CERN-EP/80-55
28 April 1980

SCINTILLATION EFFICIENCY OF GAS PROPORTIONAL SCINTILLATION COUNTERS

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ABSTRACT

The photo-ionization proportional scintillation chamber, that couples a pure noble gas scintillation counter to a photo-ionizing gas multi-anode proportional chamber, allows both a very good energy resolution and an accurate space localization of ionizing radiation to be obtained. This paper describes a calculation, based on the known detector parameters and on the measured energy resolution, that allows the estimation of the scintillation efficiency in the secondary light emission process. For krypton the efficiency is estimated to be $97 \pm 20\%$, implying that most of the energy available from the external field is radiated by the electrons as secondary scintillation since kinetic energy losses are small. The relevance of such a result, especially when compared with the values obtained for xenon and argon, is also discussed.

(Submitted to Nuclear Instruments and Methods)

1. INTRODUCTION

The ultraviolet (UV) light emission of noble gases and their mixtures corresponding to their excitation by drifting electrons under an electric field in the absence of charge multiplication is the basis of the gas proportional scintillation counter. The performance of these detectors has been studied and they are finding wide applications in several fields of science mainly because of favourable characteristics concerning energy resolution.

The same process combined with the spatial resolution capabilities of the multiwire proportional chambers led to the development of the photo-ionization proportional scintillation (PIPS) detector^{1,2)}. It features good energy and space resolutions, good multihit capabilities, large areas of detection and stability of operation.

In parallel with detector development the mechanism of proportional scintillation in noble gases had also received attention^{3,4)}, although much research should still be carried on especially concerning this process in mixtures of noble gases and for wider variations of pressure and electric fields⁵⁾. In particular an important parameter relevant to the physics of the process, dependent both on its mechanism and on the distribution function of the migrating electrons, is the efficiency with which the energy supplied by the electric field is converted into excitation of the medium, atomic excitation in the case of noble gases. It is the aim of this work to give details of some data concerning this parameter.

2. EXPERIMENTAL TECHNIQUES

The measurements were made in a device very similar in structure to that described in a preliminary paper²⁾, but where clean materials and gases were used (Fig. 1). It is essentially a PIPS detector, the gas proportional scintillation counter (GPSC) being coupled to a photo-ionization detector (PID) by a LiF window. To avoid reflections from the top part of the detector, just above the absorption region brass was the material used, and a well collimated beam of 5.9 keV X-rays

was admitted into the counter through a small mylar window in its centre. The absorption and scintillation gaps, the last one being 1 cm wide, defined by well stretched grids, were supported by teflon insulators, the last grid being 1 mm above the LiF window. The GSPC container was built in aluminium and the usual requirements of purity associated with this type of detector were maintained. The filling gas, krypton at 1 atm, was continuously circulated through a purifier (calcium turnings at 380 °C) and through the detector in a closed circuit. The PID was operated with a mixture of argon, triethylamine (TEA) and methane in a flow regime^{6,7)} and is described in detail in Ref. 2; for a wide range of low concentrations of TEA and methane the efficiency of detection of photons was constant, typical values of the concentrations being $\sim 3\%$ and $\sim 10\%$, respectively. The detector was bombarded simultaneously with 5.9 keV X-rays from two collimated and filtered ^{55}Fe sources, one beam directed into the GSPC and the other into the PID. Pulses are taken from the latter detector through a charge amplifier and the ratio of mean pulse heights corresponding to X-ray interactions in the GSPC and in the PID defines the transfer efficiency t . In the determination of t as a function of the voltage across the scintillating gap, two criteria were used to assure that charge multiplication was absent: the linearity of this function and the appearance of a decreased resolution with increasing voltages above a critical value. Indeed, a faster than linear rise of t and a deterioration of the energy resolution are associated with the threshold for charge multiplication.

3. DATA ANALYSIS AND DISCUSSION

Let L be the number of photoelectrons in the PID per electron produced in the GSPC, H the number of photons produced by one electron migrating in the scintillating gap, and T the number of electrons in the PID arising from one photon. Then $L = HT$ and, in the described conditions, $\bar{H} = (w_1/w_2) (t/\bar{T})$, where w_1 and w_2 are respectively the mean energy to make an ion pair in the gas fillings of the GSPC and the PID, independent of the energy deposit and of the charge gain of the PID. The scintillation efficiency at a certain voltage V (in volts) across the scintillating gap is then defined as $\epsilon = \bar{H}U/V$, where U (in eV) is the mean energy

associated with inelastic collisions. From the practical point of view the scintillation efficiency will be quoted at its maximum value, just before charge multiplication. The energy per ion pair in krypton w_1 is taken as 24.3 eV⁸⁾; unfortunately no information is available concerning w_2 . The mean energy to make an ion pair in pure argon is $w_2 = 26.2$ eV⁸⁾, and this value decreases by $\sim 1\%$ when 5% of CH₄ is added. This small effect is considered to be due to the ionization of methane by highly excited states of argon, more important effects being associated with contaminants ionizable by the metastable state of argon, like acetylene and ethylene, for which the maximum decrease in the mean energy to make an ion pair is, respectively, 26% and 11%⁹⁾. TEA is also ionizable by the metastable states of argon, and then a reasonable guess for w_2 is 23 ± 2 eV.

Let us now consider the calculation of $\bar{T}$. For fixed gas fillings, pressures and applied electric fields, and for a certain structure of the PIPS detector, as a first step $\bar{T}$ is determined by the spatial distribution of the photon sources. This spatial distribution is itself determined by several factors: collimation of the beam of X-rays, nature of the interaction processes that lead to the energy deposition in the counter, diffusion processes associated both with migration of electrons on the absorption and on the scintillating gaps and, with much less relevance, diffusion processes associated with the formation of the dimers responsible for the light emission⁴⁾. A second step arises concerning the transmission of the photons through the LiF window and the grids, function of the angle of incidence of the photons, the spectral distribution of UV light from krypton and the variation of the transmission of the window with wavelength. The third step, photoelectric interactions in the PID, is conditioned by the mean free path of the photons, its spectral distribution, and the variation of photo-ionization efficiency with wavelength. In krypton, 5.9 keV X-rays interact mainly on the L shell and the mean value of its fluorescence yield is 0.021 ± 0.002 ¹⁰⁾. To 98% of the events corresponds then an energy deposition that is spatially determined essentially by the range of 4.2 keV electrons. The practical range [for its definition see the paper by Williams¹¹⁾] of these electrons in krypton at atmospheric pressure is $\sim 200 \mu\text{m}$ ¹²⁾.

Concerning diffusion effects and using the values of the diffusion coefficient transverse to the field given in the paper by Lowke and Parker¹³⁾ the standard deviation arising from this process is $\sim 150 \mu\text{m}$. It is then reasonable to take full account of the spatial distribution of the photon sources by assuming that it corresponds to a Gaussian distribution with standard deviation of $300 \mu\text{m}$ for a 5.9 keV X-ray beam of negligible diameter.

Recently the emission spectra from krypton as observed through a LiF window were determined⁴⁾. This spectrum was corrected assuming average behaviours for the transmission of the LiF window for the reflection of the diffraction grating of the UV monochromator and for the detection efficiency of sodium salicylate, used in the experiment quoted¹⁴⁾, and these two spectral distributions are considered to be reasonable limits for the spectral emission from krypton. The transmittance of the LiF window used in this experiment was determined⁷⁾ and from the behaviour of n with λ for LiF, the variation of its attenuation length with λ was calculated. The data on the variation of the photo-ionization efficiency of TEA with λ , as quoted in Ref. 6 is too high by a factor of 1.3, although small errors are associated with its relative values⁷⁾. A value of $37 \pm 5\%$ for the peak efficiency of TEA was assumed in the calculations. The mean free path for the photons in the PID was taken on the basis of an absorption cross-section above the ionization threshold of $\sim 50 \text{ MB}$.

Taking into account the above considerations and the geometry of the set-up used for the measurements, $\bar{T}$ was determined to be 0.023 ± 0.003 , using a Monte-Carlo simulation. Excluding the error in the peak efficiency of TEA, of the order of 13%, the error in $\bar{T}$ is $\sim 5\%$. Such a small error is mainly due to the fact that, within 3%, the window used, of 25 mm radius, behaves essentially as an infinite window even for a diameter (FWHM) of the column that corresponds to the source of the photons of 2.4 mm, on account of the large increase of reflectance and light paths with angle of incidence, for large angles. Then the highest $\bar{H}$, mean number of photons produced by one electron, before charge multiplication, at $V = 3600$ volts (gap widths of 1 cm) is 340 ± 60 , corresponding to a measured t -value of 7.5 ± 0.5 .

The three-body collisions responsible for proportional scintillation in krypton at atmospheric pressure in the absence of charge multiplication, involve directly the atomic states 3P_2 and 3P_1 , but all 1s states of Paschen are likely to be involved¹⁵⁾. Higher excited states are not populated, this being essentially due to the fast decrease with energy of the distribution function of the migration electron as, in similar conditions of pressure, the emission associated with rare gas discharge shows clearly the atomic lines corresponding to those states⁴⁾. Then for U, the mean energy involved in an inelastic collision, a mean value is taken of the energies of the 3P_2 , 3P_1 , 3P_0 and 1P_1 states, the error being less than 5%. For krypton $U = 10.2$ eV and then the maximum scintillation efficiency is $\epsilon = 97 \pm 20\%$.

4. CONCLUSION

There are no previous measurements concerning the scintillation efficiency of krypton or any other data that could give reliable information on this parameter. On the other hand, several results have been obtained for xenon: a value of $\sim 3\%$ is implied by the data of reference 16, a more recent compilation gives a scintillation efficiency of $\sim 20\%$ ¹⁾ and the last results^{17,18)} correspond to values of 58% and 50%. The highest value, 75%, is implied by the data of Andresen et al.¹⁹⁾. This largest value was obtained without the use of wavelength shifters and in very good conditions of purity.

Reference 1 compares light outputs from xenon, krypton and argon before charge multiplication, at atmospheric pressure, for the same energy deposition, and the ratios 100:40:7 are quoted. Nevertheless, these results correspond to data obtained with the thickness of the wavelength shifter optimized for xenon and in contact with the scintillator, were of a technical nature and, in view of the measured efficiency of 75% for xenon¹⁹⁾ and $97 \pm 20\%$ for krypton, they imply that a study of argon in good conditions of purity is needed. The situation now is that the scintillation efficiencies of krypton and xenon reach large values, in agreement with theoretical estimates, but the generally accepted low light output of argon implies a clear disagreement with the predicted estimate of the

order of 80% ²⁰). The situation is made worse by the fact that the mechanism leading to light emission by noble gases excited by drifting electrons at several hundred Torr is now well established.

Experimental and theoretical studies of the electron distribution functions and of the mechanism of light emission, especially pressure dependence, are needed both from the point of view of understanding the processes, and also because only then is it possible to predict and control the relevant detector developments. After all, from the very beginning, xenon has been the only scintillator whose properties have been more or less fully exploited. The use of other noble gases and possibly their mixtures is an almost open field from the point of view of optimizing energy, position and time information.

Acknowledgements

Financial help from Instituto Nacional de Investigacao Cientifica and Junta Nacional de Investigacao Cientifica y Tecnologica (Portugal) is acknowledged.

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Figure caption

Fig. 1 : The photo-ionizing proportional scintillation chamber. A pure noble gas scintillation counter is coupled, through a LiF window, to a multi-anode proportional chamber; in the drawing, dashed lines represent crossed wire meshes and the dots anode and cathode wires. The ionizing radiation (soft X-rays) is absorbed in the low-field gas volume between grids 1 and 2, and the liberated electrons induce secondary light emission in the high field region between grids 2 and 3. Some of the emitted photons traverse the window and photo-ionize the gas in the lower chamber, where photoelectrons are detected after a conventional avalanche amplification.

Fig. 1