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Dependence of $\overline{W}$ on the Charge of Heavy Ions*

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Abstract

$\overline{W}$ values (average energy required to form an ion pair) were determined for ^{35}Cl ions in nitrogen and tissue-equivalent gas. These values were compared to previously reported $\overline{W}$ values for oxygen ions and alpha particles in the same media. This comparison was made at two specific values of energy per atomic mass unit of the incident ions. At an energy of 2.57 MeV/amu, the comparison shows $\overline{W}$ is 12% and 10% higher for oxygen ions in tissue-equivalent and nitrogen gas, respectively, relative to alpha particle $\overline{W}$. At an energy of 0.77 MeV/amu, a similar comparison shows $\overline{W}$ is 20% higher for ^{35}Cl ions and 12% higher for ^{16}O ions in tissue-equivalent gas; and 13% and 10% higher, respectively, in nitrogen gas, relative to alpha particle $\overline{W}$. These results indicate that $\overline{W}$ values depend not only on the energy per atomic mass unit of heavy ions but also on their charge.

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Introduction

In radiation dosimetry (utilizing gas filled ionization chambers) one quantity of fundamental importance is the average energy required to form an ion pair ($\bar{W}$). The literature contains many papers on measurements of $\bar{W}$ for alpha particles in various gases and a few for other heavy ions in a limited number of gases. It was expected that $\bar{W}$ would increase with decreasing velocity of the ion and this has been experimentally confirmed by many authors.[1,2,3,4] However, it was found that $\bar{W}$ was nearly constant as a function of energy for alpha particles in argon, although below about 500 keV some decrease in $\bar{W}$ was observed by Chemtob et al.[5] A review article by Myers[6] provides a summary of available $\bar{W}$ values for heavy ions. Measurement results of $\bar{W}$ for oxygen ions of a few MeV/amu energy were reported by Varma et al.[7,8] A preliminary measurement of $\bar{W}$ for chlorine ions of 27 MeV energy in Rossi tissue-equivalent gas (TE) was also made by Varma et al. The present paper briefly describes the experimental method used for measurement of $\bar{W}$ for alpha particles and heavy ions. Comparisons of $\bar{W}$ values obtained for alpha particles, oxygen ions and chlorine ions in nitrogen and TE gas are made.

Experimental Method

Details on experimental methods and procedures employed in $\bar{W}$ determination for alpha particles and for other heavy ions were reported in references 3 and 7, respectively. The cylindrical ionization chamber used in these measurements was 30 cm in diameter and one meter long. The incident ions were made to stop completely in the chamber by raising the filling gas pressure. The ionization current produced by these ions was measured using a vibrating reed electrometer. The energy spectrum of alpha particles and oxygen ions was measured using a heavy ion solid state detector. The energy of the ^{35}Cl ions was determined from magnetic deflection of the beam with the field strength being measured by nuclear magnetic resonance. Research grade nitrogen and tissue-equivalent gas (64.4% methane, 32.2% carbon dioxide and 3.4% nitrogen) were used in these measurements.

Data Reduction

(a) $\bar{W}$ for alpha particles: The ratio of ionization current in argon gas (the reference gas) to that in the experimental gas was measureed. This ratio was then multiplied by previously determined $\bar{W}$ for the reference gas to yield applicable $\bar{W}$ for the experimental gas. Thus

$$\bar{W} = \frac{I_A}{I_E} \bar{W}_A \qquad (1)$$

where I_A and I_E are extrapolated saturation ionization currents in the reference and experimental gas respectively, and $\bar{W}_A$ is $\bar{W}$ for the reference gas.

The alpha particle energy at which the determined $\bar{W}$ was applicable, was determined by weighting the energy spectrum with respect to the variation in $\bar{W}$ with energy. For this purpose variation in $\bar{W}$ with energy was assumed to follow empirical relations

$$\bar{W} = a + b/E^{\frac{1}{2}} \qquad (2)$$

as suggested by Cranshaw et al.[9] and

$$\bar{W} = a_1 + b_1/E. \qquad (3)$$

Due to the small width at half maximum of the alpha energy spectrum, the $\bar{W}$ weighted mean energies obtained from relations (2) and (3) were approximately the same.

(b) $\bar{W}$ for other heavy ions: In contrast to alpha $\bar{W}$ determination in which ratios were used, absolute $\bar{W}$ was determined for other heavy ions. In this case, saturation ionization current per incident ion was measured. From this measurement, number of ion pairs formed per incident ion was determined. The mean energy per incident ion was determined by weighting the measured energy spectrum with respect to number of particles at different energies. $\bar{W}$ was determined from average energy per incident ion divided by average number of ion pairs formed per incident ion.

$\bar{W}$ Results

(a) *Alpha particles:* $\bar{W}$ for alpha particles was determined at $\bar{W}$ weighted mean energies of 0.49, 1.09, 3.12 and 5.37 MeV. Results for nitrogen and tissue equivalent gas are given in Table I. Results of a generalized least square fit to functions (2) and (3) for nitrogen and TE gas are also provided. It is of interest to note that both the empirical relations provide a good fit to the data in the energy range studied.

(b) Other Heavy Ions: $\bar{W}$ for 34.5 MeV oxygen ions[7] in nitrogen gas was found to be 38.6 $\pm$ 0.54 eV per ion pair. The $\bar{W}$ for 41.1 MeV oxygen ions[8] in tissue-equivalent gas was found to be 33.4 $\pm$ 0.47 eV per ion pair. For 27 MeV chlorine ions, preliminary $\bar{W}$ values of 37.6 $\pm$ 1.6 eV per ion pair in tissue-equivalent gas and 41.1 $\pm$ 1.6 eV per ion pair in nitrogen gas were determined. The values are preliminary due to relatively large statistical fluctuations and steady drifts with time of the beam intensity calibration. Table II summarizes these $\bar{W}$ values. Applicable $\bar{W}$ values for alpha particles, oxygen and chlorine ions at two specific energies (2.57 and 0.77 MeV/amu) are given in Table III.

Charge Dependence of $\bar{W}$

For oxygen and chlorine ions, energy dependence of $\bar{W}$ was assumed to follow a relation similar to that obtained for alpha particles. Thus, the $\bar{W}$ values for heavy ions and alpha particles were estimated at two specific velocities (MeV/amu) using equation (2). This provides for convenient comparison of values as a function of the atomic number of the incident ions. These data are shown in Table III and are also plotted in Figure 1.

It can be seen from Figure 1 and Table III, that $\bar{W}$ for oxygen ions was about 10% higher than $\bar{W}$ for alphas in tissue-equivalent gas at about 2.57 MeV/amu and about 12% higher at 0.77 MeV/amu. Similarly, $\bar{W}$ for oxygen ions was about 10% higher than $\bar{W}$ for alphas in nitrogen at both 0.77 MeV/amu energy and at 2.57 MeV/amu.

Thus these results indicate a systematic increase in $\bar{W}$ for heavy ions as a function of atomic number for a given initial velocity (MeV/amu). It is of interest to note that measurements of $\bar{W}$ for heavy ions like recoil ThC', fission fragments, and ^{7}Li reported in Myers[6] article do not show systematic change in $\bar{W}$ with either atomic number or velocity of the incident ions. However, Myers points out that $\bar{W}$ values for these ions are less reliable than those for alpha particles or protons.

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Table I(a)

$\bar{W}$ for Alpha Particles at Various Energies in Nitrogen

$\bar{W}$ Weighted Mean Energy (MeV)	Experimental $\bar{W}$ (eV/ip)	$33.53 + 5.87E^{-\frac{1}{2}}$ (eV/ip)	$35.64 + 3.34E^{-1}$ (eV/ip)
5.37	36.4 ± .07	36.1	36.3
3.12	36.5 ± .07	36.9	36.7
1.09	38.8 ± .08	39.2	38.7
.48	{42.3 ± .08	42.0	--
.50		--	42.3

Table I(b)

$\bar{W}$ for Alpha Particles at Various Energies in Tissue-Equivalent

$\bar{W}$ Weighted Mean Energy (MeV)	Experimental $\bar{W}$ (eV/ip)	$27.96 + 5.71E^{-\frac{1}{2}}$ (eV/ip)	$29.99 + 3.37E^{-1}$ (eV/ip)
5.37	30.72 ± .06	30.4	30.6
3.12	31.08 ± .06	31.2	31.1
1.09	33.58 ± .07	33.4	33.1
.49	{36.88 ± .07	36.2	--
.56		--	36.6

Table II

$\overline{W}$ Values for Oxygen and Chlorine Ions in Nitrogen and Tissue-Equivalent Gas

Mean Energy (MeV)	Ion	$\overline{W}$ Experimental (eV/ion pair) Nitrogen	Tissue Equivalent
34.5	^{16}O	38.6 ± 0.54	--
41.1	^{16}O	38.9 ± 0.54	33.4 ± 0.47
27.0	^{35}Cl	41.1 ± 1.08	37.6 ± 1.06

Table III

Extrapolated $\overline{W}$ for Alpha Particles, Oxygen and Chlorine Ions in Nitrogen and TE Gas at 2.57 and 0.77 MeV/amu

Energy (MeV/amu)	Ion	$\overline{W}$ (eV/ion pair) Nitrogen	TE
2.57	Alpha	35.4 ± .07	29.8
2.57	^{16}O	38.9 ± 0.54	33.4 ± .47
0.77	Alpha	36.5 ± .07	31.08 ± .08
0.77	^{16}O	40.1 ± .6	34.08 ± .05
0.77	^{35}Cl	41.1 ± 1.8	37.06 ± 1.6

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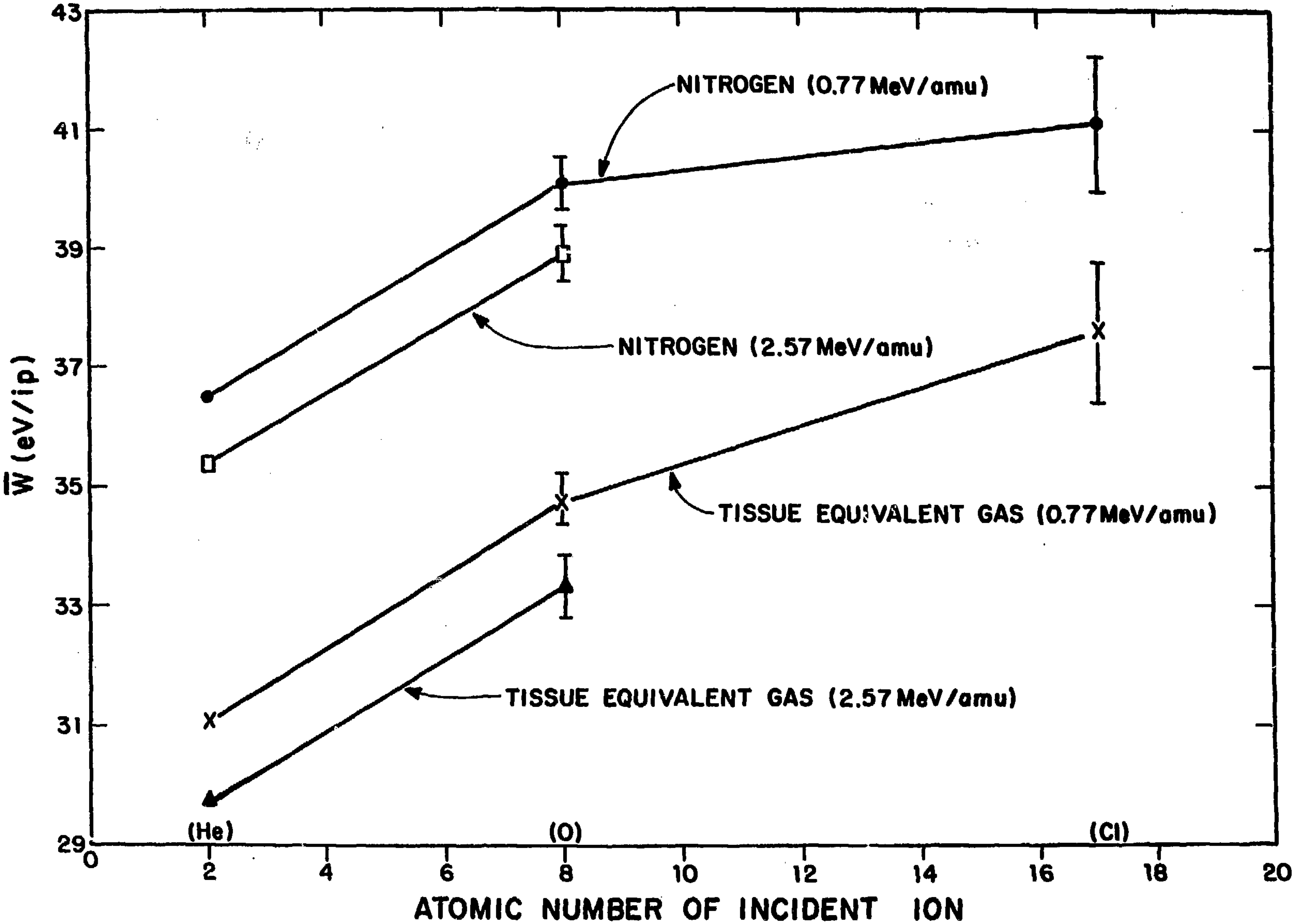

Figure 1. Variation of $\overline{W}$ in nitrogen and tissue-equivalent gases for heavy ions as a function of atomic number of incident ions. (Where no error bars are indicated, the errors are smaller than the points.)