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Calculation of the Ionization Yield in He by Incident Ar^+ and H^+ Ions with the Initial Energies of 1 and 0.1 MeV

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Synopsis. The classical binary-encounter theory was used to calculate the $G(He^+)$ due to the direct action of incident particles and that due to the secondary electrons. The results show that both values depend greatly on the quality of the radiation used.

The passage of heavy ions in matter causes the formation of various excited and ionized atoms through two processes: (i) the direct action of the incident ion and (ii) the indirect action resulting from the electrons ejected in (i). This note will present the results of calculation of the number of He^+ ions produced in (i) and (ii) respectively when a 1- or 0.1-MeV Ar^+ or the proton has been completely absorbed in He at 0 °C and 1 atm.

Method of Calculation

Non-empirical calculation was made on the basis of the classical binary-encounter approximation.[1] The advantage of this method is that it gives, in a simple way, an estimate of the cross sections as reasonable as the Born approximation over a wide range of energies of the incident particles.[2]

The incident particle with a mass of M, a charge of Ze, and a velocity of V_1 is assumed to collide with the atomic electron with a mass of m, a charge of e and a velocity of v_1. Let V_2 and v_2 be their respective velocities after the collision. When the energy transferred, $E=(1/2)m(v_2^2-v_1^2)$, exceeds the ionization energy, I, of the atomic electron, the ionization of the atom occurs, the kinetic energy of the ejected electron being $E-I$.

The differential cross section, σ_E, for transferring the energy, E, is expressed as:[2]

(i) If $2V_1 \geq v_2+v_1$, $E \leq 2m_1V_1(V_1-v_1)$,

$$\sigma_E = \frac{2\pi Z^2e^4}{mV_1^2}\left(\frac{1}{E^2}+\frac{2mv_1^2}{3E^3}\right) \tag{1}$$

(ii) If $v_2-v_1 \leq 2V_1 \leq v_2+v_1$,

$2mV_1(V_1-v_1) \leq E \leq 2mV_1(V_1+v_1)$,

$$\sigma_E = \frac{\pi Z^2e^4}{3V_1^2v_1E^3}\left\{4V_1^3-\frac{1}{2}(v_2-v_1)^3\right\} \tag{2}$$

(iii) If $E/V_1 \geq m(v_2+v_1)$,

$$\sigma_E = 0 \tag{3}$$

The energy spectrum, $y_p(T)$, of the incident particle as defined by Spencer and Fano,[3] can be expressed as the inverse of its stopping power. The stopping power may be obtained by integrating $E\sigma_E$ over E from E_{min} to E_{max}. E_{min} was set equal to 21.2 eV, the lowest singlet excitation energy of He. E_{max} is given by $2mV_1(V_1+v_1)$. Once $y_p(T)$ is obtained, the number of the He^+ ions produced directly by the incident particle of initial energy, T_o, may be calculated:

$$N_p(He^+) = N\int_I^{T_o} Q_{ion}(T)\cdot y_p(T)dT \tag{4}$$

Here, $Q_{ion}(T)$ is the probability that the He^+ ion will be formed in a collision with the particle with the energy of T and is obtained by integrating σ_E over a pertinent range of E. N is the number of He atoms per unit of volume, and I, the first ionization energy of He (24.6 eV). The G-value is given by $100\cdot N_p(He^+)/T_o$.

The ionization yield due to secondary electrons was calculated as follows. The energy spectrum of the electrons was obtained by Eqs. 1, 2, and 3, with the aid of the $y_p(T)$-curve mentioned above. Then, we could use the previous results[4] to calculate the ionization yields in He due to these ejected electrons.

It should be mentioned that, in the present calculation of the stopping power of the incident particle, we neglected the contributions from such modes of energy loss as the excitations and charge exchange of the projectile (Ar^+) and nuclear collisions. These omissions may slightly decrease the $G(He^+)$ due to incident particles, but the main features of the present results would not be changed.

The applicability of the present method is demonstrated by the facts that (i) the total yield of the ionization and excitation in He by incident 100-keV electrons calculated by the present method is in agreement with the experimental results,[4,5] and that (ii) the observed spectrum of the kinetic energy of the ejected electron on impacting 100-keV protons on He[6] can be well represented by Eq. 1, as is shown in Fig. 1.

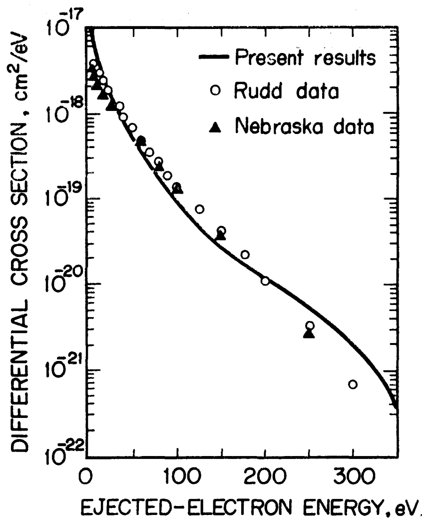

Fig. 1. Differential cross section for ejection of electrons by 100-keV protons in He.

Results

In Fig. 2, the values of $T\cdot Q_{ion}(T)\cdot y(T)$ are plotted agaisnt $\ln(T)$ according to Platzman's method.[7] The

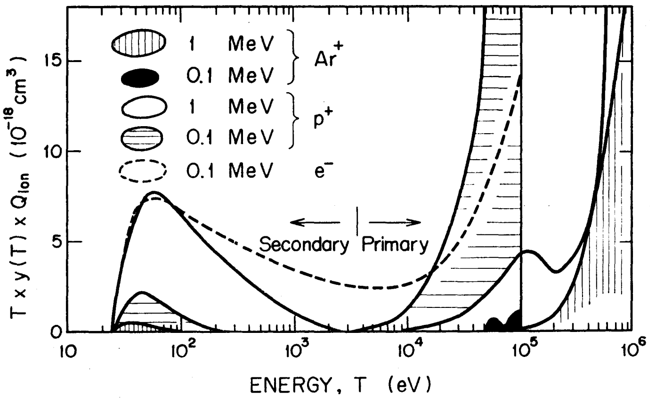

Fig. 2. Contribution of different portions of the slowing-down spectra of the incident particles ("Primary") and the ejected electrons ("Secondary") to the total ionization of He. Coordinate values for 1-MeV incident particles should be multiplied by 10.

area under the curve is proportional to the yield, thus demonstrating the contribution to the yield from a given energy range of the ion or the electrons. In the cases of 1- and 0.1-MeV Ar^+, the yield due to secondary electrons is small compared to that due to the interaction of the incident ion. In the case of the 1-MeV proton, the two processes give approximately the same yield. The energy spectrum of the secondary electrons in this case is similar to that in the case of the incident 100-keV electron.

The *G*-values of the two processes for each incident particle are compiled in Table 1.

Table 1. *G*-values of He^+ for different radiations

Incident particle	Energy (MeV)	Direct[a)]	Indirect[b)]	Total
Ar^+	1	0.59	0.02	0.61
Ar^+	0.1	0.016	0	0.016
p^+	1	1.75	1.04	2.79
p^+	0.1	1.35	0.15	1.50
e^-	0.1			2.42[c)]

a) Ionization due to the direct action of incident particles.
b) Ionization due to the electrons ejected in a).
c) From Ref. 4.

Conclusion

The observed *G*-values of the radiolysis products generally depend on the type and energy of the radiation used. Many radiation chemists seem to ascribe this effect to the different spatial distributions and not to the different primary yields of the products initially formed in the radiation action. The present calculation has been concerned only with the primary yield and not with the spatial distribution. The results clearly show that the primary yield itself depends on the quality of the radiation used. Thus, the yields in addition to the spatial distributions must be taken into consideration for a better understanding of the "LET-effect" in radiation chemistry.

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