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Advances in cloud-chamber techniques and measurements
of W-value in a tissue-equivalent gas.

T. Budd, M. Marshall and C.S. Kwok.*

Abstract

The study of low-energy electrons is of special interest to radio-biology as electrons of around 1 keV are especially biologically damaging. A cloud chamber is available which can make visible individual ions in the tracks of low-energy electrons. Work on the theory of droplet formation and growth has enabled a tissue-equivalent gas of higher resolution to be used in the chamber. Techniques of Infra-red and mass spectroscopy have been developed to provide accurate assessment of the various gas and vapour pressures in the chamber. A new x-ray set has been built to allow electrons produced from carbon characteristic x-rays (0.28 keV) to be studied. This system has been tested and initial results obtained. W-values have been measured and results of (35.9 ± 0.2) eV/(ion pair) for electrons from carbon x-rays and (31.0 ± 0.5) eV/(ion pair) for electrons from aluminium x-rays (mean electron energy 0.76 keV) have been obtained. Fano factors have been found to be in the region of 0.25 for carbon x-rays and 0.4 for aluminium x-rays. Proximity functions and other microdosimetric properties will be derived in the future and these results will form a further paper.

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1. Introduction.

In recent years there has been particular interest in the role of low-energy electrons in radio-biology. It has been found that, for a given dose, electrons of around 1 keV are particularly biologically damaging (Goodhead 1977). Electrons of around this energy are formed as delta rays from higher energy particles and are present in most particle tracks. A study of such electrons may thus be helpful in the development of theories of radiation damage.

A low-pressure cloud-chamber has been constructed at Harwell which can be used to photograph and resolve droplets formed on individual ions in the tracks of low-energy electrons (Hodges and Marshall 1977). The experimental techniques have now been substantially improved. Classical nucleation theory has been extended (Kwok and Marshall 1978) with the result that it has been possible to predict and use a tissue-equivalent gas of higher resolution. Infra-red spectroscopy work has enabled accurate measurements to be made of the partial pressures of vapours actually existing in the chamber after a series of experiments. Finally, a new x-ray set has been designed and built to enable electrons from carbon characteristic x-rays (0.28 keV) to be studied.

This paper describes these advances in experimental techniques and presents measurements of the mean energy loss per ion pair (W-value) for low energy electrons in a tissue equivalent gas. The variance in W-value (Fano factor) is also derived and the results are compared with results from other recent sources.

2. Experimental techniques.

2.1 The cloud chamber construction and operation.

Details of the cloud chamber have been described previously by Hodges and Marshall (1977). The chamber is made to high-vacuum specifications and contains a mixture of permanent gases and vapours which are unsaturated before expansion. By expanding the chamber from this unsaturated (dry) condition it is possible to obtain 100% condensation efficiency on charged nuclei with very little condensation on uncharged aggregates.

Immediately after each expansion the chamber is irradiated by a pulse of mono-energetic low-energy x-rays. These x-rays undergo photo-electric interactions in the cloud chamber to produce photo-electrons and Auger electrons. These electrons cause ionisations in the gas mixture as they slow down and droplets form on each ion. Photographs are taken after each irradiation using two orthogonal cameras arranged to focus on a small active volume in the middle of the chamber. The droplet images in each cluster on the film are then counted.

2.2 The gas mixture used and the method of determination.

A high-resolution tissue-equivalent gas mixture has been developed for this work. The mixture was chosen to have a low gas density and yet allow a rapid growth from ions to droplets of a size which can be photographed. Kwok and Marshall (1977) have made extensions to classical nucleation theory and have been able to obtain a useable gas mixture with a resolution some eight times better than that used in the previous work of Hodges and Marshall (1976) and Budd and Marshall (1978). This improved mixture is shown in table 1. It was chosen to be atomically close to the ICRP definition of total soft tissue in reference man (ICRP 23, 1975). The total pressure in the chamber varied during the experiments due to leakage and due to the formation of irradiation products. It was 1.2 kPa (9 Torr) before the experiment and 1.6 kPa (12 Torr) at the end.

Because of the variation with time in the composition of the gas mixture in the cloud chamber it is necessary to be able to draw off and analyse gas samples from the chamber. The partial pressures of permanent gases were obtained using standard mass spectroscopy techniques. However, these techniques are not suitable for quantitative measurements of the amounts of vapour present as the vapours adsorb profusely onto the walls of the spectrometer. Instead an infra-red spectroscopy technique was developed using a modified Perkin-Elmer spectrometer (model 580). To reduce adsorption of vapours onto the gaskets of the standard cells special silicone rubber gaskets were used and to work at the low pressures used in the cloud chamber special high vacuum greaseless stopcocks were fitted. Adsorption bands at 1060, 1070, and 2906 cm^{-1} were used for ethanol measurements and

1636, 1653, 1685 1696 and 1700 cm^{-1} were used for water measurements. It was found that absorption in ethanol bands was modified by the presence of water and a series of calibrations with different water content was required. Full details of the techniques are described by Kwok (1979).

Several irradiation products were found in the final analysis. These were probably due to alpha irradiations which were carried out at the same time as the x-ray experiments described here. In addition a significant leakage of air into the chamber occurred during the experiments.

2.3 The x-ray set and x-ray spectra obtained.

To enable a high enough intensity of carbon x-rays to penetrate to the centre of the cloud chamber a special x-ray set was built (figure 1), which works on a glow discharge principle. The tube is continuously pumped and contains Helium at about 150 Pa. Under these conditions an electron beam of up to 20 mA may be obtained from the cathode at an operating voltage of 1.15 kV. The electron beam is swept to the side of the tube by electro-magnetic switching coils except during a 2 ms period just after the chamber is expanded. During this period the beam is allowed to fall onto a thin transmission target. For carbon x-rays this consists of a carbon foil of thickness $125\text{ }\mu\text{g cm}^{-2}$ supported by a fine metal grid and placed in a stainless steel holder. X-rays from this target enter the chamber through a mylar window of thickness $6\text{ }\mu\text{m}$. The x-ray set is positioned at a slight angle to this window to ensure that the electron beam can not fall directly on the chamber window if a hole is burnt in the target.

The x-ray spectra produced by the x-ray set were analysed using a gas-flow proportional counter built for measuring very low-energy spectra (Cairns Desborough and Holloway (1970)). The x-ray tube and counter were mounted on a dummy chamber with attenuation between the x-ray source and the sensitive volume in the counter matched to the actual attenuation when the x-ray set was used on the chamber. The spectra measured for carbon and aluminium x-rays are shown in figure 2. The line widths are indistinguishable from those of a single line spectra as measured with this type of counter and the bremsstrahlung contributions are under 5% in both cases. It was later found that the

tube voltage for aluminium x-rays could be reduced substantially below that used in figure 2 and thus the spectra finally quoted will be even more pure.

3. Results and discussion.

3.1 Measurement of condensation efficiency.

Before quantitative results can be obtained from the cloud chamber it is important to ensure that the condensation efficiency is close to 100 %. Figure 3 shows the number of droplets obtained from carbon x-rays when running the chamber at different expansion ratios. There is a clear plateau region on the curve below the onset of condensation on uncharged particles. This plateau is assumed to represent 100 % condensation efficiency. Photographs of background condensation were also taken at each expansion ratio so that a background correction could be made to the measured data. In the plateau region this correction was of the order of 1 %.

3.2 Estimation of W-values.

Typical pictures of electron tracks obtained from carbon and aluminium x-ray interactions are shown in figure 4. The mean number of droplets counted per event and the electron W-values derived from this are shown in table 2. Standard errors on these figures are also given. The values are derived from 600 carbon x-ray interactions and 400 aluminium x-ray interactions.

The mean number of droplets counted per event divided by the x-ray energy gives the W-value for the x-ray. The W-value for an electron differs from the x-ray value because the ions produced in the formation of the electron are not included. For carbon x-rays one ion pair (2 droplets) should be subtracted. For aluminium x-rays the situation is complicated by the formation of an Auger electron as well as a photo-electron in most cases. The expected interactions, their relative probabilities and the energies of the electrons produced are shown in table 3. The probabilities are derived from McMaster (1969) and the electron energies from Lederer, Hollander and Perlman (1967). The photo-electron and Auger electron ionisations produced from a

given event are difficult to separate with any accuracy as the tracks are superimposed on one another. because of this, only a mean W-value has been estimated for the electrons involved. These electrons vary in energy from 0.27 keV to 1.47 keV with a weighted mean energy of 0.76 keV. Because of the range of electron energies involved, the W-value obtained will be slightly different from that which would be obtained from mono-energetic electrons of this mean energy. Where an Auger electron is involved, 3 ions are formed in producing the initial electrons, 1 doubly charged positive ion and 2 negative ions. As an Auger electron is formed in an estimated 92 % of the interactions (table 3), 2.92 droplets have been subtracted from the mean number counted when calculating the W-value.

The W-value obtained for electrons from carbon x-rays is significantly higher than that obtained for electrons from aluminium x-rays. This is due to a changing competition between ionisation and excitation at very low energies. The W-value of tissue-equivalent gases for low-energy electrons have been measured recently by Combecher (1978) and by Smith and Booz (1978). Table 4 shows a comparison of their results with those obtained here. Our results show good agreement with Smith and Booz but differ significantly from Combecher. The precision of our results is better than Smith and Booz and this demonstrates some advantage in a cloud chamber approach over other techniques. Also shown in table 4 is an earlier value obtained in the cloud chamber by Hodges and Marshall (1977). This is not for a tissue-equivalent gas but is included for a comparison.

3.3 Estimation of Fano factors.

The Fano factor for electron tracks of a given energy is defined as the measured variance of the number of ion pairs produced divided by the number of ion pairs. The values obtained are (0.25 ± 0.08) for electrons produced by carbon x-rays and (0.40 ± 0.12) for electrons produced by aluminium x-rays. The larger factor for aluminium may be due in part to the method of taking together each of the possible combinations of photo-electrons and Auger electrons shown in table 3. However, variance measurements are critically affected by occasional events with exceptional numbers of droplets. It is difficult to determine whether an unusual event is genuine or is an artifact caused

by, for example, an event being partly out of focus in a photograph. Different observers applied different rejection criterion in these cases and obtained significantly different values for the Fano factor. The standard errors quoted above include both inter-observer and intra-observer contributions.

Alkhazov, Komav and Vorab'ev (1967) estimated Fano factors of 0.34 for hydrogen and generally lower values for polyatomic molecules (0.26 for methane for example). The present results would seem to be compatible with this range of values, allowing for the size of the experimental errors involved.

4. Conclusions.

Photographs of electron tracks in a cloud chamber have been successfully obtained for electrons formed from carbon characteristic x-rays (0.28 keV) and from aluminium characteristic x-rays (1.55 keV). A new high-resolution tissue-equivalent gas mixture has been used and the actual gas composition of samples from the chamber has been analysed. W-values have been measured and values of (35.9 ± 0.2) eV/(ion pair) at 0.28 keV for electrons from carbon x-rays and (31.0 ± 0.12) eV/(ion pair) for electrons from aluminium (mean electron energy 0.76 keV) have been obtained. Fano factors have also been obtained and values of (0.25 ± 0.08) and (0.40 ± 0.12) respectively have been obtained.

Further work is in progress to deduce proximity distributions and other microdosimetric parameters and these results will be published as a separate paper.

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Table 1.

Analysis of gas mixture in the chamber.

a) Analysis of molecular composition.

Gas	Partial Pressure (Pa)		
	Before Experiments	After Experiments	Mean
Water Vapour	600 ± 25	560 ± 28	580 ± 38
Ethanol Vapour	183 ± 8	192 ± 9	188 ± 12
Oxygen	224 ± 3	279 ± 21	251 ± 20
Hydrogen	187 ± 3	364 ± 28	275 ± 22
Nitrogen	< 1	71 ± 5	35 ± 3
Acetaldehyde	< 1	77 ± 5	38 ± 3
Carbon Dioxide	< 1	53 ± 4	26 ± 2
Carbon Monoxide	< 1	63 ± 5	31 ± 3

b) Analysis of relative atomic composition.

Atom	Relative Number of Atoms (%)	
	Mean chamber Mixture	ICRP 23 (1975) Reference Man
Hydrogen	67.4 ± 2.7	63.1
Carbon	11.2 ± 0.6	11.8
Oxygen	20.0 ± 0.8	24.0
Nitrogen	1.3 ± 0.1	1.1

Table 2.

Summary of results obtained from the cloud chamber.

Irradiation	Energy (keV)	No. of Droplets Observed (Background Corrected)	Mean Electron Energy (keV)	Auger Electron Probability	W-value (ev/ ion pair)
Carbon x-rays	0.28	17.5 ± 0.1	0.28	0.	35.9 ± 0.2
Aluminium x-rays	1.55	94.2 ± 1.5	0.76	0.92	31.0 ± 0.5

Table 3.

Photo-electric interactions expected in the cloud chamber.

Interaction		Relative Probability	Photo Electron Energy (keV)	Auger Electron Energy (keV)
Atom	Shell			
Hydrogen	K	0.0	1.47	-
Carbon	K	9.4	1.20	0.27
	L	0.8	1.48	-
Nitrogen	K	2.7	1.08	0.39
	L	0.2	1.48	-
Oxygen	K	79.9	0.95	0.52
	L	6.9	1.48	-

Table 4

Comparison of W-values obtained with other recent work.

Reference	Relative atomic composition of gas mixture (%)				W-value at 0.28 keV ev/ion pair	W-value at 0.76 keV ev/ion pair
	H	C	O	N		
This work	67.4	11.2	20.0	1.3	35.9 ± 0.2	31.0 ± 0.5
Smith & Booz (1978)	60.6	22.7	15.2	1.5	35.8 ± 2.3	29.0 ± 1.7
Combecher (1978)	60.5	22.7	15.2	1.5	35.	34.
Hodges & Marshall (1977)	86.8	5.6	5.6	0.4		29.6 ± 0.4

A.E.R.E. R9609 FIG.1. DIAGRAM OF THE GLOW DISCHARGE X-RAY SET.

A. E. R. E. R9609 FIG.2. X-RAY SPECTRA USED, MEASURED WITH A GAS-FLOW PROPORTIONAL COUNTER.

A.E.R.E. R9609 FIG. 3. CONDENSATION EFFICIENCY IN THE CHAMBER FOR CARBON X-RAY IRRADIATIONS.

(a) Tracks produced from carbon x-rays

(b) Tracks produced from aluminium x-rays

AERE-R 9609 Fig. 4

Typical pictures of electron-tracks in the cloud chamber