# The mechanism and kinetics of ozone formation in a pulse radiolysis study of the Ar-O₂ system

Krzysztof Wojciechowski,
Dorota Sugier,
Karol Wnorowski,
Jan Kowalczyk,
Antoni Jówko

Abstract The mechanism and kinetics of O_3 formation after an electron pulse have been studied in the Ar-O₂ systems by time resolved optical measurements at $\lambda = 260$ nm. The second order rate constant of energy transfer from excited Ar(4s,4p) states to O_2 molecules:

(1) $Ar^*, Ar^{**} + O_2 \rightarrow O_2^* + Ar$,
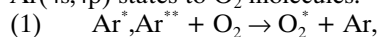
was found to be $(8.9 \pm 2.1) \times 10^{-10}$ cm³·s⁻¹. It was found also the evidence of the third order process contribution to the energy transfer:

(2) $Ar^*, Ar^{**} + Ar + O_2 \rightarrow$ products,

with the rate constant in the range $(1.5–3.7) \times 10^{-29}$ cm⁶·s⁻¹. The rate constant of the deactivation of excited ozone molecules by O_2 was found to be $(5.1 \pm 0.6) \times 10^{-15}$ cm³·s⁻¹.
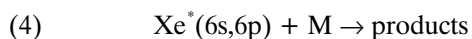
Key words pulse radiolysis • argon • oxygen • ozone

K. Wojciechowski✉, D. Sugier, K. Wnorowski,
J. Kowalczyk, A. Jówko
Department of Chemistry,
University of Podlasie,
54 3 Maja Str., 08-110 Siedlce, Poland,
Tel.: +48 25-6431007, Fax: +48 25-6442045,
E-mail: kwoj@ap.siedlce.pl

Introduction

The energy transfer process from excited rare gas atoms to various molecules was extensively studied by the Setser group [10, 12, 15], mainly for $Xe(^3P_2)$ and $Kr(^3P_2)$ lowest metastable excited states. Our earlier studies of this process showed that the rates of energy transfer from $Xe(^3P_1)$ resonance state to molecules increase with Xe pressures [17–19, 21, 22]. The same effect was found for higher excited Xe atoms generated in the pulse radiolysis experiments [20]. It was shown that the third order energy transfer reaction:

(3) $Xe^*(6s,6p) + Xe + M \rightarrow$ products
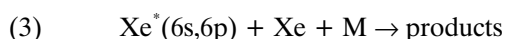
is responsible for such "pressure" effect. The rate constants of reaction (3) for a number of molecules were found to be in the range from $(1–2) \times 10^{-28}$ cm⁶·s⁻¹ for such molecules as CH_4, C_2H_6, CCl_4, $SOCl_2$ and for many other simple molecules up to 2×10^{-27} cm⁶·s⁻¹ for HCl [17–22]. In all cases, reaction (3) competes effectively with the second order energy transfer reactions:

(4) $Xe^*(6s,6p) + M \rightarrow$ products

as the k_4 rate constants are in the range from 3×10^{-10} cm³·s⁻¹ up to 8×10^{-10} cm³·s⁻¹, even for low Xe pressures (27–133 hPa).

A review of the literature data on this subject gives only little evidence of existing "third order" energy transfer from other rare gases to molecules (3). Collins and Lee [2, 3] reported this process in the He-M system with the rate constants varying from 1×10^{-30} cm⁶·s⁻¹ for

M = Kr to 8×10^{-30} cm^6·s^{-1} for M = C$_3$H$_8$. For the Ar-M system, the only evidences found for the existence of such process are for the Ar-N$_2$ system [5] and our recent pulse radiolysis data for the Ar-H$_2$O system [9].

In this paper, the results of the investigations of the energy transfer processes in Ar-O$_2$ system will be presented.

Experimental

The pulse radiolysis system is based on SINUS-5 (produced by the Institute of High Energy, Tomsk, Russia) pulsed electron accelerator giving 12 ns single 350 keV electron pulses of total energy about 8 J and dose rate D$_r$ = $(6.9 \pm 0.6) \times 10^{26}$ eV·g^{-1}·s^{-1}.

Ar-O$_2$ and Ar-O$_2$-SF$_6$ mixtures were irradiated in a stainless steel vacuum-proof chamber of volume 1000 cm^3 mounted on the accelerator output. The gases pressure in the reaction chamber was measured within 1% with an MKS 116A Baratron pressure transducer.

A xenon arc UV-VIS lamp (XHBO 150 W) was used as an analysing light source in the reaction chamber. A nine-reflection multiple-pass system with outside mounted mirrors was used for the observation of transients (λ = 91 cm). For more details see our previous papers [7, 9].

The time-resolved absorption spectra of ozone at λ = 260 nm (near the maximum, λ_{max} = 254 nm) formed during irradiation of the Ar-O$_2$ mixtures after passing through a 7400 Applied Physics 0.5-m monochromator were amplified by a Hamamatsu (R928) photomultiplier and registered by a 2440 Tektronix digital oscilloscope coupled to a PC computer. Typical oscilloscope absorption traces of ozone are shown in Fig. 1. The
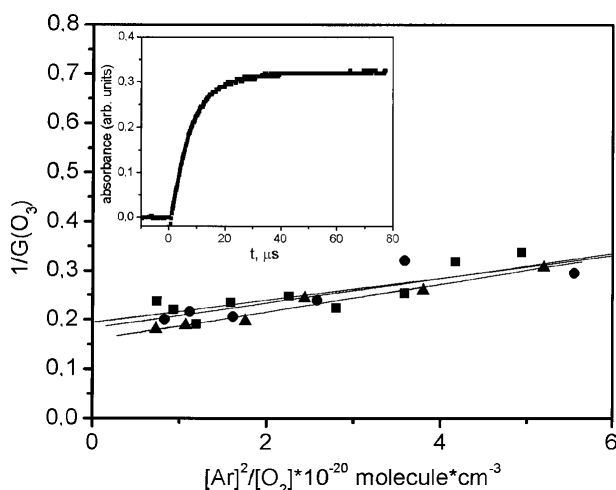

Fig. 1. The plots of $1/\Delta G(O_3)$ *vs.* [Ar]^2/[O$_2$]. (■) – the total pressure 931 hPa, P(O$_2$) range 8–186 hPa (●) – the total pressure 798 hPa P(O$_2$) range 13–130 hPa; (▲) – the total pressure 655 hPa, P(O$_2$) range 13–107 hPa. For O$_2$ pressures above 60 hPa, the amount of ozone produced directly in the radiolysis of O$_2$ were subtracted from the total ozone amount produced in the Ar-O$_2$ mixture. For the intercepts and slopes of the lines see data in Table 1. Insert figure – typical oscilloscope absorption trace of ozone registered at λ = 260 nm in the pulse radiolysis of Ar-O$_2$ mixture. (P(Ar) = 798 hPa and P(O$_2$) = 133 hPa.)

Simplex method was used for the fitting of experimental absorbance *vs.* time curves using a kinetic equation of stable species formation:
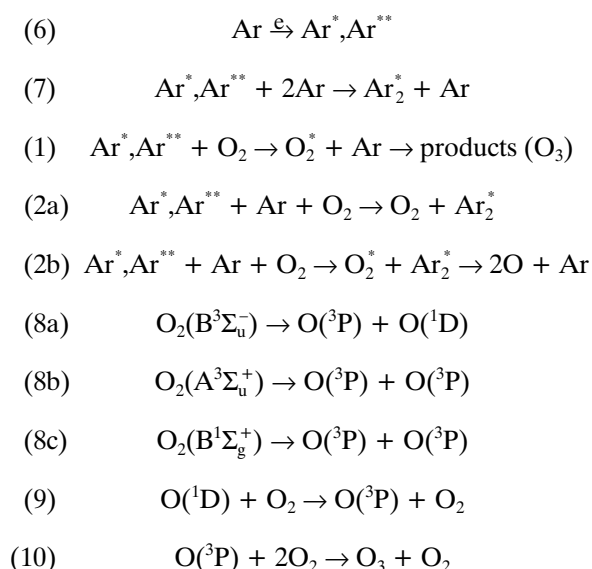
$$(5) \qquad A(t) = A_{max}(1 - \exp(-k_{exp} \cdot t))$$

where A_{max} – maximum ozone absorbance, k_{exp} – experimental pseudo-first order rate constant of ozone formation. The $G(O_3)$ values were found on the basis of ozone dosimetry ($G(O_3)$ = 6.2 for the O$_2$ + 0.5%SF$_6$ system [9]).

Oxygen and argon gases from Linde Gas Poland were used without purification. The SF$_6$ gas obtained from Merck was of research purity and before use was purified by "trap to trap" cycles. All experiments were perrormed at ambient temperatures (295 $\pm$ 3 K).

Results and discussion

In pulse radiolysis of the Ar/O$_2$ mixtures only ozone is formed as a stable product. As the stopping power is almost the same for Ar and O$_2$ (S(O$_2$) = 1.102 and S(Ar) = 1.14 [6]) at low O$_2$ concentrations (<10.0%), approximately all the amount of ozone was formed via sensitized process in which the energy is absorbed by argon and then transferred into O$_2$ molecules.

Earlier studies of rare gas radiolysis mechanism and kinetics showed that the electronically excited Ar(^{3}P$_{1,2}$), denoted below as Ar*, and higher excited Ar(4p,4d) atoms denoted below as Ar** are formed. About 40% of all the excited Ar atoms formed are in the lowest 4s states and the rest are in the Ar**(4p,4d) states [14]. The Ar* and Ar** atoms decay via energy transfer processes to O$_2$ molecules competing with the process of Ar$_2^*$ formation. A simplified reaction scheme for Ar-sensitized radiolysis of O$_2$ is shown below:

$$(6) \qquad Ar \xrightarrow{e} Ar^*, Ar^{**}$$

$$(7) \qquad Ar^*, Ar^{**} + 2Ar \rightarrow Ar_2^* + Ar$$

$$(1) \qquad Ar^*, Ar^{**} + O_2 \rightarrow O_2^* + Ar \rightarrow products\ (O_3)$$

$$(2a) \qquad Ar^*, Ar^{**} + Ar + O_2 \rightarrow O_2^* + Ar_2^*$$

$$(2b) \quad Ar^*, Ar^{**} + Ar + O_2 \rightarrow O_2^* + Ar_2^* \rightarrow 2O + Ar$$

$$(8a) \qquad O_2(B^3\Sigma_u^-) \rightarrow O(^3P) + O(^1D)$$

$$(8b) \qquad O_2(A^3\Sigma_u^+) \rightarrow O(^3P) + O(^3P)$$

$$(8c) \qquad O_2(B^1\Sigma_g^+) \rightarrow O(^3P) + O(^3P)$$

$$(9) \qquad O(^1D) + O_2 \rightarrow O(^3P) + O_2$$

$$(10) \qquad O(^3P) + 2O_2 \rightarrow O_3 + O_2$$

The steady state kinetic analysis of the above reaction scheme leads to the kinetic equation for the $G(O_3)$ dependence on O$_2$ and Ar concentrations for two cases:

$$(11) \qquad \frac{1}{G(O_3)} = \frac{1}{2G(Ar^*)} \cdot \left(1 + \frac{k_7[Ar]^2}{k_1[O_2]} + \frac{k_{2a}[Ar]}{k_1}\right)$$

$$(12) \qquad \frac{1}{G(O_3)} = \frac{1}{2G(Ar^*)} \cdot \left(\frac{\left(1 + \frac{k_7[Ar]^2}{k_1[O_2]} + \frac{k_{2b}[Ar]}{k_1}\right)}{\left(1 + \frac{k_{2b}[Ar]}{k_1}\right)}\right)$$

Kinetic eq. (11) takes into account reaction (2a) (the ozone precursors i.a. O atoms are not formed) and (12) takes into account reaction (2b) (reaction (2b) leads to O atoms – ozone precursors).

Earlier studies of the energy transfer processes for the Xe-M systems showed that for the lowest Xe(6s) states the third order energy transfer processes do not lead to the dissociation of such molecules as H$_2$S or C$_2$H$_6$ [19], but in pulse radiolysis study of the Xe-RX system (RX = CH$_2$F$_2$, CHF$_3$, CHF$_2$Cl, CHFCl$_2$ and CF$_3$Cl) the products of the third order energy transfer reaction were observed (XeCl*/XeF* excimers) [20]. It seems that in the case of radiolysis of the Ar-O$_2$ systems the third order energy transfer process should also lead to the excited O$_2$ molecules which then dissociate to O atoms.

For the constant Ar concentrations eqs. (11) and (12) give the linear plots of $1/G(O_3)$ $vs.$ $[Ar]^2/[O_2]$:

$$(13) \qquad \frac{1}{G(O_3)} = A + B\frac{[Ar]^2}{[O_2]}$$

where:

$$A = \frac{1}{2G(Ar^{*,**})} \cdot \left[1 + \frac{k_{2a}[Ar]}{k_1}\right] \qquad \text{for (11) and}$$

$$A = \frac{1}{2G(Ar^{*,**})} \qquad \text{for (12)}$$

$$B = \frac{k_7}{2G(Ar^{*,**})k_1} \qquad \text{for (11) and}$$

$$B = \frac{k_7}{2G(Ar^{*,**})(k_1 + k_{2b}[Ar])} \qquad \text{for (12)}$$

Figures 1 and 2 show the experimental plots of $1/G(O_3)$ $vs.$ $[Ar]^2/[O_2]$. The obtained intercepts (A-values) and slopes (B-values) are shown in Table 1.

From the intercept values (A), the radiation yields $G(Ar^{*,**}) = 2.83 \pm 0.22$ for the Ar-O$_2$ system and $G(Ar^{*,**}) = 1.0 \pm 0.1$ for the Ar-O$_2$-SF$_6$ system were found. The first yield is in good agreement with the literature value $G(Ar^{*,**}) = 3.05$ [8]. In the radiolysis of the Ar-O$_2$ system in the presence of SF$_6$ as an electron

Table 1. The kinetic parameters obtained from $1/G(O_3)$ $vs.$ $[Ar]^2/[O_2]$ plots shown in Figs. 1 and 2 and k_1 rate constants calculated for $k_7 = 1.28 \times 10^{-30}$ cm^6·s^{-1} and $k_2 = 0$

P(Ar) [hPa]	A	B·10^{22} [cm^3/molec.]	$((A/B)·k_7 \times 10^{10}$ $(k_1))$ [cm^3·s^{-1}]
		Ar-O$_2$	
666	0.159 ± 0.008	2.84 ± 0.27	7.2 ± 0.8
800	0.183 ± 0.017	2.53 ± 0.43	9.3 ± 1.5
933	0.194 ± 0.110	2.27 ± 0.11	10.95 ± 0.6
		Ar-O$_2$+0.5%SF$_6$	
800	0.453 ± 0.029	7.00 ± 0.50	8.3 ± 0.6

scavenger much lower $G(Ar^{*,**}) = 1.0$ value was found what suggests that a large amount excited Ar atoms $(G(Ar^{*,**}) = 1.8)$ are produced via Ar ionization processes and then ion recombination.

In Table 1, there are also shown the two body energy transfer k_1 rate constants calculated from (13) for $k_{2a} = 0$, $k_{2b} = 0$ and $k_7 = 1.28 \times 10^{-30}$ cm^6·s^{-1}. The k_7 rate constant taken for calculation is the mean value from the literature data ($k_7 = 1.23 \times 10^{-30}$ cm^6·s^{-1} [1]; 1.44×10^{-30} cm^6·s^{-1} [11]; 1.18×10^{-30} cm^6·s^{-1} [16]. The k_1 rate constant varied from 6.15×10^{-10} cm^3·s^{-1} to 11.7×10^{-10} cm^3·s^{-1} (see data in Table 1). The k_1 rate constant found from these experiments is much higher than previously found for energy transfer from Ar(4s) to O$_2$ $k_1 = 2.2 \times 10^{-10}$ cm^3·s^{-1} [15] and close to Sadeghi et al. [14] quenching rate constants for Ar(2p$_1$) ($k_1 = 7.6 \times 10^{-10}$ cm^3·s^{-1}), Ar(2p$_5$), ($k_1 = 7.2 \times 10^{-10}$ cm^3·s^{-1}), Ar(2p$_6$), ($k_1 = 4.6 \times 10^{-10}$ cm^3·s^{-1}) and Ar(2p$_8$), ($k_1 = 6.3 \times 10^{-10}$ cm^3·s^{-1}).

Taking the literature energy transfer rate constants for Ar(4s) equal to 2.2×10^{-10} cm^3·s^{-1} [5, 15], for Ar(4p) states equal to 7×10^{-10} cm^3·s^{-1} [14] and the contribution of Ar(4s) states equal to 40% of all Ar excited states formed in pulse radiolysis of argon [20], the k_1 rate
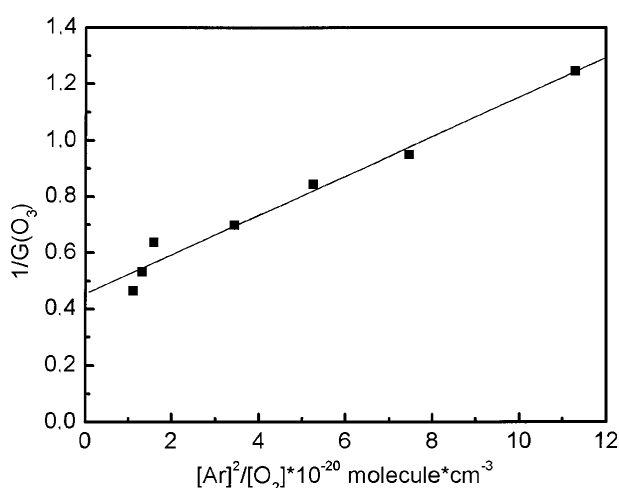

Fig. 2. The plot of $1/\Delta G(O_3)$ $vs.$ $[Ar]^2/[O_2]$ – (■) – the total pressure 798 hPa + 0.5% SF$_6$, P(O$_2$) range 13–107 hPa. For O$_2$ pressures above 60 hPa, the amount of ozone produced directly in the radiolysis of O$_2$ were subtracted from the total ozone amount produced in the Ar-O$_2$ mixture. For the intercept and slope of the line see data in Table 1.
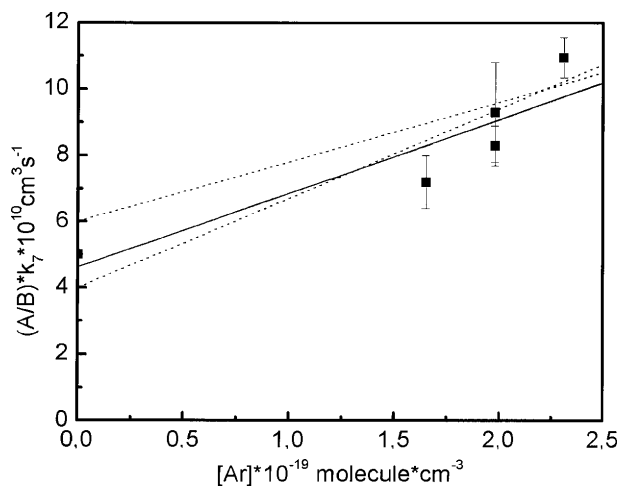
Fig. 3. The plots of $(A/B)\cdot k_7$ vs. [Ar]. Solid line for $k_1 = 5 \times 10^{-10}$ cm$^3\cdot$s^{-1} and $k_2 = 2.3 \times 10^{-29}$ cm$^6\cdot$s^{-1}. Dotted lines – simulations according to eq. (14) taking $k_1 = 4 \times 10^{-10}$ cm$^3\cdot$s^{-1} and $k_2 = 2.7 \times 10^{-29}$ cm$^6\cdot$s^{-1} (lower line) or $k_1 = 6 \times 10^{-10}$ cm$^3\cdot$s^{-1} and $k_2 = 1.8 \times 10^{-29}$ cm$^6\cdot$s^{-1} (upper line).

Fig. 4. The plots of k_{exp} vs. [O$_2$]: (■) – the total pressure of Ar + O$_2$ – 931 hPa – $k_{10} = (5.71 \pm 0.11) \times 10^{-15}$ cm$^3\cdot$s^{-1}; (●) – the total pressure of Ar + O$_2$ – 798 hPa, $k_{10} = (4.97 \pm 0.08) \times 10^{-15}$ cm$^3\cdot$s^{-1}; (▲) – the total pressure of Ar + O$_2$ – 655 hPa, $k_{10} = (5.46 \pm 0.17) \times 10^{-15}$ cm$^3\cdot$s^{-1}.

constant (energy transfer rate constant from both Ar(4s) and Ar(4p) states) value can be estimated as being equal to $(5.0 \pm 1.0) \times 10^{-10}$ cm$^3\cdot$s^{-1}. As our experimental k_1 values are higher than the above k_1 value this can be the evidence of the contribution of the third order energy transfer process (reactions (2a) and/or (2b)) in the sensitized Ar-O$_2$ radiolysis.

In Fig. 3, the plot of $(A/B)\cdot k_7$ vs. [Ar] concentration is shown. The linear dependence has been expected if reactions (2a) and/or (2b) would be included into the reaction scheme as from eqs. (11), (12) and (13) we have:

(14) $$\frac{A}{B} \cdot k_7 = k_1 + k_2[\text{Ar}]$$

As it is seen, our experimental data can be fitted as a linear dependence of $(A/B)\cdot k_7$ vs. argon pressure (the point at [Ar] = 0 was taken as being equal to 5×10^{-10} cm$^3\cdot$s^{-1}). The k_2 rate constant was found to be $(2.3 \pm 0.6) \times 10^{-29}$ cm$^6\cdot$s^{-1}. The simulations of eq. (14) for lower and higher k_1 values at [Ar] = 0 ($k_1 = 4 \times 10^{-10}$, and 6×10^{-10} cm$^3\cdot$s^{-1}) give the k_2 rate constants equal to 2.7×10^{-29} cm$^6\cdot$s^{-1} and 1.8×10^{-29} cm$^6\cdot$s^{-1}, respectively.

Unfortunately, due to the scatter of results and a relatively small Ar pressure range (666–933 hPa) at which the experiments were done, rather a low accuracy of k_1 and k_2 rate constants must be pointed out. The above discussion shows that the third order energy transfer rate constant, k_2, in the electron beam irradiated Ar-O$_2$ system should be in the range from 1.8×10^{-29} to 2.7×10^{-29} cm$^6\cdot$s^{-1}. It is in agreement with the data for Ar-H$_2$O pulse radiolysis study where the third order energy transfer rate constant was found to be $(1.8 \pm 1.4) \times 10^{-29}$ cm$^6\cdot$s^{-1} [9].

The kinetics of ozone formation

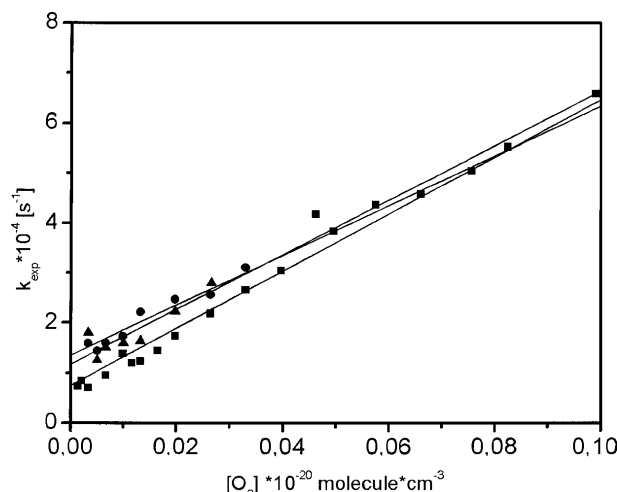Earlier studies on the kinetics of ozone formation showed that ozone is produced only in reaction (10)

with the rate constant $k_{10} = 2.8 \times 10^{-34}$ cm$^6\cdot$s^{-1} [13] (high pressure limit) as the all O(^{1}D) atoms are quenched to O(^{3}P) in a few nanoseconds ($k_9 = 4 \times 10^{-11}$ cm$^3\cdot$s^{-1} [4]) by O$_2$ molecules.
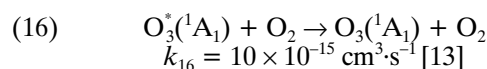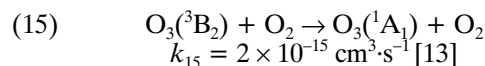
There is also strong evidence that it is a two-step process in which the excited O$_3$(^{1}A$_1$)* and O$_3$(^{3}B$_2$) molecules are formed. Stable ozone (O$_3$(^{1}A$_1$)) molecules are produced by the collisions of O$_3$(^{1}A$_1$)* and O$_3$(^{3}B$_2$) with O$_2$ molecules [13].

From the time resolved ozone absorption spectra, we have found pseudo-first order rate constants (k_{exp}) of ozone formation. In Fig. 4 there are shown the plots of k_{exp} vs. O$_2$ concentrations at constant Ar pressures. As it is seen, linear dependencies were found for all the experimental series. The slopes can be assigned to the two-body deactivation of O$_3$ excited molecules by O$_2$:

(10) $$\text{O}_3^* + \text{O}_2 \rightarrow \text{O}_3 + \text{O}_2$$
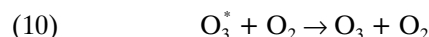
The experimental value of k_{10} is equal to $(5.4 \pm 0.3) \times 10^{-15}$ cm$^3\cdot$s^{-1}.

The analysis of Ramirez et al. [13] of the mechanism of ozone formation suggests that the k_{10} rate constant should be treated as a sum of the rates for reactions:

(15) $$\text{O}_3(^3\text{B}_2) + \text{O}_2 \rightarrow \text{O}_3(^1\text{A}_1) + \text{O}_2$$
$$k_{15} = 2 \times 10^{-15} \text{ cm}^3\cdot\text{s}^{-1} [13]$$

(16) $$\text{O}_3^*(^1\text{A}_1) + \text{O}_2 \rightarrow \text{O}_3(^1\text{A}_1) + \text{O}_2$$
$$k_{16} = 10 \times 10^{-15} \text{ cm}^3\cdot\text{s}^{-1} [13]$$

As the $[\text{O}_3^*] = [\text{O}_3(^3\text{B}_2)] + [\text{O}_3^*(^1\text{A}_1)]$, from the k_{10}, k_{15} and k_{16} rate constants it should be found that the yields of O$_3$(^{3}B$_2$) and O$_3$(^{1}A$_1$) states are equal to 0.575 and 0.425, respectively. This is in agreement with Ramirez et al. [13] data, who reported that about 60% of all excited ozone molecules are formed in O$_3$(^{3}B$_2$) states and the rest are O$_3^*$(^{1}A$_1$) molecules.

Conclusions and remarks

The analysis of the data from pulse radiolysis of the Ar-O$_2$ system showed that the excited Ar atoms are formed with the total yield $G(\mathrm{Ar}^*) = 2.83 \pm 0.22$. In the presence of an electron scavenger (SF$_6$) $G(\mathrm{Ar}^*) = 1.0 \pm 0.1$, which means that Ar* and Ar** atoms are formed also via ionization processes with the yield $G(\mathrm{Ar}^*) = 2.83 - 1.0 = 1.83$.

The O$_2$ excited molecules which then dissociate to O(^{3}P) and O(^{1}D) atoms are produced in the two-body energy transfer process (reaction (1)) with the rate constant $k_1 = (8.9 \pm 2.1) \times 10^{-10}$ cm$^3 \cdot$s^{-1}, if it is the only possible energy transfer process (i.e. $k_2 = 0$). The analysis of the experimental data showed that there is also possible the third order energy transfer process (reaction (2)). It was found that the k_2 rate constant should be equal to $(2.3 \pm 0.6) \times 10^{-29}$ cm$^6 \cdot$s^{-1}. In this case, the k_1 rate constant should have a lower value $(5 \pm 1) \times 10^{-10}$ cm$^3 \cdot$s^{-1}.

It seems that the experiments for the higher Ar pressures should give stronger evidence for the participation of reaction (2) in the energy transfer process in Ar-sensitized radiolysis.

References

1. Birot A, Brunet H, Galy J, Millet P (1975) Continuous emission of argon and krypton in the near ultraviolet. J Chem Phys 63:1469–1473
2. Collins CB, Lee FW (1979) Measurement of the rate coefficients for the bimolecular and termolecular de-excitation reactions of helium (2^{3}S) with selected atomic and molecular species. J Phys Chem 70:1275–1285
3. Collins CB, Lee FW, Tepfenhart WM, Stevefelt J (1983) Modelling of ion-molecule reactions at high pressures. J Chem Phys 98:6079–6090
4. DeMore WB, Sander SP, Golden DM *et al.* (1997) Chemical kinetics and photochemical data for use in stratospheric modelling. JPL Publication, evaluation number 12, 97-4:1
5. Firestone RF, Chen Mon-Chao (1978) Bimolecular and "three-body" quenching of resonance state argon atoms by nitrogen at argon pressures in the 200–700 torr region. J Chem Phys 69:2947–2948
6. Huyton DW, Woodward TW (1970) Ionisation measurements and some ionic reactions in gas phase radiolysis. Radiat Res Rev 2:205–234
7. Jówko A, Kowalczyk J, Wojciechowski K, Foryś M (1996) Collisional quenching of Xe and Kr excited atoms by molecular additives. Radiat Phys Chem 48:481–486
8. Jówko A, Symanowicz M, Bartkiewicz E (1985) The excitation energy transfer processes in the rare gas-hydrogen chloride systems. Radiat Phys Chem 26:49–52
9. Jówko A, Wnorowski K, Kowalczyk J, Wojciechowski K (2001) Kinetics of the OH radical formation in the pulse radiolysis of Ar-H$_2$O gaseous mixtures. Radiat Phys Chem 61:27–34
10. Klots JH, Velazco JE, Setser DW (1979) Reactive quenching studies of Xe(6s,^{3}P$_2$) metastable atoms by chlorine containing molecules. J Chem Phys 71:1247–1262
11. Langhoff H (1988) The origin of the third continua emitted by excited rare gases. Opt Comm 68:31–34
12. Piper LG, Velazco JE, Setser DW, Lo G (1979) Reactions between argon and noble gases. J Chem Phys 69:3323–3340
13. Ramirez JE, Bera Ranajit K, Hanrahan RJ (1984) Formation of ground state ozone on pulse radiolysis of oxygen. Radiat Phys Chem 23:685–688
14. Sadeghi N, Setser DW, Francis A, Czarnetzki U, Dobele HF (2001) Quenching rate constants for reactions of Ar(4p'[1/2]$_0$, 4p[1/2]$_0$, 4p[3/2]$_2$, 4p[5/2]$_2$) atoms with 22 reagent gases. J Chem Phys 115:3144–3153
15. Velazco JE, Klots JH, Setser DW (1978) Rate constants and quenching mechanisms for the metastable states of argon, krypton and xenon. J Chem Phys 69:4357–4372
16. Wieme W, Lenaerts J (1981) Excimer formaton in argon, krypton and xenon discharge afterglows between 200 and 400 K. J Chem Phys 74:483–493
17. Wojciechowski K (1998) The mechanism and kinetics of energy transfer processes in Xe-CCl$_4$-M (M = CO, CO$_2$) mixtures irradiated by xenon resonance light. Radiat Phys Chem 53:47–53
18. Wojciechowski K (1998) The mechanism and kinetics of energy transfer processes in the Xe-CCl$_4$-M (M = CH$_4$, C$_2$H$_2$, C$_2$H$_4$, C$_2$H$_6$, C$_3$H$_6$ and C$_3$H$_8$). Radiat Phys Chem 53:37–46
19. Wojciechowski K, Foryś M (1999) The mechanism of three-body process of energy transfer from excited xenon atoms to molecules. Radiat Phys Chem 54:1–10
20. Wojciechowski K, Kowalczyk J, Jówko A (1998) Pulse radiolysis study of energy transfer processes in Xe-M mixtures (M = CH$_2$F$_2$, CHF$_3$, CHF$_2$Cl, CHFCl$_2$ and CF$_3$Cl). Radiat Phys Chem 53:417–424
21. Wojciechowski K, Rosa M, Jówko A, Foryś M (1993) Energy transfer processes in the xenon sensitized photolysis of hydrogen chloride and carbon tetrachloride. Nukleonika 38;2:31–47
22. Wojciechowski K, Rosa M, Symanowicz M, Jówko A, Foryś M (1994) Energy transfer processes in the xenon sensitised photolysis of SOCl$_2$, S$_2$Cl$_2$ and PCl$_3$. Nukleonika 39;4:35–50