be published in Nuclear Instrum. Methods)

Multiwire proportional chambers (MWPC) may provide a useful tool for dealing with many problems concerned with the localization of X-ray quanta. The accuracy in the determination of the spatial coordinates of a single quantum in a chamber is controlled by several factors:

- the spatial extension of the secondary electrons produced by the absorption of the quantum;
- the mean free path of the secondary X-rays emitted by the absorbing atom;
- the chamber parameters: detection thickness and wire spacing;
- the read-out method.

At LURE, we are trying to build large-size detectors, having a large angular aperture ($\sim 90^\circ$), accuracies better than 1 mm (FWHM), high counting-rate capabilities (~ 1 MHz), and high efficiencies ($\sim 100\%$ at 8 keV); in this paper we will discuss some problems encountered in this enterprise.

1. THE ABSORPTION PROCESS

At the X-ray energies we are concerned with, up to 30 keV or so, the dominant absorption process is the photoelectric effect. The conversion efficiency ϵ for a layer of thickness x can be conveniently expressed as a function of the mean free path for absorption λ , as given by

$$\epsilon = 1 - e^{-x/\lambda}.$$

The absorption length λ is specific to each material and depends on the photon energy. In Fig. 1 we have plotted the photoelectric absorption length for some noble and organic gases often used in proportional counters, at normal pressure and temperature (NTP)¹⁾. As an example, we can see that an 8 keV photon has a mean free path for absorption of about 6 mm in xenon and 50 mm in argon; for a given energy, the detector thickness and/or the gas composition have to be selected to obtain the desired efficiency.

The large step decrease in the absorption length when crossing each of the characteristic electronic shell energies has as a consequence that the largest fraction of quanta of energy E_x are absorbed in the layer of energy E_I ($I = K, L, M \dots$) just below E_x . The process results in the emission of a photoelectron of energy $E_1 = E_x - E_I$. Following the ionization, the excited atom or molecule returns to the ground state, and the excess energy can be radiated in one of two competitive processes: fluorescence or Auger electron emission. In the first process an internal rearrangement takes place with the emission of a cascade of

photons of energy corresponding to the difference between the energy levels; normally, only the first transition brings enough energy to concern us, resulting in a photon of energy $E_I - E_J$ ($E_J < E_I$), the so-called escape radiation. In the Auger process, instead, a pair of radiationless internal transitions occur with the emission of one electron of energy E_2 close to, but smaller than $E_I - E_J$ ²⁾.

The fraction of absorption processes resulting in the emission of photons, or fluorescence yield ω , is an increasing function of the absorber atomic number. Table 1 gives some experimental values of K- and L-shell fluorescence yields for several noble gases ³⁾:

Table 1

Fluorescent yield for
some noble gases

	Argon	Krypton	Xenon
ω_K	0.12	0.64	0.88
ω_L	$< 2 \cdot 10^{-4}$	$< 2 \cdot 10^{-2}$	0.11

The two competing processes contribute in a different way to the limiting accuracy of localization that can be achieved in a detector. The range in the gas of the electron (or the electrons) emitted produces a spread in the original charge distribution, while in the case of fluorescent decay the emitted photon can convert elsewhere in the detector volume.

1.1 Range of the photoelectrons and Auger electrons

As far as the first effect is concerned, it should be noticed that emission of the photoelectron occurs, at these energies, preferentially around a plane perpendicular to the incoming quantum direction. The subsequent multiple elastic and ionizing collisions with the gas molecules somehow randomize the primary electron trajectory, but a definite secondary charge asymmetry persists, and this contributes to the limiting accuracy. The practical range of electrons in the gas may be considered as a good limit of the charge asymmetry. Figure 2 shows the range-energy relationship for several gases at NTP, as computed from existing data in this energy range ²⁾. For example, in argon, X-rays of 5.9 keV will produce a photoelectron of 2.8 keV with a range of around 100 μm and, if no other effects were involved, this is roughly the limiting accuracy of localization we may expect to find.

Emission of an Auger electron obviously contributes to the asymmetrization of the detected charges, and is dominant when its energy is larger than the one of the photoelectrons. In Fig. 3 we have represented, as a function of incoming photon energy, the limiting accuracy we may expect in argon and xenon at NTP as being due to the emission of a photoelectron (curve labelled E_1), and in the case where an Auger electron appears (curve E_2 ; the probability of emission in this case is also indicated).

1.2 Emission of secondary photons

Things are more complicated when we take into account the X-ray emitted in a fluorescent decay. The mean free path of such a quantum in the emitting gas is rather long, its energy being just below an electronic shell edge, as is apparent from Fig. 1. Table 2 gives the value of the absorption length for the indicated fluorescent X-rays and the corresponding energies.

Table 2

Transitions	Argon		Krypton		Xenon	
	keV	mm	keV	mm	keV	mm
K_{α_1}	2.96	31.8	12.6	96	29.8	192
K_{β_1}	3.19	39.2	14.1	130	33.6	267
L_{α_i}			1.59	2.7	4.1	4.5
L_{β_1}			1.64	2.8	4.4	5.4

Depending on the characteristics of the detectors, the conversion of a fluorescent photon in the sensitive volume results in the rejection of the event or in a degraded spatial resolution. For example, using energy discrimination, it is possible to accept only events in the escape peak, thus eliminating the long-range secondary conversions. On the contrary, careful choice of a mixture of gases or use of pressurized detectors may limit the spread due to fluorescent quanta to within tolerable limits. Bateman et al.⁴⁾ have analysed these effects in great detail for a xenon-filled proportional counter and for energies around 40 keV, relevant to certain medical application.

In our range of applications, 5 to 20 keV, the dominant absorption process in xenon takes place in the L-shell, and the emitted X-ray, as from Table 2, has

a mean free path for absorption of about 5 mm; if it is not possible to discriminate the primary and the secondary charge, as is the case for gas counters in this range of spatial separation, the effect will produce a halo of events distributed around the real absorbing point. (As seen in Table 1, this happens in xenon in about 10% of the cases.)

2. METHODS OF MEASUREMENT OF THE CONVERSION POINT

The accuracy in the measuring of the interaction point of the converted X-ray quantum is dominated by two factors.

i) The amplification of the charges deposited in the gas occurs on thin anode wires with a finite wire spacing. The most convenient spacing is 1 mm for small-size chambers (below 20 cm) and 2 mm for large-size chambers (~ 1 m).

For a long time it was considered that the accuracy in the direction orthogonal to the anode wires could never be better than the wire spacing. We have shown that this is wrong in at least two cases: the case where there is charge-sharing between wires, and the case where the azimuth of the avalanches produced by a punctual photoelectron, around an anode wire, can be determined because of the high accuracy of the measuring method.

ii) The coordinate of the avalanches along the anode wires can be determined using the signals induced on cathode wires or strips orthogonal to the anode wires⁵⁾. Here only the photoelectron range and the avalanche asymmetry contribute to the limiting accuracy that can be achieved.

Many methods have been developed for this purpose⁶⁻⁹⁾. They rely either on special delay lines or various current division methods. Remarkable accuracies, of the order of 100 μ m, have been obtained for the coordinates along the wires for reasonably small chambers. Since because of their simplicity these methods are widely described in many publications, we will draw attention to the properties of the direct determination of the charge centroid of the avalanches which we are using¹⁰⁻¹²⁾. Figure 4 shows the principle of the method. Avalanches on a wire produce positive ions very close to the wire, since the mean free path for ionizing collisions is only of the order of one micron. In the very intense electric fields close to the wire, the positive ions are very fast and induce positive charges on all electrodes surrounding the anode wires: charges X_i and Y_i on the cathodes strips parallel and orthogonal to the anode wires, B and C in the neighbouring wires.

The centroid of the induced pulses $x = \sum x_i X_i / \sum X_i$ and $y = \sum y_i Y_i / \sum Y_i$ can be calculated either by a computer or by fast appropriate circuits in times of

the order of a microsecond. Several models of such circuits exist on the market. The remarkable features of this method are the following:

- it relies only on a local measurement: in other words it is independent of the chamber size;
- it gives the ultimate accuracy attainable in a chamber. The limitation comes from the noise of the amplifiers. We have found with cheap amplifiers ($\sim 3 \$$ each) that the electronics contributed to about $\sigma = 7 \mu\text{m}$ in the errors -- with better amplifiers it could be improved by one order of magnitude. However, at this level of accuracy we observe that the limitation comes essentially from real physical effects in the spatial extension of the charges to be localized.

A few examples¹²⁾ will illustrate the power of the method.

Figure 5 shows the centre of gravity determination on three parallel beams of 1.5 keV X-rays, 200 μm apart along the anode wire; with a xenon filling the accuracy is $\sigma = 35 \mu\text{m}$, corresponding almost entirely to the range of the photoelectrons.

In argon same measurement gives $\sigma = 45 \mu\text{m}$, thus showing at which level of accuracy the real physical extension of the charges is measured.

Figure 6 shows three beams, 500 μm apart, in the direction perpendicular to the wires: we see that although the accuracy is now degraded to $\sigma = 100 \mu\text{m}$, the beams are clearly distinct. The separation is better if we use the ratio B/C of the pulses induced on the neighbouring wires instead of the centroid.

For a uniform irradiation over a wire, a bidimensional image can be constructed plotting the B/C ratio on the abscissa, and the ratio of the pulse heights on the cathodes on the ordinate. The result is a ring-shaped distribution (Fig. 7), where each dot corresponds to the measured average position of the positive ion cloud asymmetry, in the plane perpendicular to the anode wire. For a uniform irradiation, and if the direction of arrival on the anode of the primary electron cloud is preserved as a strong asymmetry in the avalanche produced, this is just what could be expected.

The best illustration of the previous statements is the radiograph of a copper mask, with letters of 50 μm thickness cut into the copper (Fig. 8). The height of the letters is 1.5 mm. With 2 mm wire spacing in the chamber, and using avalanches on only one anode wire centred on the mask, we obtain a two-dimensional map.

We may then conclude that provided the gas filling and the geometry guarantee a correlation of 100 μm between a conversion point of a quantum and the centroid of its charge deposited in the gas, two-dimensional chambers with this spatial accuracy can be built.

What we have gained with this exceptional accuracy of the centroid method is, in addition to other advantages, a possibility of interpolation between wires in the absence of any charge-sharing between wires.

3. GEOMETRICAL FACTORS - DRIFT SPACES

The finite thickness of the absorbing medium introduces an error whenever the trajectories of the quanta are not perpendicular to the detector plane. For a given thickness, this limits the angular range acceptable from a point source. On the other hand, a maximum thickness is usually required for high efficiency.

Two solutions enable the difficulty to be overcome: high pressures or radial fields.

The first solution has been adopted by Cork et al.¹³⁾. With a thickness of 8 mm of xenon, at 5 bars, and a beryllium window of 0.1 mm thickness, they have realized a compromise between all these requirements in a flat chamber of $20 \times 20 \text{ cm}^2$. The beautiful results obtained by this group with this chamber are certainly a strong incentive to try to overcome the difficulties related to geometry and to try to reach higher accuracies with larger angular apertures, which is the aim of the second solution¹⁴⁾.

The quanta are absorbed in a drift space that is thick enough to ensure nearly 100% efficiency. The electric field in this space is radial and diverges from a point where the sample is located (Fig. 9). The ionization electrons drift along the lines of force and are transferred to a MWPC through the grid electrode and then localized. The radial fields can be produced by spherical windows and grids, or by suitably printed electrodes; this is under investigation. The parameters of our first operative chamber are:

entrance window: 18 cm radius; 40 μm thick Al window

exit grid: 28 cm radius, stainless steel

drift length: 10 cm

angular aperture: 87° .

The preliminary study revealed quite interesting features. Drifting of the ionization electrons over distances of 12 cm to 17 cm to the MWPC did not degrade the accuracy but improved it. The charge cloud, having an initial size of $\sim 200 \mu\text{m}$, is expanded to a size greater than the wire spacing of 2 mm; this charge-sharing allows interpolation of the position of the charge centroid between the wires, thus yielding a continuous response in all directions.

We obtained an accuracy of 0.8 mm (FWHM) in all coordinates, even at angles as large as 40° , with 0.5 mm contributed by our electronic analogue method of reading out the charge centroid in times of the order of 5 μsec .

This study revealed that large-size chambers (one or more square metres), of the type used in high-energy physics, can be built for this purpose and can yield a great accuracy. This would make possible the use of large chambers in the cases where large-cell crystals have to be used. For such applications, radial fields produced by printed circuits on flat entrance windows may be more practical and will be investigated.

4. RATE LIMITATIONS

Very high rates, such as 10^7 counts/sec, are frequently encountered in high-energy physics, where usually every anode wire is connected to a separate counter. The analogue methods usually used to read out the coordinate along the wire rarely permit rates above 100 kHz. However, it is possible to design various digital methods to read out the cathode wires with much higher rates. There is, however, a limitation intrinsic to the chamber, due to the space charge of the positive ions left behind by the avalanches¹⁵). These ions create a dead region of long duration (~ 20 μ sec) and an extension of about 0.2 mm along the wire. At rates of about 10^4 sec per millimetre of wire they begin to introduce a substantial loss of amplifications, 50% or more.

In diffraction patterns where intensities of weak and intense spots have to be measured with an accuracy of a few percent, this is a factor which should be taken into consideration. Let us assume that 10^6 photons sec^{-1} scattered by a crystalized protein are collected on the chamber. About 2×10^5 photons sec^{-1} are localized in the diffraction spots; the remaining 8×10^5 photons sec^{-1} due to thermal scattering, Compton scattering, and above all scattering by the glass capillary and the mother liquor, are distributed over all the chamber. If we assume a dynamic range of 1 to 100 between intensities of some hundreds of diffraction spots occurring simultaneously, the most intense reflections correspond to a mean rate of about 10^4 photons sec^{-1} , and this is more or less the limit at which an efficient detection can be made.

At this rate, a data collection system could measure about 10^4 Bragg reflexions hour^{-1} .

5. CONCLUSION

From the research undertaken to build large-aperture, highly accurate, efficient detectors for photons in the energy range around 10 keV, we may conclude that apertures of the order of 90° , accuracies of the order of 1 mm, efficiencies of 90%, and rates of the order of 1 MHz are difficult but possible goals which we should be capable of attaining in the near future.

REFERENCES

- 1) Data for noble gases are taken from W.H. McMaster, Compilation of X-ray cross-sections, UCRL-50174 (1969); for the organic compounds, the absorption has been computed using data for the constituents from the same source.
- 2) See for example: I. Bergström and C. Nordling, The Auger effect, in alpha-, beta- and gamma-ray spectroscopy (ed. K. Siegbahn) (North Holland Publ. Co., Amsterdam, 1968), p. 1526.
- 3) Computed from existing data on light elements, as reviewed by H. Kanter, Phys. Rev. 121, 461 (1961).
- 4) J.E. Bateman, M.W. Waters and R.E. Jones, Nuclear Instrum. Methods 135, 235 (1976).
- 5) G. Charpak, D. Rahm and H. Steiner, Nuclear Instrum. Methods 80, 13 (1970).
- 6) R. Grove, L. Lim, V. Perez-Mendez and J. Sperinde, Nuclear Instrum. Methods 89, 257 (1970).
- 7) D.M. Lee, J.E. Sobottka and K.A. Thiessen, Nuclear Instrum. Methods 104, 179 (1972).
- 8) C.J. Borkowski and M.R. Kopp, Rev. Sci. Instrum. 46, 951 (1975).
- 9) V. Radeka, IEEE Trans. Nuclear Sci NS-21, 51 (1973).
- 10) G. Charpak, A. Jeavons, F. Sauli and R. Stubbs, CERN 73-11 (1973).
- 11) A. Breskin, G. Charpak, C. Demierre, S. Majewski, A. Policarpo, F. Sauli and J.C. Santiard, Nuclear Instrum. Methods 143, 29 (1977).
- 12) G. Charpak, G. Petersen, A. Policarpo and F. Sauli, Progress in high-accuracy proportional chambers, submitted to Nuclear Instrum. Methods, July 1977.
- 13) C. Cork, D. Fehr, C. Hamblin, W. Vermon, W.N. Yuong and V. Perez-Mendez, J. Appl. Cryst. 7, 719 (1974).
- 14) G. Charpak, Z. Hajduk, A.P. Jeavons, R. Kahn and R.J. Stubbs, Nuclear Instrum. Methods 122, 1307 (1974).
- 15) F. Sauli, Principles of operation of multiwire proportional chambers CERN 77-09 May 1977, p. 67 ff.

Figure captions

- Fig. 1 : Photoelectric absorption length in some gases.
- Fig. 2 : Electrons range-energy relationship in some gases.
- Fig. 3 : Limiting accuracy in gas counters as a function of photon energy. Limitation of the accuracy by the range of the photoelectrons, at TPN (E_1) and the emission of Auger electrons (E_2).
- Fig. 4 : Measurement of the charge centroid of induced pulses:
- a) The cathodes are made of wires connected in strips. The pulses induced on strips close to the avalanche and on neighbouring wires are used to calculate the charge centroid.
 - b) Coordinate system.
- Fig. 5 : Accuracy along the wire. Three beams of 1.5 keV X-rays 200 μm apart.
- Fig. 6 : Accuracy between wires.
- Three beams of 5.9 keV X-rays, one centred on an anode wire, the other two 500 μm on each side:
- a) Ratio B/C on neighbouring wires.
 - b) Centroid.
- Fig. 7 : Distribution of the centroid of avalanches around an anode wire.
- Abscissa : ratio B/C
- Ordinates: ratio of the total charges induced on the two cathodes.
- Fig. 8 : Bidimensional radiograph from a single wire.
- Letters of 1.5 mm height, 50 μm width, cut out in a copper mask.
- Beam of 1.5 keV X-rays.
- Anode wires 2 mm apart.
- Fig. 9 : The spherical drift chamber.
- Drift space of 10 cm
 - Entrance window: radius of 18 cm, 40 μm Al
 - Exit window : radius of 28 cm, stainless-steel grid
 - Useful aperture: 87°

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

CERN

Fig. 8

Fig. 9