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Pressure effect in the X-ray intrinsic position resolution in noble gases and mixtures

C.D.R. Azevedo,[a,1] P.M. Correia,[a] D. González-Díaz,[b] S. Biagi,[c] A.L.M. Silva,[a] L.F.N.D. Carramate[a] and J.F.C.A. Veloso[a]

[a] *I3N - Physics Department, University of Aveiro*
Campus Universitário de Santiago 3810-193 Aveiro, Portugal
[b] *CERN*
CH-1211 Geneva 23, Switzerland
[c] *Uludağ University, Faculty of Arts and Sciences*
Physics Department, Bursa,Turkey

E-mail: cdazevedo@ua.pt

Abstract: A study of the gas pressure effect in the position resolution of an interacting X- or gamma-ray photon in a gas medium is performed. The intrinsic position resolution for pure noble gases (Argon and Xenon) and their mixtures with CO_2 and CH_4 were calculated for several gas pressures (1-10 bar) and for photon energies between 5.4 and 60.0 keV, being possible to establish a linear match between the intrinsic position resolution and the inverse of the gas pressure in that energy range.

In order to evaluate the quality of the method here described, a comparison between the available experimental data and the calculated one in this work, is done and discussed. In the majority of the cases, a strong agreement is observed.

Keywords: Gaseous detectors; Gaseous imaging and tracking detectors; Charge transport and multiplication in gas; Detector modelling and simulations I (interaction of radiation with matter, interaction of photons with matter, interaction of hadrons with matter, etc)

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[1] Corresponding author.

Contents

1 Introduction

Previous works have shown that the intrinsic position resolution for X and gamma-ray detection in a gas medium depends mainly on the photon energy and on the gas choice [1]. Moreover, it shows that the position resolution reaches a minimum value when the photon energy is slightly higher than the atom K-shell energy of the gas.

The main drawback when using gas as radiation detection medium arises from the low photon detection efficiency. The most usual way to overcome this problem is to increase the gas pressure, thus increasing the number of gas atom/molecules per unit volume. Also, the pressure increase will benefit the energy resolution and light production when electroluminescence measurement is needed [2–4]. It is expected that the pressure increase will reduce the electrons diffusion in the gas medium, which will in turn result in a better position resolution when compared to the value obtained at atmospheric pressure [5, 6]. Nevertheless, secondary effects such as X-ray fluorescence process, can play a major role on the position resolution, thus improving or degrade the resolution value depending on the geometry [1].

Experimental measurements have shown that the increase of gas pressure leads to an improving of the position resolution [2, 7, 8], however the measurement technique relies on detectors where the position resolution measured depends on the detector gain and on the electron diffusion in the gas. Thus, in order to decouple the position resolution from the detector gain, the intrinsic position resolution of pressurized pure noble gases (Ar and Xenon, in the pressures range 1-10 bar) was calculated, studied and compared with the available experimental data.

In order to compare the obtained simulated results with the available experimental data [7–9], mixtures of pure noble gases with molecular VUV-quenchers, namely CO_2, and in the case of Ar, also with CH_4, were included in this study.

2 Method

For the calculations a software tool which includes secondary processes like X- ray fluorescence, Auger, Coster-Kronig and Shake-off was used: Degrad [10]. This software tool, developed by S. Biagi, is at the moment able to calculate the atomic cascade initiated by X-ray photons or electrons interacting in the gas, returning the number of ionizations, excitations and the position of each thermalized electron [11].

For each simulated interaction, the detection position was defined as the center-of-gravity of the generated charge. In the absence of a detailed topological analysis of the ionization trails (as, e.g. in [12], such a definition likely represents the ultimate accuracy limit in most practical X-ray gas detectors.

An image of the obtained centroid positions of each individual charge cluster was constructed and an analysis chain similar to the method present in [1] was applied to the results. The position resolution was taken as the Full Width at Half Maximum (FWHM) of a Gaussian function fitted to the projected data of the constructed image, following the Line Spread Function (LSF) method used in [13].

For each condition, 500.000 events were generated using Degrad2.13. All the events were considered to interact in (X,Y,Z)=(0,0,0) in order to simulate an infinitesimal point-like interaction. An electric field of 300 V.cm^{-1}.bar^{-1} was considered. The gas temperature was set to 20 ^{o}C and, in order to speed up the calculations, the electrons were considered thermalized when their energy follows 1 eV bellow the lowest excitation energy of the main gas in the mixture. Compton events are negligible for the studied energy range, therefore they were not considered in the analysis.

3 Results and discussion

The position resolution in pure Noble gases and their mixtures with CH_4 and CO_2 (Ar/10%CH_4, Ar/20%CO_2, Ar/30%CO_2, Xe/10%CO_2, pure Argon and pure Xenon) in pressures ranging from 1 to 10 bar for photon interactions with energies between 5.4 and 60.0 keV were calculated considering an infinite gas volume. Figure 1 presents the obtained results(where error bars are smaller than the data point size) plotted as function of the inverse of the pressure. By fitting the data with a linear function (dashed lines) it becomes clear the linear relation between the calculated position resolution and the inverse of the gas pressure, as already referred in [7].

$$FWHM \propto \frac{1}{P} \tag{3.1}$$

This demonstrates that it becomes possible to calculate the position resolution for a given pressure by just dividing the position resolution value at 1 bar (see results in [1]) by the pressure value.

Another exercise is to multiply the position resolution by the pressure value: the calculated data points will be overlaid for all the pressures. That assumption is verified in Figure 2(a) and plotted as a function of the photon energy. In this plot we can also observe a small degradation of the position resolution depending on the fraction of quencher in the gas mixture.

The explanation for the data curves profile shown in Figure 2 are explained in ref [1] and are related to the K and L shells of the used gas.

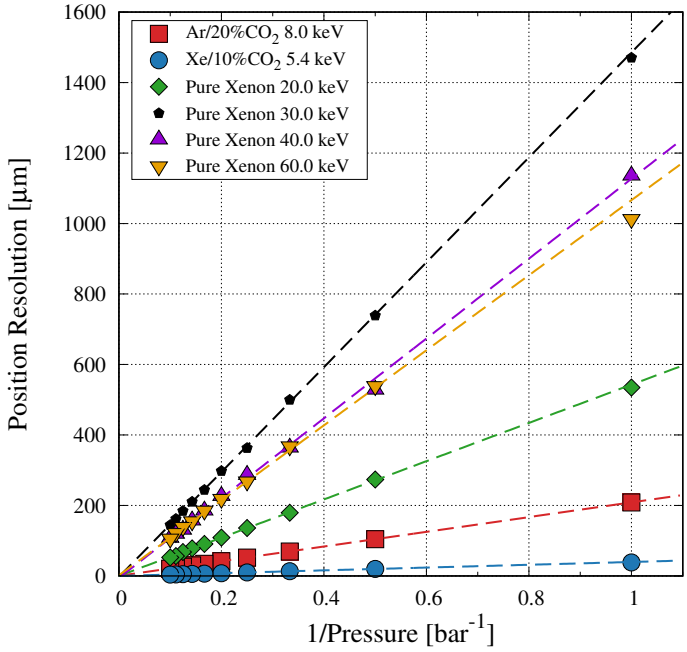
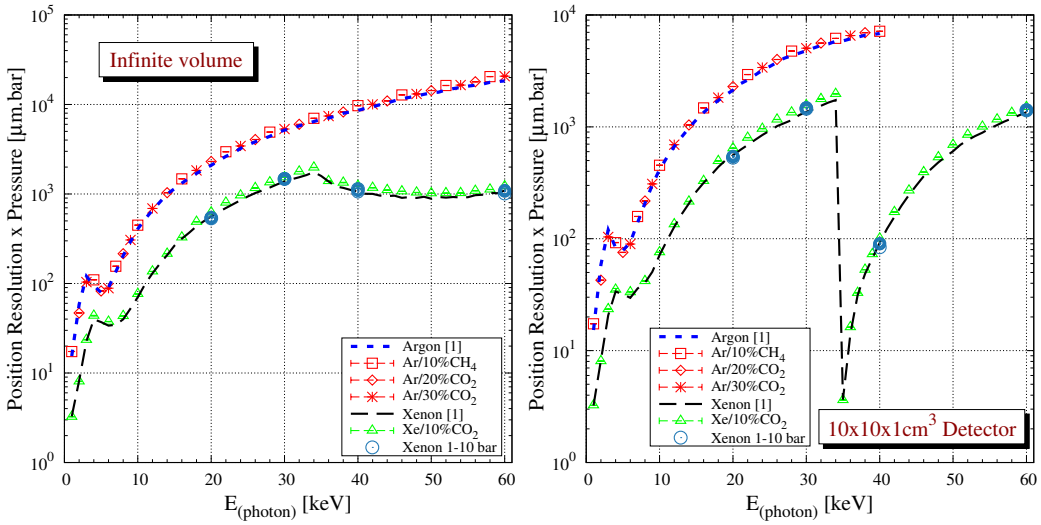


Figure 1. Position resolution as a function of the inverse of the pressure for different photons in Argon and Xenon mixtures with CO_2, considering an infinite volume. Dashed lines are the fits of a linear function to the calculated data points.



(a) (b)

Figure 2. Position resolution multiplied by pressure value as a function of the photon energy for: a) an infinite volume; b) 10x10x1 cm^3 detector. All data points, except (open circles O), were obtained at 1 bar.

In order to infer if this scaling still valid for a finite gas volume, calculations were performed on a typical volume of 10x10x1 cm^3 volume. The results are presented in Figure 2(b) where the $1/P$ scaling can be again observed by multiplying the position resolution by the pressure value. A minor degradation of the position resolution value dependence with the fraction of quencher in the gas mixture is again observed for the used energy range.

4 Comparison with experimental data

The calculated results for a 10x10x1 cm^3 volume were compared with the available experimental data for Xe/10%CO_2 and Ar/20%CO_2 from ref [7] and are shown in Figure 3.

It can be observed a good agreement between the experimental and the calculated data for Ar/20%CO_2 mixtures. The slightly better values achieved in the simulation can be explained since we are just calculating the intrinsic gas position resolution, i.e., other parameters like the electron diffusion in gas along the drift distance were not taken into account.

For Xe/10%CO_2 the experimental and calculated data are not in as good agreement compared to the previous mixture, mainly due to the experimental data deviation from the $1/P$ behaviour. In fact the experimental data follows the inverse of the pressure square-root showing that the position resolution for such small values is being dominated by the electrons diffusion in the gas [5] (that was not taken into account for the calculations). This is also one of the reasons for the deviations pointed in [7] where the authors expect a value of 6 μm for the position resolution, which is in accordance to our calculations. In Figure 3(b) is also shown the experimental values corrected to the diffusion effect (closed data points) by multiplying the data by the square root of the pressure. In this case we can observe a good agreement between the experimental corrected data and this work for both, 8.0 keV and 5.4 keV photons. We believe that this fact could be again being related to experimental conditions.

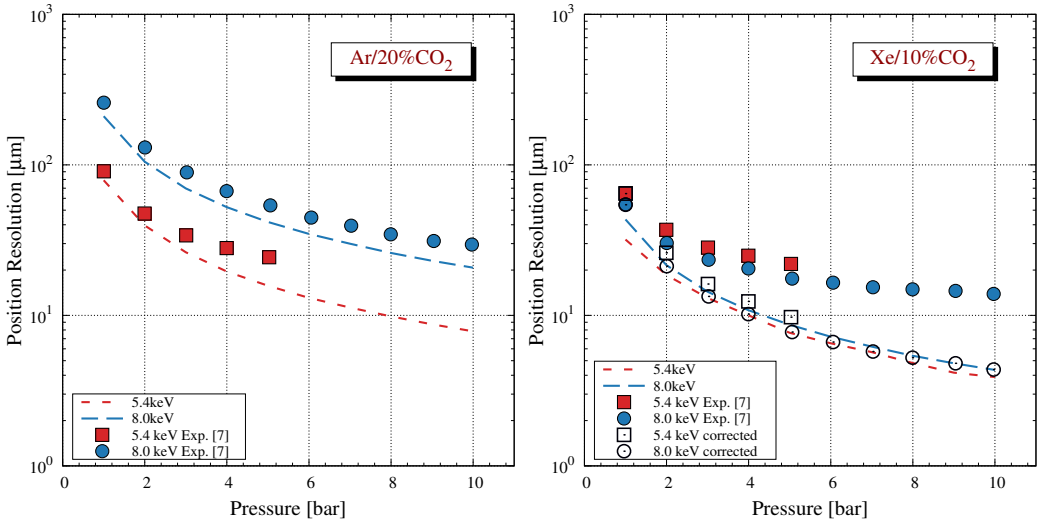
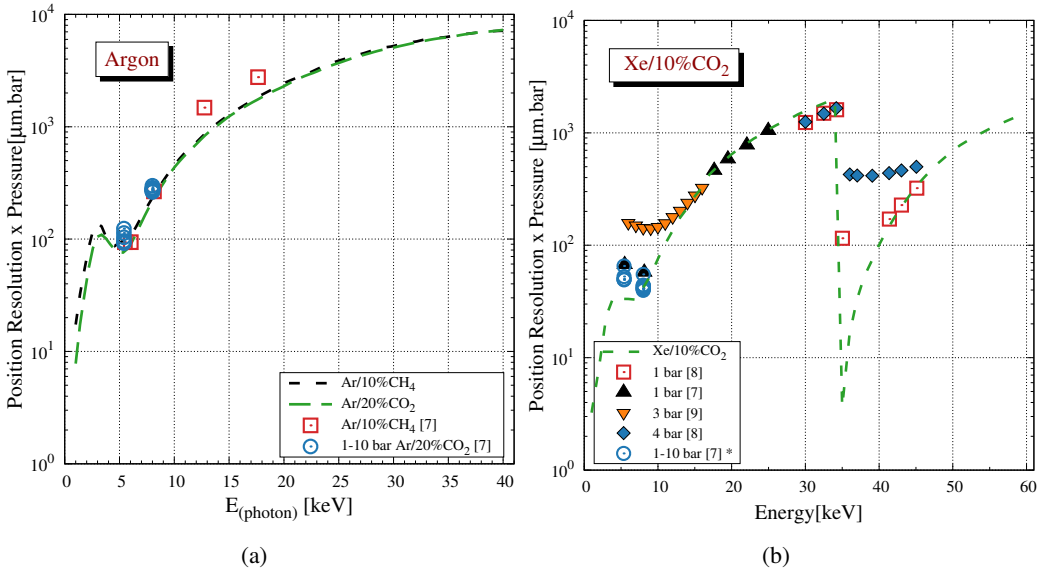


Figure 3. Position Resolution multiplied by the pressure as a function of photon energy: a) Argon/20%CO_2; b) Xe/10%CO_2. Lines are calculations at 1 bar (this work) while points are experimental results from [7–9]

The experimental position resolution data from Figure 2(b) and Figure 3(b) (corrected values) plus the data obtained in refs [8, 9], were multiplied by the pressure and are presented in Figure 4. Again, a good agreement between the calculated and the experimental data is observed, with exception for low energy photons. This can be explained by the experimental limitations: low energetic photons present low signal-to-noise ratios and are affected by the electronic noise, thus degrading the position resolution as explained in [7]. As the photon energy increases, the signal-to-noise ratio also increases, improving the agreement (Figure 4(b), 3 bar experimental data set - ▽). Another difference between both data is observed after the Xenon K-shell (34.6 keV). For the 1 bar data set the explanation is the same as pointed before. After the K-shell, the photoelectron kinetic energy will decrease leading to the emission of a fluorescence photon that has high escaping probability for relatively slim detectors, thus degrading the position resolution. This means that, in such case, the detector will only detect the small energy of the photoelectron being again affected by the electronic noise. When the photon energy further increases the position resolution will approach the intrinsic: 1 and 4 bar data sets (□,◇) in Figure 4(b). The values for the experimental data sets 1-10 bar (O) in Figure 4(b) were deconvoluted from the electron diffusion prior to the multiplication by the pressure (see Figure 3(b) discussion).



(a) (b)

Figure 4. Position Resolution multiplied by the pressure as a function of photon energy for: a) typical Argon mixtures; b) Xe/10%CO_2. Lines are calculations at 1 bar (this work) while points are experimental results from [7–9]. *The experimental values in b) were deconvoluted from the electron diffusion prior to the multiplication by the pressure.

5 Conclusions

This work presents the influence of the gas pressure on the intrinsic position resolution for pure Ar, Xe and mixtures with CO_2 and CH_4. A linear behavior between the position resolution and the inverse of pressure was observed for pressures between 1-10 bar and for photon energies ranging from 5.4-60.0 keV.

A minor position resolution degradation when using mixture with CO_2 percentages as high as 30% was also observed.

A good agreement between the calculated and experimental data was observed. In the case of Xe/10%CO_2 mixtures, deviations from the experimental data were observed, explained by the electron diffusion in the experimental data, that was not taken into account during the calculations.

For low energy photons, the deviations between experimental and calculated data are explained by the influence of the signal-to-noise ration and its influence on the degradation of the experimental position resolution.

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