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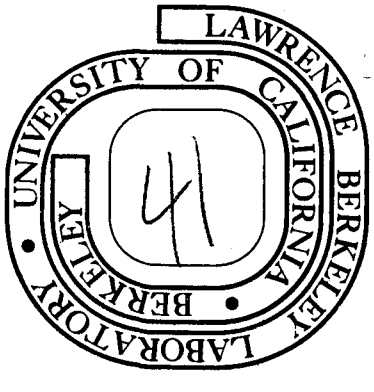

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# A Measurement of the Average Energy Required to Create an Ion Pair in Nitrogen by High-Energy Ions

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W IN NITROGEN FOR HIGH-ENERGY IONS

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At energies above ~10 MeV/amu, it is expected that the average energy required to create an ion pair, 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 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 36.3 $\pm$ 1.9, 35.3 $\pm$ 1.5, and 34.6 $\pm$ 1.4, respectively, were obtained for nitrogen gas . These values are in agreement with one another and, within the experimental errors, are consistent with the value of 34.6 $\pm$ 0.3 eV for electrons. Treating the 22 measurements as independent determinations of W for high-energy ions gives a value of W of 35.2 $\pm$ 0.9 eV/ion pair.

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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 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).

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 W required to produce an iron pair in the nitrogen gas is known.

Determinations of W for charged particles in the energy range of the Bevalac (200-2000 MeV/amu) are therefore needed. Apart from the report of preliminary measurements by one of the present authors, no values of W for high energy charged particles with $Z$ greater than 2 have been published in the literature (5,7).

Several years ago Whyte (8) reviewed published experimental values of W for electrons and found no significant variations with electron or photon energy, and calculated a "best value" of $34.6 \pm 0.3$ eV. The value of W for electrons, often referred to in the literature as $W_\beta$, is thus known to better than 1%.

It is known that at energies of a few MeV/amu the value of W for nuclei differs significantly from that for electrons. Thus, Whyte (8) pointed out that published measurements of W for alpha particles in the energy range 5-6 MeV were somewhat higher than $W_\beta$, having a weighted mean value of 36.39 $\pm$ 0.04 eV. Measurements with protons also gave values higher than $W_\beta$; for example, Schaller et al. (9) measured 37.0 eV using 1 MeV protons. These differences are even greater for ions of higher charge. Varma and his colleagues (10,11) have reported values of 38.6 $\pm$ 0.5 eV and 38.9 $\pm$ 0.5 eV per ion pair in nitrogen for 35 MeV and 41.1 MeV oxygen ions, respectively.

Dennis (12) has summarized experimental data on the variation of W with mass, charge, and energy for several ions in various gases. From this compilation he has derived empirical formulae that express W in terms of atomic number, mass, and kinetic energy of the ion (12,13). Adapting this empirical approach, Turner et al. (14) calculated a value of 35.1 eV for 70 MeV pions in the "plateau region," a value in good agreement with the measured value of 35.8 $\pm$ 0.7 eV by Zaider et al. (15). This agreement suggests that the empirical formulae of Dennis (12) are of value in practical dosimetry and, according to Dennis, make it possible to estimate W for any ion "with an error not exceeding 10% to 15% and possibly not exceeding 5% in many cases."

However, although the variation of W for charged particles with mass, charge, and for kinetic energy below a few MeV/amu is reasonably well understood (at least empirically) our interest in this paper is at much higher energies. Several authors have concluded that at energies above about 10 MeV/amu, W for charged particles will take on the value $W_\beta$, independent of mass, charge, or kinetic energy. For example, although the value of

36.4 eV quoted for alpha particles is higher than $W_\beta$, it represents an average over the entire range of the particle. In some careful experiments in nitrogen, Jesse (16) showed that W was a function of alpha particle velocity, increasing as the particle slowed down. He concluded that, for alpha particles in nitrogen, W tended to the value $W_\beta$ for energies above 4 MeV. This tendency toward $W_\beta$ was confirmed, for protons at high energies, by Bakker and Segrè (17). More recently, Goodman et al. (3) have reported that the effective value of W in tissue-equivalent gas for 429 MeV/amu $Ar^{18+}$ ions was the same as that for $^{137}Cs$ photons.

It is to be expected, therefore, that values of W for charged particles in the energy range 250-500 MeV/amu will have a value of 34.6 eV. Nevertheless, good experimental technique requires that W be measured. This paper describes the determination of W for 250 MeV/amu $C^{6+}$ ions, 375 MeV/amu $Ne^{10+}$ ions, and 479 MeV/amu $A^{18+}$ ions.

## IONIZATION CHAMBER THEORY

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, W, by the equation:

$$W = 10^6 \rho s e \left(\frac{dE}{dx}\right)_{N_2} \cdot \frac{N}{Q}, \qquad (1)$$

where W is measured in eV and:

$\rho$ is the density of nitrogen in ionization chamber, g $cm^{-3}$

s is the separation between the collection plates, cm

e is the electronic charge, coulomb

$\left(\frac{dE}{dx}\right)_{N_2}$ is the mass stopping power of the particles in the nitrogen within the chamber, MeV $g^{-1}$ $cm^2$.

The parameters $\rho$,N, and Q can be measured experimentally; the mass stopping power of the ions in the gas can then be calculated with good accuracy (18) and thus W determined.

## 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 so as 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, and are spaced 1 cm from the high voltage electrode and 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 make it possible to use the chambers to explore the uniformity of the radiation fields used in the experiments. Two chambers, of different size, were used in these measurements. The smaller of the two (chamber A) was used for the carbon measurements; the larger chamber (chamber B) was used for the neon and argon measurements. The dimensions of both

chambers are given in Table I. Each region of these chambers may be operated as an independent ionization chamber, if desired, making separate determinations of W possible. When the chambers are used in this way, W is given by

$$W = 10^6 \rho_{se} \left(\frac{dE}{dx}\right)_{N_2} \frac{N\{r_1,r_2\}}{Q\{r_1,r_2\}} , \qquad (1a)$$

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 (1a) assumes that all the ions produced between $r_1$ and $r_2$ are collected and are due to the particle fluence between these radii. These assumptions are reasonable because the measurements were made with beams of low divergence. Measurements made using all six regions for various beam distributions show these assumptions to be valid. 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 using only the beam focussing elements over radiation fields as large as those used in these measurements. Many measurements have explored the beam intensity distribution of large radiation fields

at the Bevalac (4,5,7). They all show that for the defocussed 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:

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

where $\phi_o$ is the particle fluence on the beam axis and $\sigma$ is the standard deviation of the distribution.[1]

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 midradius of the annular regions of the ionization chambers. From these measurements the values of $\phi_0$ and $\sigma$ in Eq. (2) 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 $\phi_o$, the total number of particles crossing a circle of radius r, N(r), is given by:

$$N(r) = 2\pi\sigma^2\phi_o\left(1 - e^{-r^2/2\sigma^2}\right) . \qquad (3)$$

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:

$$F_c\hat{\phi}_m A = 2\pi\sigma^2\phi_0\left(1 - e^{r^2/2\sigma^2}\right) ,$$

whence, for the central circular collecting region,

$$F_c = \frac{2\sigma^2}{r^2}\left(1 - e^{-r^2/2\sigma^2}\right) \tag{4}$$

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

$$N\{r_i, r_{i+1}\} = 2\pi\sigma^2\hat{\phi}(r_m)\left[\frac{e^{-r_i^2/2\sigma^2} - e^{-r_{i+1}^2/2\sigma^2}}{e^{-r_m^2/2\sigma^2}}\right] \tag{5}$$

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:

$$F_a = \frac{2\sigma^2}{r_{i+1}^2 - r_i^2}\left[\frac{e^{-r_i^2/2\sigma^2} - e^{-r_{i+1}^2/2\sigma^2}}{e^{-r_m^2/2\sigma^2}}\right] . \tag{6}$$

Substitution into Eqs. (4) and (6) 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:

$$N\{r_i, r_{i+1}\} = F(\sigma, i, i+1)\ \hat{\phi}_m A \quad , \tag{7}$$

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:

$$\hat{\phi}(r) = \frac{1}{2\pi}\int_0^{2\pi} \phi_r(\theta)\ d\theta \quad , \tag{8}$$

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 dosimeters[2] was rotated about the beam axis. The parameters $\phi_0$ 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° intervals on the lucite plate; on the smallest annular chamber, it was possible only to locate six holes at intervals of 30°. 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. (8) may be approximated by the average of the dosimeter readings at radius r:

$$\hat{\phi}(r) = \frac{1}{2\pi}\int_0^{2\pi} \phi_r(\theta)\, d\theta \simeq \frac{1}{n} \sum_{i=1}^{n} gL_i(r) \quad , \tag{9}$$

where there are n dosimeters at distance r from the beam axis, $L_i(r)$ is the reading of the dosimeter of the ith dosimeter, and g is a factor that converts dosimeter readings to heavy ion 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 (TLU), emitted by a dosimeter exposed to a fluence, $\phi$, of charged particles is given by:

$$L = 1.602 \times 10^{-8} \cdot \varepsilon \cdot \frac{\tau}{f} \left(\frac{dE}{dx}\right)_{LiF} , \qquad (10)$$

where $\varepsilon$ is the dosimeter efficiency for the ions relative to $^{60}Co$ photons[3] and $\tau$ is the light emitted per unit exposure (R). The value of f is 0.805 rads/R (19); substituting into Eq. (10) and rearranging, we see that in a uniform radiation field the ion fluence, $\phi$, is given by:

$$\phi = \frac{5.025 \times 10^{7}}{\varepsilon\tau\left(\frac{dE}{dx}\right)_{LiF}} \; L . \qquad (11)$$

Comparison with Eq. (9) shows that g is given by:

$$g = \frac{5.025 \times 10^{7}}{\varepsilon\tau\left(\frac{dE}{dx}\right)_{LiF}} \qquad (12)$$

Thus, if L, $\varepsilon$, and $\tau$ are measured and $\left(\frac{dE}{dx}\right)_{LiF}$ 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 $^{11}C$ from $^{12}C$ (20,21). 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 $\varepsilon$ the charged particle irradiation have been made and are summarized in Table II. These measurements are described elsewhere (5,22,23).

When using $^{7}LiF$ thermoluminescent dosimeters it is good experimental technique to always expose control dosimeters to $^{60}Co$ 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. (1a), (7), (9), and (12) we obtain:

$$W = 5.025 \times 10^{13} \frac{\rho s e S}{\varepsilon \tau} \frac{F(\sigma,i,i+1)A}{Q\{r_1,r_{i+1}\}} \left\{\frac{1}{n}\sum L_i(r)\right\} \quad , \qquad (13)$$

where S is the ratio of the stopping power of $N_2$ 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:

$$W = 8.050 \times 10^{-6} \frac{\rho s}{\varepsilon \tau} \cdot FA \frac{\hat{L}}{Q_m} \quad , \qquad (14)$$

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

## EXPERIMENTAL MEASUREMENTS

Measurements of W were made using 250 MeV/amu $C^{6+}$ ions, 375 MeV/amu $Ne^{10+}$, 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 W that were determined.

The largest sources of statistical fluctuations in the values of W are due to variations in sensitivity of the individual thermoluminescent dosimeters and in the accuracy of the dosimeter calibration, and to inhomogeneities in the radiation field. The dosimeters used in these measurements were selected to lie within $\pm$5% of the mean of the batch. The standard deviation of a single dosimeter reading was determined to be $\pm$2.65%. Thus, in those cases where 12 or more dosimeters were used, the standard deviation on the mean, assuming a uniform radiation intensity, would be less than 1%. Statistical fluctuations due to beam inhomogeneity are more difficult to assess. It is greatest for the central collecting region where dosimeters are placed only at the center of the electrode. Analysis of the data of Table III shows that the standard deviation of a single estimate of W is $\pm$3.3%; it is estimated that about 3% of this is due to beam nonuniformity. The influence of this source of fluctuations was reduced in these measurements by using six separate radiation fields. 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. Inspection of Eq. (14) shows that the major source of systematic error

is the absolute accuracy with which the charge collected is measured; in this case the accuracy was judged to be ±1%.

In the prototype chamber (chamber A) the plate separation was known to an accuracy of ±2% but in Chamber B the plate separation was known to better than 1%. Uncertainties in the density of nitrogen, ratio of stopping power, collecting plate area, and geometrical correction factors are negligible by comparison.

Combining these errors we obtain values of W of 36.3 ± 1.9, 35.3 ± 1.5, and 34.6 ± 1.4 eV/ion pair for carbon, neon, and argon ions, respectively, where the errors quoted are now absolute errors.

## CONCLUSIONS AND SUMMARY

The three values of W obtained are in agreement with each other and with the value of 34.6 ± 0.3 eV/ion pair for electrons. While (as always) more measurements are needed at different energies and with different species of ions the present data are consistent with the suggestion that at these energies W is independent of ion charge and kinetic energy and has the value 34.6 eV/ion pair. Combining these three sets of data as a value of W for high energy charged particles in nitrogen, we obtain a value of 35.2 ± 0.9 eV/ion pair.

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## FOOTNOTES

[1]The full width, half maximum (FWHM) of the distribution is given by:

$FWHM = 2.355\ \sigma$.

[2]1/8-in. x 1/8-in. x 0.035-in. Harshaw $^{7}LiF$ thermoluminescent dosimeters were used during these measurements.

[3]$\varepsilon$ is defined by:

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

TABLE I

Dimensions of the Ionization Chambers

| Chamber | Region | Geometrical shape | Inner radius (cm) | Outer radius (cm) |
|---|---|---|---|---|
| A | 1 | Circular | 0 | 1 |
| | 2 | Annular | 1 | 2 |
| | 3 | Annular | 2 | 3 |
| | 4 | Annular | 3 | 4 |
| | 5 | Annular | 4 | 5 |
| B | 1 | Circular | 0 | 0.5 |
| | 2 | Annular | 0.5 | 1.5 |
| | 3 | Annular | 1.5 | 2.5 |
| | 4 | Annular | 2.5 | 4.5 |
| | 5 | Annular | 4.5 | 6.5 |
| | 6 | Annular | 6.5 | 8.5 |

TABLE II
Summary of Measurements for $^{7}LiF$ Thermoluminescent Dosimeters

| Irradiation | Energy (MeV/amu) | Stopping power in $^{7}LiF$ (MeV $g^{-1}cm^{2}$) | $\varepsilon$ |
|---|---|---|---|
| $^{60}C_0$ Photons | | 2.5 | 1.00 |
| $H^{1+}$ | 798 | 1.89 | 1.08 $\pm$ 0.08 |
| $C^{6+}$ | 252 | 116 | 0.89 $\pm$ 0.02 |
| $O^{8+}$ | 1050 | 112 | 0.90 $\pm$ 0.05 |
| $O^{8+}$ | 300 | 186 | 0.82 $\pm$ 0.05 |
| $Ne^{10+}$ | 375 | 259 | 0.73 $\pm$ 0.03 |
| $A^{18+}$ | 447 | 749 | 0.52 $\pm$ 0.02 |

TABLE III
Summary of W Measurements

| Run number / Chamber region | Nitrogen density, ρ ($g\ cm^{-3}$) | Beam size, FWHM (cm) | Dosimeter calibration, (TLU/R) | Geometrical factor, F | Collection plate area, A ($cm^2$) | Average thermoluminescent dosimeter reading, L (TLU)[a] | Charge collected, Q ($C \times 10^8$) | W[b] (eV) |
|---|---|---|---|---|---|---|---|---|
| $C^{6+}$ ions; 250 MeV/amu; ρ = 0.89; s = 1.07; weighted mean W = 36.3 ± 0.4[b] (±1.9)[c] eV | | | | | | | | |
| 1/A5 | $1.21 \times 10^{-3}$ | 11.3 | 1.20 ± 0.04[d] | 0.996 | 28.27 | 71.2 | 55.44 | 35.3 ± 1.0 |
| 2/A5 | $1.21 \times 10^{-3}$ | 11.3 | 1.20 ± 0.04[d] | 0.996 | 28.27 | 142.9 | 110.9 | 35.4 ± 1.0 |
| 3/A5 | $1.21 \times 10^{-3}$ | 10.2 | 3.806 ± 0.025 | 0.996 | 28.27 | 73.4 | 17.64 | 36.0 ± 1.0 |
| 4/A5 | $1.21 \times 10^{-3}$ | 10.2 | 3.730 ± 0.025 | 0.996 | 28.27 | 71.3 | 17.09 | 36.9 ± 1.0 |
| 5/A5 | $1.19 \times 10^{-3}$ | 13.9 | 3.741 ± 0.025 | 0.997 | 28.27 | 130.4 | 33.80 | 35.8 ± 1.0 |
| 6/A5 | $1.19 \times 10^{-3}$ | 13.9 | 3.756 ± 0.025 | 0.997 | 28.27 | 70.7 | 170.60 | 38.3 ± 1.0 |
| $Ne^{10+}$ ions; 375 MeV/amu; ρ = 0.73; s = 1.08; weighted mean W = 35.3 ± 0.2[b] (±1.5)[c] eV | | | | | | | | |
| 1/B1 | $1.135 \times 10^{-3}$ | 12.2 | 5.037 ± 0.042 | 0.998 | 0.7854 | 202.5(2) | 1.19 | 35.9 ± 1.0 |
| /B2 | | | | 0.995 | 6.283 | 192.2(12) | 8.88 | 36.3 ± 0.5 |
| /B3 | | | | 0.996 | 12.57 | 186.8(24) | 17.0 | 36.9 ± 0.5 |
| /B4 | | | | 0.985 | 43.98 | 152.0(24) | 52.3 | 33.7 ± 0.4 |
| /B5 | | | | 0.989 | 69.12 | 116.2(24) | 61.4 | 34.7 ± 0.4 |
| $Ar^{18+}$ ions; 479 MeV/amu; ρ = 0.523; s = 1.085; weighted mean W = 34.6 ± 0.2[b] (±1.4)[c] eV | | | | | | | | |
| 1/B1 | $1.116 \times 10^{-3}$ | 12.7 | 4.867 ± 0.056 | 0.998 | 0.7854 | 748.9(2) | 6.251 | 36.0 ± 1.0 |
| /B2 | | | | 0.996 | 6.283 | 738.9(12) | 49.99 | 35.4 ± 0.6 |
| /B3 | | | | 0.996 | 12.57 | 677.4(24) | 94.77 | 34.3 ± 0.6 |
| /B4 | | | | 0.983 | 43.98 | 589.7(24) | 302.3 | 33.3 ± 0.5 |
| /B5 | | | | 0.989 | 69.12 | 443.1(24) | 342.5 | 33.9 ± 0.5 |
| 2/B1 | $1.140 \times 10^{-3}$ | 11.9 | 5.074 ± 0.058 | 1.000 | 0.7854 | 682.0(2) | 5.715 | 35.1 ± 0.8 |
| /B2 | | | | 0.995 | 6.283 | 659.1(12) | 43.33 | 35.7 ± 0.6 |
| /B3 | | | | 0.995 | 12.57 | 609.9(24) | 81.06 | 35.3 ± 0.6 |
| /B4 | | | | 0.984 | 43.98 | 533.2(24) | 244.9 | 35.4 ± 0.6 |
| /B5 | | | | 0.988 | 69.12 | 377.0(24) | 280.7 | 34.4 ± 0.6 |
| /B6 | | | | 0.993 | 94.28 | 254.5(24) | 265.1 | 33.7 ± 0.5 |
| Average W for 22 measurements = 35.0 ± 0.1[b] (35.2 ± 0.9)[c] eV | | | | | | | | |

[a]Figures in parentheses refer to number of dosimeters.
[b]Statistical errors.
[c]Figures in parentheses are absolute errors.
[d]The TLD reader used during these runs was different from that used in all other runs.

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