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Detection Efficiency of Position-Sensitive Proportional Counter for Low (100-1000 eV) and High (1-100 keV) Energy X Rays

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In the high-resolution X-ray spectroscopy, position-sensitive proportional counters (PSPC) have often employed to determine the position of X-rays diffracted by single crystals. In order to design the PSPC available in various energy regions of X rays, the detection efficiency has been systematically estimated from an approximate formula, in which the attenuation of photons in window material and the absorption of photons in counting gas are taken into accounts. The estimations have been performed for three window materials (Mylar film, polypropylene and beryllium plate) and seven counting gases (CH_4, C_2H_6, C_3H_8, C_4H_{10}, Ar + 10%CH_4, Kr + 10%CH_4 and Xe + 10%CO_2); results are obtained as functions of energy of X rays and pressure of counting gas.

KEY WORDS: Proportional Counter/ Position-Sensitive/ X rays/ Detection Efficiency/

1. INTRODUCTION

We have been developing position-sensitive proportional counters (PSPC) of two different types, which are used for flat crystal X-ray spectrometers: the counter of one type is mainly sensitive for soft X rays (100-1000 eV)[1,2] while that of the other type is sensitive for X rays with higher energies (1-60 keV).[3,4] The structures of those PSPCs are different according to the energy region of X rays to be detected. Materials with low-Z elements such as hydrogen, carbon and oxygen are used in the entrance window of the PSPC for the soft X rays. Gases with high-Z elements such as Kr and Xe are used in the counting gas of the PSPC for the high-energy X rays. Therefore, it is important to estimate the detection efficiency of the PSPC with available window materials and counting gases.

In the present estimation, the shape of PSPC is assumed to be rectangular parallelepiped for simplicity. The detection efficiency of the PSPC with such a shape is approximately expressed by

$$D(E,P) = \exp(-\mu_W \cdot \rho_W \cdot x_W)\,[1 - \exp(-\mu_G \cdot \rho_G \cdot x_G)], \qquad (1)$$

where μ_W is the mass attenuation coefficients of window materials (cm^2/g), ρ_W is the density of window materials (g/cm^3), x_W is the thickness of window materials (cm), μ_G is the mass absorption coefficients of counting gas (cm^2/g), ρ_G is the density of counting gas (g/cm^3) and x_G is the thickness of PSPC (cm). The coefficients ρ_W and ρ_G are functions

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of X-ray energies E. Assuming that the counting gas follows the equation of state for the ideal gas, the density ρ_G in Eq. (1) is estimated from

$$\rho_G = P \cdot \omega_G / (R \cdot T) \tag{2}$$

where P is pressure of the counting gas (Torr), ω_G is atomic or molecular weight of the counting gas (g/mol), R is the gas constant ($= 6.24 \times 10^4$ Torr cm^3/mol/K), T is temperature of counting gas (K). Thus, the detection efficiency is given as functions of the energy of X rays E and the pressure of the counting gas P.

The attenuation and absorption coefficients, μ_W and μ_G, are quoted from Refs. (5)–(9); the coefficients at K and L edges are obtained by extrapolating the values in those references. The program code for the efficiency $D(E,P)$ has been written by a commercially available software (DBASE III PLUS). The code mainly consists of the data base for attenuation and absorption coefficients and atomic binding energies, the interpolation of those values and the calculation of the detection efficiency.

2. PSPC FOR LOW-ENERGY X RAY

There are mainly two problems in the detection of soft X rays (< 1000 eV) by gas-filled proportional counters. One is the absorption of X rays in window materials. Polypropylene or Mylar (polyethylene terephthalate) are used as the window film. The

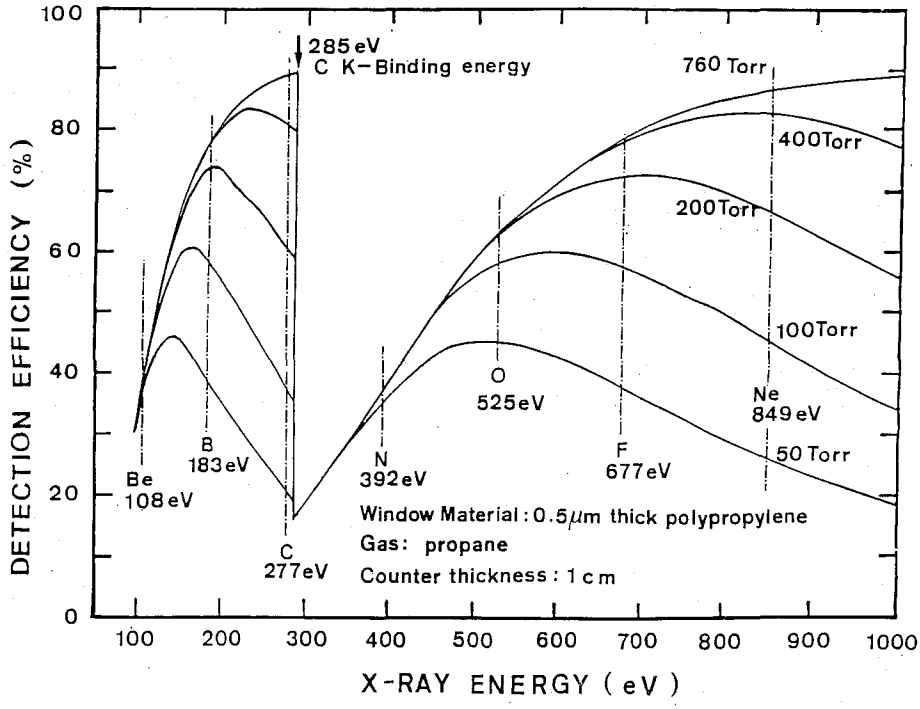

Fig. 1. Detection efficiency of propane (C_3H_8) as a function of the gas pressure; the window material is 0.5-μm thick polypropylene and the counter thickness is 1 cm.

smallest thickness we can achieve is at most 0.5 μm, which is still too thick for X rays with energies below 100 eV. The other problem is the counter gas. For detecting soft X rays, the counter is usually mounted in a vacuum chamber to avoid the absorption of X ray by air. Therefore, the counter is operated at gas pressures so low as not to break out the thin window. Pure organic molecular gases such as methane (CH_4) and ethane (C_2H_4) are usually employed as the counting gas because of their high gas gains at low pressures. Since these gases contain only hydrogen and carbon atoms, the detection efficiency at low pressures does not become sufficient for higher-energy X rays near 1000 eV.

The sensitive volume of the counter used in our previous works[1,2] is 10 mm in thickness and 100 × 20 mm^2 in window area. In the present work, the detection efficiency of this counter geometry has been estimated according to Eq. (1). The estimations have been performed for methane (CH_4), ethane (C_2H_4), propane (C_3H_6) and isobutane (C_4H_8). Typical results obtained with 0.5-μm thick polypropylene film and propane gas is given by Fig. 1. The steep decrease of the efficiency at 285 eV is caused by the K edge of carbon atoms in the polypropylene film. It is noted that the efficiency for nitrogen (392 eV) and oxygen (525 eV) K X rays is much decreased by this absorption effect of carbon atoms.

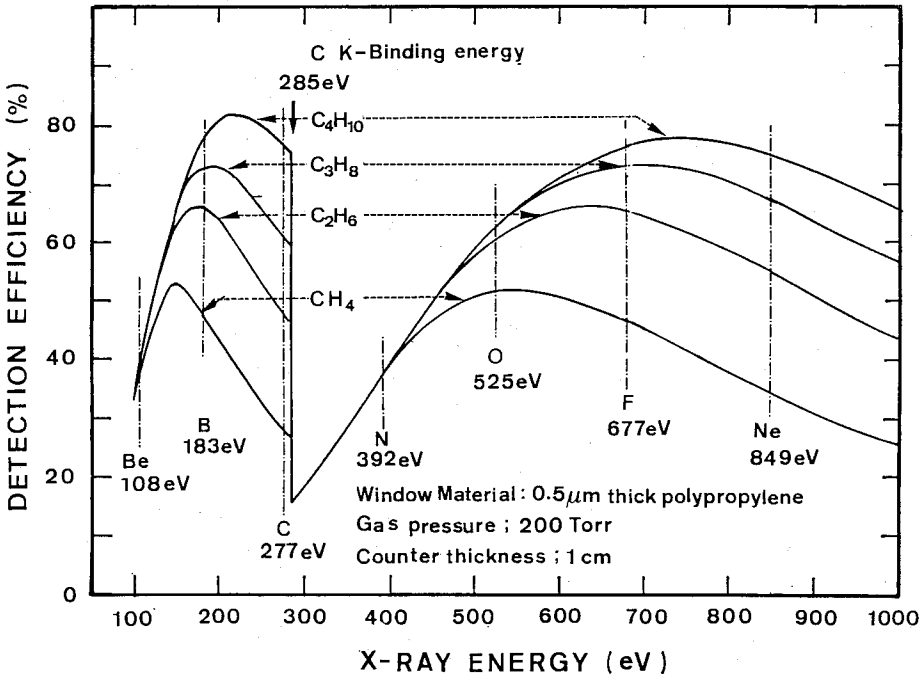

Fig. 2. Detection efficiencies of methane (CH_4), ethane (C_2H_6), propane (C_3H_8) and isobutane (C_4H_{10}) at a gas pressure of 200 Torr; the window material is 0.5-μm thick polypropylene and the counter thickness is 1 cm.

The gas pressure which the 0.5-μm thick polypropylene can hold is at most 200 Torr. The efficiency calculated for CH_4, C_2H_4, C_3H_6 and C_4H_8 at 200 Torr is given by Fig. 2. The best efficiency can be obtained with C_4H_8 gas, as expected. With efficiencies at least more than 30%, the present PSPC can detect X rays of beryllium (108 eV), boron (183 eV), carbon (277 eV), nitrogen (392 eV), oxygen (525 eV), fluorine (677 eV), neon (849 eV). However, the detection of X rays of lower Z elements, i.e., lithium (54 eV) and helium (24 eV), is practically impossible.

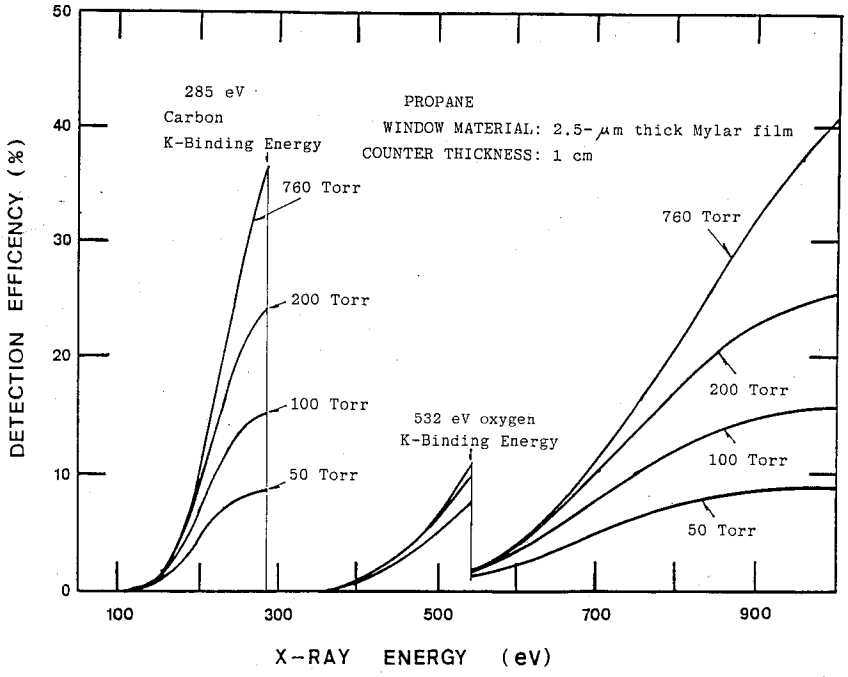

Fig. 3. Detection efficiency of propane (C_3H_8) as a function of the gas pressure; the window material is 2.5-μm thick Mylar film and the counter thickness is 1 cm.

In Fig. 3, results for the 2.5-μm thick Mylar film are shown as a function of the gas pressure of propane (C_3H_8). The 2.5-μm thick Mylar can be used at pressures less than 500 Torr. Since Mylar contains carbon and oxygen atoms, there exists two sharp decreases in the efficiency curve, i.e., at the K edges of carbon (285 eV) and oxygen (532 eV). It is seen from Fig. 3 that this film are available for detecting carbon X rays ($D = \sim 25\%$ at 277 eV) and oxygen X rays ($D = \sim 5\%$ at 525 eV), but not useful for nitrogen X rays ($D < 1\%$ at 392 eV).

3. PSPC FOR HIGH-ENERGY X RAY

Mixtures of rare gases and some molecular gases are used for the detection of high-energy X rays (> 1 keV). Pressurized gas including high-Z elements such as krypton and

xenon are necessary to detect efficiently X rays with energies more than 20 keV. In our previous work,[4] a PSPC for high-energy X rays were developed by utilizing high-pressure counting gas, up to 10 atm. A duralumin box of $64 \times 64 \times 240\ mm^3$ is used as a counter body, the center of which is holed through with 36 mm diameter. The one side of the body has an opening for a window frame, to which a 1-mm thick beryllium window plate is welded. The sensitive volume of the counter is 30 mm in thickness and 120 mm in length. The detection efficiencies for some gas mixtures, i.e., Ar + 10%CH_4, Kr + 10%CH_4 and Xe + 10%CO_2, have been estimated from Eq. (1), assuming that the thickness of the counter is 3 cm and the window material is 3-mm thick beryllium plate. The estimations have been performed as functions of X-ray energy (1 – 100 keV) and gas pressure (1 – 10 atm).

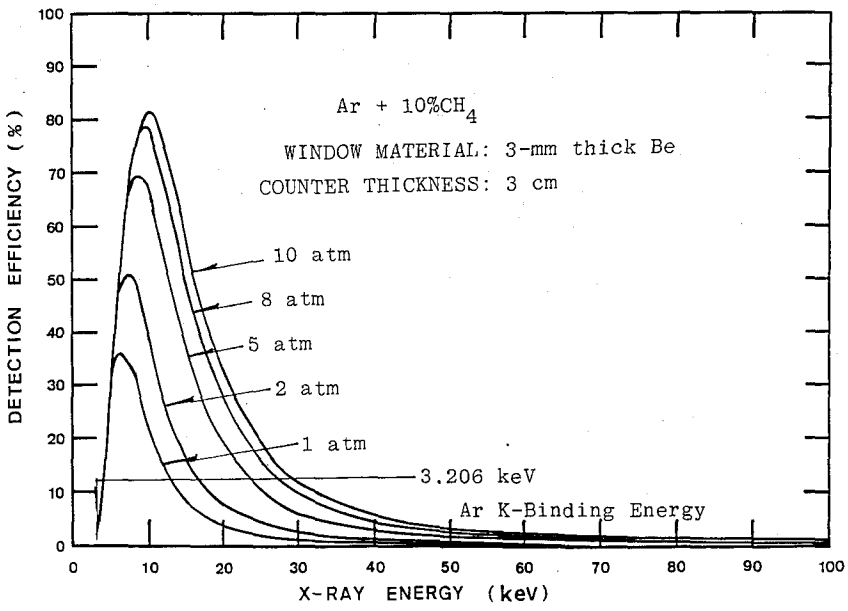

Fig. 4. Detection efficiency of Ar + 10%CH_4 as a function of the gas pressure; the window material is 3-mm thick beryllium and the counter thickness is 3 cm.

Results for Ar + 10%CH_4 are shown in Fig. 4. This gas mixture can be used in the region of 5 – 20 keV, where the efficiency is more than 30% as long as the pressure is 10 atm. Results for Kr + 10%CH_4 and Xe + 10%CO_2 are given by Figs. 5 and 6, respectively. As seen in those figures, the efficiency steeply increases at K edges of krypton (14.3 keV) and xenon (34.6 keV). The mixture of Kr + 10%CH_4 is useful in the region of 10 – 50 keV, while that of Xe + 10%CO_2 is useful in the region of 35 – 100 keV. Thus, for detection of high-energy X rays, it is desired to select counting gases according to the energy region of X rays to be detected.

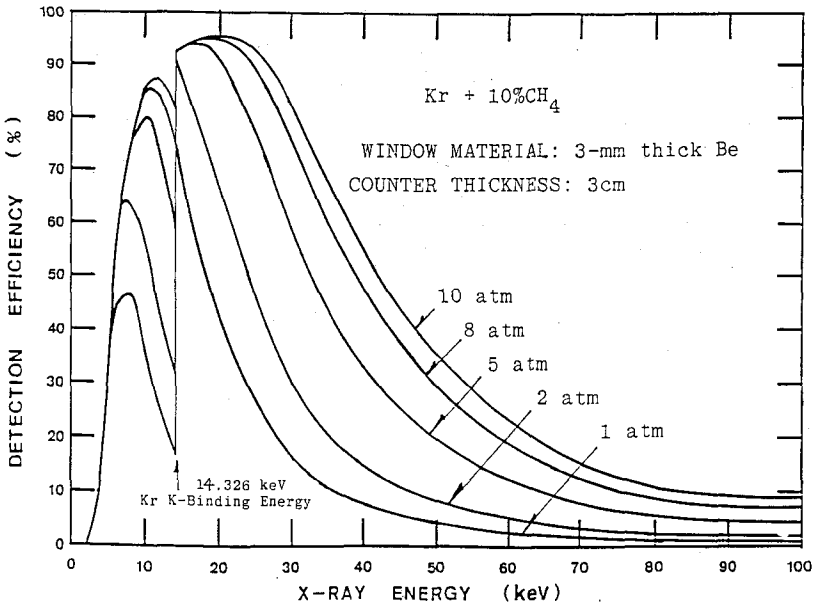

Fig. 5. Detection efficiency of Kr + 10%CH_4 as a function of the gas pressure; the window material is 3-mm thick beryllium and the counter thickness is 3 cm.

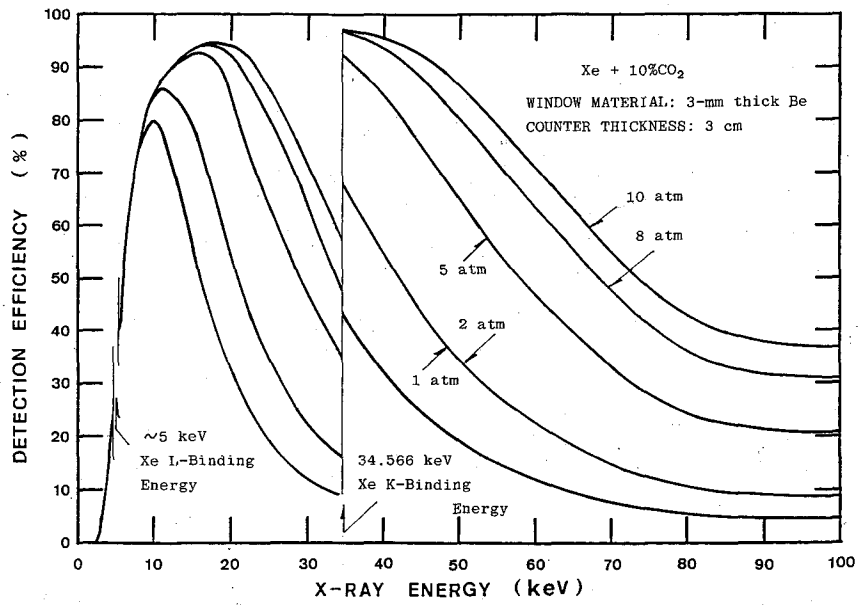

Fig. 6. Detection efficiency of Xe + 10%CO_2 as a function of the gas pressure; the window material is 3-mm thick beryllium and the counter thickness is 3 cm.

4. CONCLUDING REMARKS

The present calculation indicates that pure organic molecular gases, CH_4, C_2H_6, C_3H_8 and C_4H_{10}, are avialble for the detection of soft X rays. In our recent work, we have found that pentane (C_5H_{12}) is also useful in the soft X-ray detection; the vapour pressure is ~500 Torr at 25 °C. When pentane is used, the detection efficiency becomes higher than that of C_4H_{10}. Hexane (C_6H_{14}) is also available though the vapour pressure is considerably low i.e., 150 Torr at 25 °C.

The present results obtained for the gas mixtures, Ar + 10%CH_4, Kr + 10%CH_4 and Xe + 10%CO_2, are not precise enough for high-energy X rays which can ionize K and L shells of Ar, Kr and Xe atoms in the gas mixtures. Some of K X rays produced by such ionizations can escape from the counter. The escape of K X rays causes another peak in the energy spectrum, which corresponds to the difference between the whole energy of incident X rays and the energy of escaping K X rays; this peak is called escape peak. The ratio of the escape to the full peak depends on the incident energy and the counter geometry. When the thickness of counter is relatively small, the ratio increases with increasing the incident energy. Events of the escape peak results in a better position resolution than those of the full peak.[10] Therefore, for more precise discussions, it is required to estimate detection efficiencies for events of the escape and full peaks separately. For this purpose, it is planned to measure the escape to full peak ratio for the gas mixtures.

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