Equivalence of Pure Propane and Propane-TE Gases for Microdosimetric Measurements

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INTRODUCTION

In microdosimetry tissue-equivalent proportional counters (TEPCs) are commonly assumed to measure the distribution of energy imparted in micrometric volumes of tissue when irradiated by ionizing radiation. To achieve this aim the elemental composition of the walls and the filling gas of a TEPC is chosen as similar as possible to that of tissue. In this respect, propane-based tissue-equivalent gas is generally accepted as a good approximation for the elemental composition of tissue, and represents at present the most frequently used filling gas of TEPCs. Sometimes however, for instance for measurements in space environment, the use of pure C_3H_8 is preferred. The use of pure gas instead of gas mixture has the advantage that the composition of a pure gas does not change over time due to a different absorption of the gas components with the detector walls. From this point of view, the use of pure propane as the filling gas, especially in case of a sealed TEPC, offers practical advantages: (i) the composition of the filling gas is more stable on long-time operation, and (ii) higher gas gains can be reached as compared with the C_3H_8-TE gas mixture. The disadvantage of using pure C_3H_8 gas instead of the C_3H_8-TE gas is related to the different atomic composition of C_3H_8 (mass fractions: 18.3% H, 81.7% C) as compared with that of the commonly accepted C_3H_8-TE gas mixture (mass fractions: 10.3% H, 56.9% C, 3.5% N, 29.3% O).

It was the aim of this study to develop an experimental procedure which can be applied in measurements with C_3H_8-filled TEPCs to get a detector response very similar to that of TEPCs filled with the C_3H_8-TE-gas mixture.

MATERIAL EQUIVALENCE

In radiation dosimetry, two sites of different materials are considered equivalent if the absorbed dose or the mean imparted energy ε to each site are equal. Applying this principle to a TEPC filled either with the C_3H_8-TE-gas mixture or with pure C_3H_8 requires that the mean energy imparted by ionizing radiation to the detector volume is independent of the filling gas, and it can be expressed by equation (1).

$$(S/\rho)^{C_3H_8} \cdot (D\rho)^{C_3H_8} = (S/\rho)^{C_3H_8\text{-TE}} \cdot (D\rho)^{C_3H_8\text{-TE}} \qquad (1)$$

Here, $(S/\rho)^{C_3H_8\text{-TE}}$ and $(S/\rho)^{C_3H_8}$ are the mass collision stopping powers of the primary particle in the C_3H_8-TE and in pure C_3H_8 gases, respectively, $(D\rho)^{C_3H_8}$ and $(D\rho)^{C_3H_8\text{-TE}}$ are the masses per area of the site diameter in the two different gases, and ρ is the gas density.

A TEPC measures the distribution of ionizations created in the sensitive volume of the counter, which is converted later to a distribution of energy imparted using an appropriate calibration factor. In view of this fact, the equivalence of different filling gases of a TEPC should be based more on the equality of ionization distributions rather than on the equality of the distributions of imparted energy. To define material equivalence based on ionizations, let us assume single primary particles penetrating through the detection volume of a TEPC on one of its diameters *D*. If the range of the primary particles is longer than the diameter of the gas cavity, the mean number of primary ionizations caused by a particle inside the detection volume is given by the ratio $(D\rho)/(\lambda\rho)_{ion}$ where $(D\rho)$ is the mass per area of the particle's track length within the target, and $(\lambda\rho)_{ion}$ is the mass per area of the mean free path-length with respect to primary ionization. $(\lambda\rho)_{ion}$ is proportional to the reciprocal of the ionization cross section of the target material and depends on the type and energy of ionising particles.

TEPCs filled with pure C_3H_8 have the same response function as TEPCs filled with the C_3H_8-TE, if the measured ionization spectra are the same for the same radiation field. This means that, at least, the number of primary ionizations must be the same:

$$\frac{(D\rho)^{C_3H_8}}{(\lambda\rho)_{ion}^{C_3H_8}} = \frac{(D\rho)^{C_3H_8\text{-TE}}}{(\lambda\rho)_{ion}^{C_3H_8\text{-TE}}} \qquad (2)$$

Here, $(\lambda\rho)_{ion}^{C_3H_8}$ and $(\lambda\rho)_{ion}^{C_3H_8-TE}$ are the masses per area of the mean free ionization path lengths for C_3H_8 and the C_3H_8-TE-gas mixture. Therefore, the mass per area $(D\rho)^{C_3H_8}$ which is equivalent to $(D\rho)^{C_3H_8\text{-TE}}$ varies as a function of energy and particle type. To estimate the site size $(D\rho)^{C3H8}$ of a TEPC filled with pure C_3H_8 which leads to the same response function as the TEPC filled with the C_3H_8-TE-gas according to Equation (2), the ratio $(\lambda\rho)_{ion}^{C3H8}/(\lambda\rho)_{ion}^{C3H8-TE}$ is plotted in Figure 1 for electrons and protons as a function of particle energy *E*.

The mass stopping-power ratio $(S/\rho)^{C_3H_8\text{-TE}}/(S/\rho)^{C_3H_8}$ in the C_3H_8-TE and in pure C_3H_8 gases is also plotted for comparison. As it can be seen, the ratio $(\lambda\rho)_{ion}^{C3H8}/(\lambda\rho)_{ion}^{C3H8-TE}$ as a function of energy is smaller and less dependent on energy than the corresponding ratio of (S/ρ). Hence TEPCs filled with pure C_3H_8 are expected to give a response similar to that of TEPCs filled with the C_3H_8-TE mixture if the propane gas density is reduced to satisfy the

equivalence equation:

$$(D\rho)_{ion}^{C3H8} / (D\rho)_{ion}^{C3H8-TE} = (\lambda\rho)_{ion}^{C3H8} / (\lambda\rho)_{ion}^{C3H8-TE} \quad (3)$$

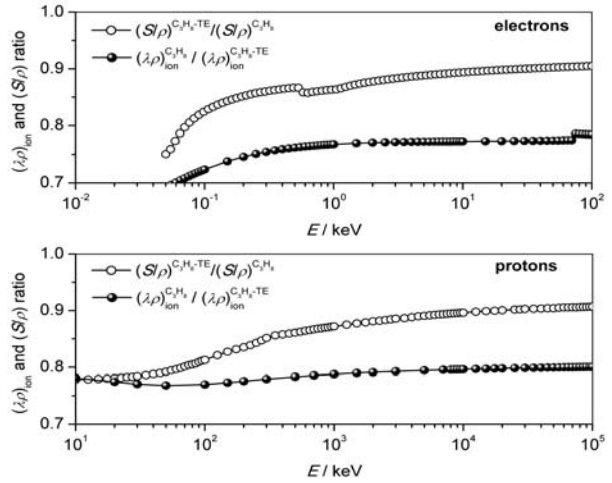

Fig. 1: Ratio $(\lambda\rho)_{ion}^{C3H8} / (\lambda\rho)_{ion}^{C3H8-TE}$ for electrons and protons. (S/ρ) for protons are taken from ref. 1, (S/ρ) for electrons from ref. 2.

Equation 3 gives an average factor of 0.75 for the gas density of pure C_3H_8 as compared with the gas density of C_3H_8-TE, to get the same equivalent site size d:

$$d = \frac{(D\rho)^{C3H8-TE}}{(1\,g\,cm^{-3})} \quad ; \quad d = \frac{(D\rho)^{C3H8}}{0.75 \times (1\,g\,cm^{-3})} \quad (4)$$

METHODS AND RESULTS

To check the validity of Equation 4 measurements were performed at INFN-LNL using a spherical TEPC with an internal diameter of 5 cm (3). The TEPC was filled either with pure C_3H_8 gas or with the C_3H_8-TE-gas mixture. The mass per area of the cavity diameter $D\rho$ was varied between 0.05 mg cm^{-2} and 0.3 mg cm^{-2} by changing the gas density. To study the detector response for low-LET fields, the TEPC was exposed to a ^{137}Cs γ-source, while for high-LET fields it was exposed to fast neutrons, 0.58 MeV in mean energy, produced in the Be(p,n) reaction by bombarding a thick beryllium target with 3 MeV protons at the CN Van de Graaff accelerator of LNL. Figure 2 shows the measured microdosimetric spectra at equivalent site size d = 2 µm.

A good correspondence in the shape of the spectra is observed with only minor differences in the gamma spectra. To get an overview of the results in the whole range of site sizes from 0.5 µm to 3 µm, the dose-mean lineal energy for the gamma component was calculated. As the lower threshold of the spectral distributions was set at the noise level y = 0.4 keV µm^{-1}, this dose-mean lineal energy was indicated as y_D^+.

Figure 3 shows y_D^+ in pure propane (spheres) and in the TE-gas mixture (squares) as a function of the equivalent site size d: the agreement between the y_D^+ for propane and for the TE-gas as a function of the equivalent site size d is within the estimated "type A" standard uncertainties of 1.5%. Within these uncertainties the experimental data can be described by a power function of d (the straight lines in the figure). The y_D^+ in propane obtained without taking into account the 0.75-factor in Equation 4 is also shown (open circles). In this case an underestimation between 5% and 10% clearly demonstrates the improvement by using the 0.75-factor when using pure C_3H_8 gas.

By reducing the gas density, pure propane gas can be used as a substitute of the TE-gas mixture at site sizes 0.05 mg/cm^2 ≤ $D\rho$ ≤ 0.3 mg/cm^2.

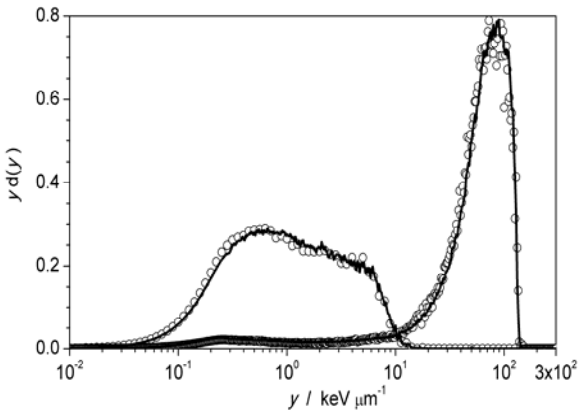

Fig. 2: ^{137}Cs and neutron microdosimetric spectra measured at d = 2 µm: C_3H_8-TE (line) and C_3H_8 (circles).

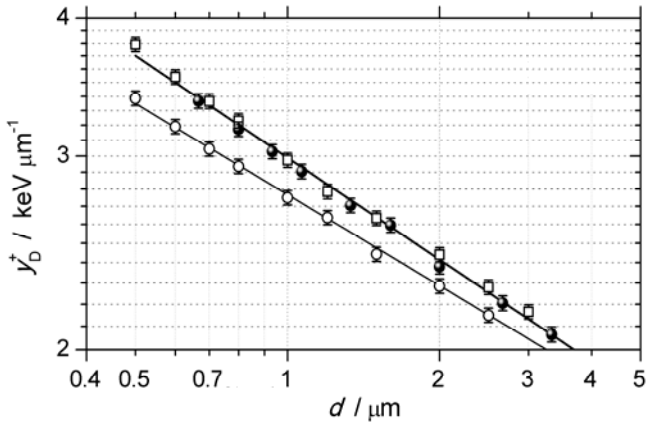

Fig. 3: Dose-mean lineal energy y_D^+ for ^{137}Cs as a function of the equivalent site size d for C_3H_8 (circles) and C_3H_8-TE (squares). y_D^+ in propane obtained without taking into account the 0.75-factor in Equation 4 is also shown (open circles).

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[1] B.Grosswendt, Radiat. Environ. Biophys. 41, 103–112 (2002).
[2] F.Salvat et al., PENELOPE 2011: OECD Nuclear Energy Agency (2011)
[3] D. Moro et al., LNL-INFN Annual Report (2011).