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March 1979
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A Measurement of the Average Energy Required to Create an Ion Pair in Nitrogen by High-Energy Ions

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W IN NITROGEN FOR HIGH-ENERGY IONS

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At energies above $\sim 10$ MeV/amu, it is expected that the average energy required to create an ion pair, $\bar{w}$, in gases will be independent of mass or charge state of the ion and with increasing energy will tend toward the value for electrons, which in nitrogen is 34.6 eV. Twenty-two measurements of $\bar{w}$ using 250 MeV/amu $^{12}C^6+$ ions, 375 MeV/amu $^{20}Ne^{10+}$ ions, and 479 MeV/amu $^{40}Ar^{18+}$ ions were made and values of $36.4 \pm 0.6$ eV, $35.4 \pm 0.8$ eV, and $34.7 \pm 0.5$ eV, respectively, were obtained for nitrogen gas.

Key words: Ionization; Radiation; Dosimetry.
INTRODUCTION

The Bevalac accelerates charged particles as massive as iron up to energies in excess of 2 GeV/amu (1). These charged particle beams are monoenergetic, of high purity, (2) and are used in a variety of radiobiological experiments. As part of this program, there is considerable interest in determining the absolute value of the relative biological effectiveness. To make this possible, it is essential that physical measurements be made with sufficient accuracy to enable the absorbed doses in tissue to be calculated to an accuracy of 5% or better.

Many different techniques of charged particle dosimetry are used at the Bevalac facility, including, for example, nitrogen-filled ionization chambers (2), tissue-equivalent ionization chambers (3), thermoluminescent dosimeters (4), nuclear emulsions (5), and a Fricke dosimeter (6,7).

Experience has shown that nitrogen-filled ionization chambers are convenient instruments for monitoring charged particle beam irradiations. Ionization chamber measurements allow the absorbed dose in the irradiated specimens to be calculated, provided the average energy required to produce an ion pair in the nitrogen gas is known.

The work reported here is directed toward the evaluation of differential values of the average energy required to produce an ion pair in nitrogen, $\bar{w}(E)$, by essentially mono-energetic charged particles in the energy range of the Bevalac (200-2000 MeV/amu), so that accurate estimates of absorbed dose may be made from measurements made with the nitrogen-filled ionization chambers. The ionization chambers used at the Bevalac facility are designed so that charged particles lose little energy in passing through the ionization chamber. The mass stopping power of the particles is therefore effectively constant in the nitrogen within the chamber. It is
the differential value, $\bar{w}(E)$, that is required for dosimetry at the Bevalac.

Apart from the report of preliminary measurements by one of the present authors, no values of $\bar{w}$ for charged particles with $Z$ greater than 2 and in the energy range of interest have been published in the literature (5,8). Neither is there an adequate theoretical understanding of the variation of $\bar{w}(E)$ with ion charge-state and energy to permit reliable extrapolations from measurements made at lower energies (9,10,11) to the energy range of ions produced at the Bevalac.

The measurements reported here therefore have both immediate application to dosimetry at the Bevalac and add to the pool of information available that will lead to a better understanding of the variations of $\bar{w}(E)$ with ion mass, charge-state and energy.

This paper contains first a brief review of the literature followed by a description of the experimental techniques used, a summary of the experimental data obtained, and finally the conclusions and summary.

**LITERATURE REVIEW**

It is first important to distinguish between the differential value of the average energy required to produce an ion pair, denoted in this paper by $\bar{w}(E)$ and the integral value, $\bar{W}$, where $E$ is the kinetic energy of the charged particle. $\bar{w}(E)$ and $\bar{W}$ are related by the equation:

$$\bar{W} = \frac{1}{E} \int_0^E \bar{w}(E) \, dE \quad .$$

(1)

Much of the literature discusses experimental determinations of $\bar{W}$.

Several years ago Whyte (12) reviewed published experimental values of $\bar{W}$ for both electrons and photons. He found no significant variations
of $\bar{W}$ with electron or photon energy implying that, for the range of energies then investigated, the integral value $\bar{W}$ was either independent of, or not strongly dependent on, the upper limit of the integral of equation 1. Whyte calculated a "best value" of $34.6 \pm 0.03$ eV for the integral $\bar{W}$ value for electrons, often referred to in the literature as $\bar{W}_\beta$.

Whyte (12) showed that the integral value $\bar{W}$ for nuclei significantly differed from the value for electrons. Published measurements of $\bar{W}$ for alpha particles in the energy range 5-6 MeV were somewhat higher than $\bar{W}_\beta$, having a weighted mean value of $36.39 \pm 0.04$ eV. Measurements with protons also gave values higher than $\bar{W}_\beta$; for example, Schaller et al. (13) measured 37.0 eV using 1 MeV protons. These differences are even greater for ions of higher charge. Varma and his colleagues (9,10) have reported values of $38.6 \pm 0.5$ eV per ion pair in nitrogen for 35 MeV and 41.1 MeV oxygen ions, respectively.

Such differences in the values of $\bar{W}$ suggested the need to study variations in the differential values, $\bar{w}(E)$, as a function of both charge state and energy of the ion. Jesse (14) investigated the value of $\bar{w}(E)$ for alpha particles with initial energy of a few MeV which represents an average over the entire range of the particle. In some careful experiments in nitrogen, Jesse showed that $\bar{W}$ was a function of alpha particle velocity, increasing as the particle slowed down. This increase in $\bar{W}$ with decrease in velocity has been experimentally confirmed by many authors (10,15,16,17). "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. (18)" (11).

Jesse (14) also concluded that, for alpha particles in nitrogen, $\bar{w}(E)$ tended to the value $\bar{W}_\beta$, for alpha particle energies above 4 MeV.
This conclusion was based upon the assumption, now known to be incorrect, that $W_0$ was independent of electron energy and that the values of stopping power for both electrons and heavy ions predicted by the Bethe equations were quite similar at high energies. The recent work of Lindhard (19) indicates the presence of charge-dependent terms in the expression for stopping-power and removes this similarity. Thus, while the theoretical support for Jesse's conclusion is without foundation, measurements by Bakker and Segré (20) seemed to confirm this tendency towards $W_0$ for the value of $\bar{w}(E)$ in the case of 300 MeV protons. More recently Goodman et al. (3) have reported that the effective value of $\bar{w}(E)$ in tissue-equivalent gas for 429 MeV/amu Ar^{18+} ions was the same as that for $^{137}$Cs photons.

While it is now understood that $\bar{w}(E)$ is a function of ion velocity, and the details of this variation are becoming quite well understood at ion energies of a few/amu and lower, our understanding is not yet sufficient to permit confident extrapolation to the energy region of interest here (a few hundred MeV/amu). Measurement of $\bar{w}(E)$ at high energies is needed. Few such measurements have been published in the literature and the differential value, $\bar{w}(E)$, of $38.6 \pm 1.16$ eV for oxygen ions of energy between 15 and 35 MeV in nitrogen measured by Varma et al. (10) did not differ significantly from the integral value of $38.6 \pm 0.54$ eV. Measurements are reported in this paper for ions of energy 250 MeV/amu, 375 MeV/amu, and 479 MeV/amu. Varma and Baum (11) have reported indications that $\bar{W}$ values depend upon the charge state of the ion at energies of $\sim 3$ MeV/amu and lower. It is important to study the dependance of $\bar{w}(E)$ on ion charge state at energy range of the Bevalac. Measurements of $\bar{w}(E)$ are reported in this paper for ions of charge $6^+$, $10^+$ and $18^+$. 
EXPERIMENTAL TECHNIQUES

1. The Biology and Medicine Division Ionization Chambers

The Biology and Medicine Division of the Lawrence Berkeley Laboratory has designed large parallel-plate, nitrogen-filled ionization chambers for dosimetry in radiobiological experiments. These chambers are constructed to present a minimum of absorbing material (~0.05 g cm\(^{-2}\)) in the heavy ion beam path. The electronic equilibrium established in the air-path through which the beam passes before entering the chamber is essentially maintained as the beam passes through the chamber. The collecting electrodes of the chambers are circular in cross section, are spaced 1 cm from the high voltage electrode, and are placed at right angles to the incident beam direction.

Many radiobiological experiments at the Bevalac utilize rather large irradiation fields (typical beam dimensions might in some cases be a full-width, half maximum of 10-12 cm). Chambers have been constructed with collecting electrodes up to 18 cm in diameter to make measurements in such radiation fields. Each collecting electrode is divided into several regions which makes it possible to use the chambers to explore the uniformity of the radiation fields used in the experiments. Two types of chambers, of different size, were used in these measurements. The smaller of the two (chamber A) was used for the carbon ion measurements; the larger chamber (chamber B) was used for the neon ion and argon ion measurements. The dimensions of both chambers are given in Table 1. Each region of these chambers may be operated as an independent ionization chamber, if desired, making separate determinations of \(\bar{w}(E)\) possible. When the chambers are used in this way, \(\bar{w}(E)\) is given by (Appendix 1):
\[ \bar{w}(E) = 10^6 \rho \frac{dE}{dx} N_2 \frac{Q(r_1, r_2)}{Q(r_1, r_2)} \]  

(2)

where \(Q(r_1, r_2)\) is the charge collected on the annular electrode (inner radius \(r_1\), outer radius \(r_2\)), and \(N(r_1, r_2)\) is the corresponding number of particles traversing the region (for the central circular electrode \(r_1 = 0\)).

Equation (2) assumes that all the ions produced between \(r_1\) and \(r_2\) are collected and are due to the particle fluence between these radii.

A possible source of systematic error in the technique used here is that the delta rays produced in the nitrogen gas of the ionization chamber have ranges which are greater than the dimensions of each annulus. The measured charge is therefore not necessarily correlated with the measured fluence. Errors due to this effect were minimized in the experimental design by making measurements in as uniform a beam as possible. Inspection of the measurements made for all six regions of the chamber in the various beam distributions used enable the magnitude of this possible source of error to be assessed. Because the average beam distributions are Gaussian in character, we would expect the charge collected at the outer chamber to be slightly raised by delta-rays from the inner chamber, if the effect is significant. Equation 2 shows that we would then expect a corresponding decrease in \(\bar{w}(E)\). Inspection of the experimental data obtained for Ne\(^{10+}\) and Ar\(^{18+}\) ions indicate a possible trend, but more data is needed to permit firm conclusions. The magnitude of the effect is less than 4% for the outer chamber and would result in an error of less than 1% in the value of \(\bar{w}(E)\) obtained by combining data from all chambers. Systematic investigation by varying beam size would better quantify the effect.

The ionization chambers were operated under conditions where an increase
In applied voltage on the collecting electrode resulted in no detectable increase in charge collected.

2. Radiation Fields

In order to obtain measurements using all regions of the large ionization chambers, beam focusing elements were adjusted to produce as large a beam spot as feasible, with minimal divergence at the ionization chamber. Typical beam dimensions have full-width, half maximum of 10-12 cm.

Beam intensities at the Bevalac are not sufficient to provide a uniform particle flux density over radiation fields as large as those used in these measurements using only the beam focusing elements. Many measurements have been made to explore the beam intensity distribution of large radiation fields at the Bevalac (4,5,8). They all show that for the defocused beam the intensity is not generally uniform or symmetrical about the beam axis, but the average particle fluence $\hat{\phi}(r)$ at a given distance $r$ from the beam axis is well expressed by a Gaussian distribution of the form:

$$\hat{\phi}(r) = \phi_o e^{-r^2/2\sigma^2},$$

where $\phi_o$ is the particle fluence on the beam axis and $\sigma$ is the standard deviation of the distribution. ($\sigma$ is related to the full width half maximum of the distribution (FWHM) by: FWHM = 2.355$\sigma$).

3. Particle Fluence Crossing the Chamber Regions

It was found convenient to sample the particle fluence over small regions using calibrated thermoluminescent dosimeters (see section 4). Dosimeters were placed on the beam axis and at the mid-radius of the annular regions of the ionization chambers. From these measurements the values
of $\phi_0$ and $\sigma$ in Eq. (3) could be determined and the number of particles crossing the chamber calculated.

In the case of the central chamber, where a dosimeter is placed on the beam axis, determining $\phi_0$, the total number of particles crossing a circle of radius $r$, $N(r)$, is given by:

$$N(r) = 2\pi r^2 \phi_0 (1 - e^{-r^2/2\sigma^2})$$  \hspace{1cm} (4)

It is sometimes convenient to relate the particle flux to the measured average fluence $\hat{\phi}_m$ and to the collecting plate area $A$, by a geometrical factor $F_c$, defined by:

$$F_c A = 2\pi r^2 \phi_0 (1 - e^{-r^2/2\sigma^2})$$

whence, for the central circular collecting region,

$$F_c = \frac{2\sigma^2}{r^2} (1 - e^{-r^2/2\sigma^2})$$  \hspace{1cm} (5)

In the case of an annular region, where dosimeters were placed at mid-radius, determining $\hat{\phi}(r_m)$, the number of particles crossing the region is given by:

$$N(r_i, r_{i+1}) = 2\pi \sigma^2 \hat{\phi}(r_m) \begin{bmatrix} -\frac{r_i^2}{2\sigma^2} & -\frac{r_{i+1}^2}{2\sigma^2} \\ e^{-\frac{r_i^2}{2\sigma^2}} - e^{-\frac{r_{i+1}^2}{2\sigma^2}} \\ e^{-\frac{r_m^2}{2\sigma^2}} \end{bmatrix}$$  \hspace{1cm} (6)

Where $r_m = \frac{r_{i+1} + r_i}{2}$.

We may define a geometrical factor, $F_a$, as before, which for annular regions is given by:
Substitution into Eqs. (5) and (7) shows that, for the chambers and radiation fields used in these measurements, the geometrical corrections were small and always less than 2%.

Given the geometrical factors we may then write:

\[
N_{r_i, r_{i+1}} = F(\sigma_{r_i, r_{i+1}}) \hat{\phi}^m A,
\]

where \(\hat{\phi}^m\) is to be determined experimentally and \(A\) is the collecting plate area.

4. Experimental Determination of Particle Fluence

The average particle fluence at a fixed radius \(r\), \(\hat{\phi}(r)\) is defined by:

\[
\hat{\phi}(r) = \frac{1}{2\pi} \int_0^{2\pi} \phi_r(\theta) \, d\theta,
\]

where \(\phi_r(\theta)\) is the ion fluence at \(r, \theta\).

Two different techniques were used to determine \(\hat{\phi}(r)\). In the first, used only for the carbon ion measurements, an array of thermoluminescent dosimeters was rotated about the beam axis. The parameters \(\hat{\phi}_o\) and \(\sigma\) of the Gaussian distribution could then be determined and \(\hat{\phi}(r)\) calculated.

In the second technique, used for all ion species, dosimeters were placed in a lucite plate which was mounted on the downstream face of the ionization chamber and centered on the beam axis. For the neon and argon ion measurements, this lucite plate was 0.2 in. thick; a series of small
holes was drilled into the back face of the plate so that two TLD chips could be located in each hole and held firmly by a lucite coverplate. The depth of these holes was such that 0.125 in. of lucite covered the dosimeter on the upstream face of the lucite plate. Holes were located at the center of the circular chamber and at the midradii of the annular chambers. Dosimeters were therefore placed at distances of 0 cm, 1 cm, 2 cm, 3.5 cm, 5.5 cm, and 7.5 cm from the center of the plate. With the exception of the smallest one, each annular chamber had 12 corresponding dosimeter holes at midradius spaced at $30^\circ$ intervals on the lucite plate; on the smallest annular chamber, it was possible to locate only six holes at intervals of $60^\circ$. Thus the lucite plate had 55 dosimeter locations with two dosimeters placed at each location. In the radiation fields used in these measurements, the line-integral of Eq. (9) may be approximated by the average of the dosimeter readings at radius $r$:

$$\hat{\phi}(r) = \frac{1}{2\pi} \int_0^{2\pi} \phi(r) \, d\theta = \frac{1}{n} \sum_{i=1}^{n} gL_i(r),$$  \hspace{1cm} (10)$$

where there are $n$ dosimeters at distance $r$ from the beam axis, $L_i(r)$ is the reading of the $i$th dosimeter, and $g$ is a factor that converts dosimeter readings to heavy fluence.

A comparison of the two experimental techniques for determining $\hat{\phi}(r)$, using carbon ions, gave agreement to better than 5%.

5. Absolute Calibrations of Thermoluminescent Dosimeters

The quantity of light emitted, $L$, in arbitrary units, emitted by a dosimeter exposed to a fluence, $\phi$, if charged particles is given by:
\[ L = 1.602 \times 10^{-8} \cdot \varepsilon \cdot \frac{T}{f} \left( \frac{dE}{dx} \right)_{\text{LiF}} \phi \]  

(11)

where \( \varepsilon \) is the dosimeter efficiency for the ions relative to \(^{60}\text{Co}\) photons, defined by:

\[ \varepsilon = \frac{\text{Quantity of light emitted per unit absorbed dose from irradiation by heavy ions}}{\text{Quantity of light emitted per unit absorbed dose from irradiation by } ^{60}\text{Co} \text{ photons}} \]

and \( T \) is the light emitted per unit exposure (R).

The value of \( f \) is 0.805 rads/R (21); substituting into Eq. (11) and rearranging, we see that in a uniform radiation field the ion fluence, \( \phi \), is given by:

\[ \phi = 5.025 \times 10^{-7} \frac{L}{\varepsilon T \left( \frac{dE}{dx} \right)_{\text{LiF}}} \]  

(12)

Comparison with Eq. (10) shows that \( g \) is given by:

\[ g = \frac{5.025 \times 10^{-7}}{\varepsilon T \left( \frac{dE}{dx} \right)_{\text{LiF}}} \]  

(13)

Thus, if \( L, \varepsilon, \) and \( T \), are measured and \( (dE/dx)_{\text{LiF}} \) calculated, the ion fluence can be determined.

Smith et al. (5) have described the techniques used to calibrate the thermoluminescent dosimeters in terms of particle fluence. Two methods have been used in the work reported here. In the first method, thermoluminescent dosimeters were exposed, simultaneously with visual detectors (e.g., nuclear emulsion (4), AgCl crystals (4)), to a few rads or less. The visual detector was then optically scanned and the dosimeter reading calibrated in terms of incident ion fluence. The known linearity of TLD
response with absorbed dose up to several hundred rads enabled the dosimeters to transfer the visual detector calibration.

In the second method, thermoluminescent dosimeters were irradiated simultaneously with activation detectors. A convenient reaction is the production of $^{11}\text{C}$ from $^{12}\text{C}$ (22,23). This second technique had the advantage that irradiations were performed corresponding to the absorbed doses used in radiobiological experiments; consequently, the linearity in response of the TLD's is not invoked, and the tedium of optical scanning was avoided.

Measurements of $\varepsilon$ for several charged particles have been made and are summarized in Table II. These measurements are described elsewhere (5,24,25).

When using $^7\text{LiF}$ thermoluminescent dosimeters, it is good experimental technique to expose control dosimeters to $^{60}\text{Co}$ photons concurrently with the charged particle exposures. If these control dosimeters are then annealed and read with the experimental dosimeters, possible fading or processing errors are eliminated.

6. Summary

Combining Eqs. (2), (7), (10), and (13), we obtain:

$$\bar{w}(e) = 5.025 \times 10^{13} \frac{\partial \varepsilon S F(\sigma,i,i+1)}{\varepsilon T} \frac{1}{n} \sum L_i(r)$$

(14)

where $S$ is the ratio of the stopping power of $\text{N}_2$ to that of LiF.

In all the measurements reported here, $s$ has the value of 1 cm and substituting the value $e = 1.602 \times 10^{-19}$ coulomb we have:

$$\bar{w}(E) = 8.050 \times 10^{-6} \frac{\partial S \ v A \ L}{\varepsilon T}$$

(15)
where \( \bar{L} \) is the average thermoluminescent dosimeter reading, and \( Q_m \) is the charge collected (in coulombs); \( \bar{w}(E) \) is in eV when \( \rho \) is measured in g cm\(^{-3}\) and \( A \) in cm\(^2\).

**EXPERIMENTAL MEASUREMENTS**

Measurements of \( \bar{w}(E) \) were made using 250 MeV/amu C\(^{6+}\) ions, 375 MeV/amu Ne\(^{10+}\) ions, and 479 MeV/amu Ar\(^{18+}\) ions.

The first measurements, using carbon ions, established the general technique for the other two species of ion. The carbon ion data are, therefore, somewhat less accurate than the neon and argon data.

Table III summarizes all the relevant experimental data and the values of \( \bar{w}(E) \) that were determined.

**Sources of Uncertainty**

The coefficient of variation in the determination of the density of nitrogen, based upon measuring ambient temperature to within \( \pm 1^\circ \text{C} \) and the gas pressure to within \( \pm 5 \text{ mm. Hg} \), was calculated to be \( \pm 0.74\% \). The error in the determination of the absolute efficiency of the dosimeters, \( \varepsilon \), which is \( \pm 2.2\% \) for C\(^{6+}\) ions, \( \pm 4.1\% \) for Ne\(^{10+}\) ions, and \( \pm 4.0\% \) for Ar\(^{18+}\) ions, is determined by the number of tracks scanned in the nuclear emulsions (5,24,25). The charge collected was measured to an absolute accuracy of \( \pm 1\% \). The absolute accuracy of the calculated values of stopping power is about \( \pm 2\% \) (26,27) but the ratio of stopping powers is known to better accuracy, and a value for the coefficient of variation in \( S \) of \( \pm 1\% \) has been assumed here. In the prototype chamber (chamber A), the plate separation was known to an accuracy of \( \pm 2\% \), but in chamber B the plate separation was known to better than 1\%. (It should be noted that since different chambers were used in each run the uncertainty in chamber separation...
enters in a random sense). Uncertainties in dosimeter calibration are summarized in Table III - and, with the exception of the first carbon ion run, were \( \sim \pm 1\% \). The coefficient of variation in dosimeter reading was determined to be given by \( 2.65\%/\sqrt{n} \) where \( n \) was the number of dosimeters used. Uncertainties in the determination of the correction factors, \( F \), and ionization chamber area, \( A \), are negligible by comparison. The coefficients of variation on the values of \( w(E) \) obtained were calculated to be between \( \pm 4\% \) and \( \pm 5\% \).

**Summary of Data and Conclusions**

The values of \( \bar{w}(E) \) obtained were:

- 250 MeV/amu C\(^{6+}\) ions: \( 36.4 \pm 0.6 \) eV
- 375 MeV/amu Ne\(^{10+}\) ions: \( 35.4 \pm 0.8 \) eV
- 479 MeV/amu Ar\(^{18+}\) ions: \( 34.7 \pm 0.5 \) eV

From the experimental data obtained it is not possible to draw firm conclusions. There is a suggestion that \( \bar{w}(E) \) is dependent upon charge state of the ion. However, with so few measurements it is also possible to conclude that the three values of \( \bar{w}(E) \) obtained do not differ significantly from one another. If the latter suggestion is accepted and the sets of data are combined, we obtain the value \( 35.4 \pm 0.3 \) eV. Further measurements of \( \bar{w}(E) \) as a function of charge state and kinetic energy are to be encouraged to see whether a variation with charge state can be definitely established.
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APPENDIX I
CALCULATION OF \( \bar{w}(E) \) FROM IONIZATION CHAMBER MEASUREMENTS

The charge \( Q \), collected under conditions of electronic equilibrium as a result of the passage of a number \( N \) of particles across the plates of a parallel-plate ionization chamber placed normally to a uniform, parallel charged particle beam, is related to the average energy required to create an ion pair, \( \bar{w}(E) \) by the equation:

\[
\bar{w}(E) = \frac{p e N}{Q} \Delta E, \tag{A1}
\]

where \( \bar{w}(E) \) is measured in eV and:
- \( p \) is the density of nitrogen in the ionization chamber, g cm\(^{-3} \);
- \( e \) is the electronic charge, coulomb;
- \( \Delta E \) is the energy absorbed in the gas, eV.

Because the change in velocity of the charged particle in passing through the nitrogen gas is small, the mass stopping power of the particles is essentially constant and Eq. (A1) may be written:

\[
\bar{w}(E) = 10^6 s e \left( \frac{dE}{dx} \right)_{N_2} \cdot \frac{N}{Q}, \tag{A2}
\]

where
- \( s \) is the separation between the collection plates, cm
- \( (dE/dx)_{N_2} \) is the mass stopping power of the particles in the nitrogen within the chamber, MeV g\(^{-1} \) cm\(^2 \).

The parameters \( N \) and \( Q \) can be measured experimentally; the mass-stopping power of the ions in the gas can be calculated with good accuracy (26,27) and thus \( \bar{w}(E) \) determined.
### TABLE I

Dimensions of the Ionization Chambers

<table>
<thead>
<tr>
<th>Chamber</th>
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<td>Annular</td>
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<td>6.5</td>
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<td>Annular</td>
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<td>8.5</td>
</tr>
<tr>
<td>Irradiation</td>
<td>Energy (MeV/μ)</td>
<td>Stopping Power in $^7$LiF (MeV g⁻¹cm²)</td>
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<td>----------------</td>
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<tr>
<td>$^{60}Co$ Photons</td>
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<td>$H^1^+$</td>
<td>798</td>
<td>1.89</td>
<td>1.08 ± 0.08</td>
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</tr>
<tr>
<td>$C^6^+$</td>
<td>252</td>
<td>116</td>
<td>0.89 ± 0.02</td>
<td></td>
</tr>
<tr>
<td>$O^8^+$</td>
<td>1050</td>
<td>112</td>
<td>0.90 ± 0.05</td>
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<tr>
<td>$O^8^+$</td>
<td>300</td>
<td>186</td>
<td>0.82 ± 0.05</td>
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</tr>
<tr>
<td>$Ne^{10+}$</td>
<td>375</td>
<td>259</td>
<td>0.73 ± 0.03</td>
<td></td>
</tr>
<tr>
<td>$Al^{18+}$</td>
<td>447</td>
<td>749</td>
<td>0.52 ± 0.02</td>
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</table>
Table III

Summary of $\bar{w}(E)$ Measurements

<table>
<thead>
<tr>
<th>Run Number/ Chamber region</th>
<th>Nitrogen density, $c$ (g cm$^{-3}$)</th>
<th>Beam size, FWHM (cm)</th>
<th>Dosimeter calibration, (TLU/R) factor, $F$</th>
<th>Geometrical plate area, $A$ (cm$^2$)</th>
<th>Collection reading, $L$ (TLU)</th>
<th>Average thermo-luminescent dosimeter reading, $Q$ (C x 10$^8$)</th>
<th>$\bar{w}(E)$</th>
</tr>
</thead>
<tbody>
<tr>
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<tr>
<td>C$^{6+}$ ions; 250 MeV/u; $c = 0.89$; $S = 1.07$; weighted mean $\bar{w}(E) = 36.4 \pm 0.6$ eV</td>
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</tr>
<tr>
<td>1/A5</td>
<td>1.21 x 10$^{-3}$</td>
<td>11.3</td>
<td>1.20 $\pm$ 0.04$^b$</td>
<td>0.996</td>
<td>28.27</td>
<td>71.2</td>
<td>55.44</td>
</tr>
<tr>
<td>2/A5</td>
<td>1.21 x 10$^{-3}$</td>
<td>11.3</td>
<td>1.20 $\pm$ 0.04$^b$</td>
<td>0.996</td>
<td>28.27</td>
<td>71.2</td>
<td>73.4</td>
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<tr>
<td>3/A5</td>
<td>1.21 x 10$^{-3}$</td>
<td>10.2</td>
<td>3.806 $\pm$ 0.025</td>
<td>0.996</td>
<td>28.27</td>
<td>71.2</td>
<td>17.09</td>
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<td>4/A5</td>
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<td>3.730 $\pm$ 0.025</td>
<td>0.996</td>
<td>28.27</td>
<td>71.2</td>
<td>17.09</td>
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<td>5/A5</td>
<td>1.19 x 10$^{-3}$</td>
<td>13.9</td>
<td>3.741 $\pm$ 0.025</td>
<td>0.997</td>
<td>28.27</td>
<td>71.2</td>
<td>33.80</td>
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<td>0.997</td>
<td>28.27</td>
<td>71.2</td>
<td>38.30</td>
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<tr>
<td>Ne$^{10+}$ ions; 375 MeV/u; $c = 0.73$; $S = 1.08$; weighted mean $\bar{w}(E) = 35.4 \pm 0.8$ eV</td>
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<tr>
<td>1/B1</td>
<td>1.135 x 10$^{-3}$</td>
<td>12.2</td>
<td>5.037 $\pm$ 0.056</td>
<td>0.998</td>
<td>0.7854</td>
<td>202.5(2)</td>
<td>1.19</td>
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<td>2/B2</td>
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<td>0.995</td>
<td>6.283</td>
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<tr>
<td>3/B3</td>
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<td>0.996</td>
<td>12.57</td>
<td>186.8(24)</td>
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<td>4/B4</td>
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<td>0.985</td>
<td>43.98</td>
<td>152.0(24)</td>
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<tr>
<td>5/B5</td>
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<td>0.989</td>
<td>69.12</td>
<td>116.2(24)</td>
<td>61.4</td>
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<tr>
<td>Ar$^{18+}$ ions; 479 MeV/u; $c = 0.523$; $S = 1.085$; weighted mean $\bar{w}(E) = 34.7 \pm 0.5$ eV</td>
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<tr>
<td>1/B1</td>
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<td>12.7</td>
<td>4.867 $\pm$ 0.042</td>
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<td>0.989</td>
<td>69.12</td>
<td>443.1(24)</td>
<td>342.5</td>
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<td>2/B1</td>
<td>1.140 x 10$^{-3}$</td>
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<td>43.33</td>
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<td>0.993</td>
<td>94.28</td>
<td>254.5(24)</td>
<td>265.1</td>
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</tbody>
</table>

$^a$Figures in parentheses refer to number of dosimeters.

$^b$The TLD reader used during these runs was different from that used in all other runs.
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