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Reaction of Nitrogen Dioxide with Alkenes and Polyunsaturated Fatty Acids: Addition and Hydrogen Abstraction Mechanisms

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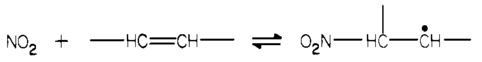
Abstract: The reactions of nitrogen dioxide in a carrier gas (nitrogen, oxygen, or air) with cyclohexene and a series of mono-, di-, and trienes is reported at NO_2 concentrations ranging from 70 ppm to 50%. A complete product analysis was made with cyclohexene, and these data allow the calculation of the fraction of the NO_2 that reacts by addition to the double bond or by abstraction of an allylic hydrogen. At high concentrations of NO_2, addition is the predominant process, in agreement with the literature. However, below 10000 ppm (1%), hydrogen abstraction predominates. We suggest this is because of competition between a reversible addition and an irreversible H-abstraction step, much as is the case for the well-known bromine atom reaction system. In fact, a kinetic analysis shows that the ratios of rate constants for addition and abstraction are similar for both NO_2 and the bromine atom. A less direct method (analysis of water formed) was used to estimate the addition to abstraction ratio for other alkenes and for esters of unsaturated fatty acids; these data are in agreement with the cyclohexene data. The autoxidation of unsaturated fatty acid esters initiated by NO_2 also was studied, and kinetic chain lengths and autoxidizability ratios are given.

Nitrogen dioxide, a ubiquitous and toxic contaminant of urban air, reacts with both alkanes and alkenes at 25 °C by free radical mechanisms.[1-8] Both in vitro and in vivo studies have shown that NO_2 initiates the autoxidation of unsaturated fatty acids in model systems and in the pulmonary lipids of whole animals;[9] this lipid peroxidation process is known to cause the destruction of pulmonary lipids[9,10] and lead to membrane damage and cell death.[11] As part of our program of study of important toxins that react by free radical mechanisms,[8,11] we have identified the major products of the reactions of NO_2 with cyclohexene over the concentration range of 70 ppm NO_2 to 50% NO_2 in a carrier gas. We also report less detailed studies with unsaturated fatty acid esters.

The literature[1-3,7,12] indicates that at ambient temperatures and high concentrations, nitrogen dioxide reacts with alkenes by addition to the double bond (eq 1). In contrast, NO_2 reacts with



$$NO_2 + -HC{=}CH- \rightleftharpoons O_2N-\overset{|}{HC}-\overset{\bullet}{CH}- \qquad (1)$$

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cyclohexane[6] and toluene[5,13] by abstraction of hydrogen atoms (eq 2). Since the benzylic hydrogen atoms of toluene are abstracted by NO_2, it might appear likely that allylic hydrogen atoms in olefins could be abstracted in a process that could compete with addition of NO_2 to the double bond. However, abstraction was not observed when 20–30% NO_2 in oxygen was allowed to react with cyclohexene in the liquid phase;[2] similarly, at low pressures of alkenes and NO_2 in the gas phase, addition is the only process reported to occur.[14] Thus, it is generally assumed that when air containing NO_2 is breathed, polyunsaturated fatty acids (PUFA) in the lungs react with NO_2 by addition and that this is the process that is responsible for the initiation of PUFA autoxidation.

$$NO_2 + R{-}H \rightarrow HONO + R\cdot \qquad (2)$$

A review of the literature shows that most of the studies of the mechanism of reaction of NO_2 with olefins in the liquid phase were done at very high concentrations of NO_2, conditions that do not model environmental exposures. Therefore, we have studied the reactions of NO_2 with olefins in nitrogen, air, or oxygen as carrier gas over a range of NO_2 concentrations from 50% to 70 ppm. Our data show that the mechanism of NO_2–alkene reactions changes from predominantly *addition* to predominantly *hydrogen abstraction* as the NO_2 concentration decreases from high percent to low parts per million (ppm) levels. Although this change of mechanism does not alter the kinetics of oxidation initiated by nitrogen dioxide, the abstraction process could lead to the formation of nitrous acid, a nitrosation agent, in lung tissue.

Experimental Section

Instrumentation. A Varian 1400 GC (FID) was used for analyses of organic materials, a Varian 920 GC (TCD) for water and nitrogen oxides analyses, and a Varian 200 GC (TCD) for preparative work.

GC Columns: 3.2 mm × 3.0 m, glass, 10% OV-101 on Chromosorb W-HP, used for analyses of cyclohexene–nitrogen dioxide reaction products; 3.2 mm × 3.0 m, glass, 10% SP-2100 on Supelcoport, used to determine benzene and 1,3- and 1,4-cyclohexadiene concentrations; 6.4 mm × 1.5 m, stainless steel, Porapak Q, used to determine water (column temperature = 120 °C) and nitrogen oxides (at ambient temperature); 3.2 mm × 3.7 m, glass, 10% DEGS-PS on Supelcoport, used for fatty acid ester analyses; 9.5 mm × 2.4 m, aluminum, 15% SE-30 on Chromosorb P, used for preparative separations.

Chemicals and Reagents. Cyclohexene (Aldrich, ca. 99%) was distilled in the presence of sodium, under nitrogen, through a 50 cm × 20 mm glass column packed with glass beads. The first two 50-mL fractions of 250 mL contained enhanced concentrations (ca. 1.2% by GC peak area) of two minor impurities. The final two fractions contained 99.8% cyclohexene.

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(1) Baldock, H.; Levy, N.; Scaife, C. W. *J. Chem. Soc.* **1949**, 2627–2633.

(2) Brand, J. C. D.; Stevens, I. D. R. *J. Chem. Soc.* **1958**, 629–638.

(3) Shechter, H. *Rec. Chem. Prog.* **1964**, *25*, 55–76.

(4) Menzel, D. B. In "Free Radicals in Biology"; Pryor, W. A., Ed.; Academic Press: New York, 1976; Vol. II, pp 181–202.

(5) Titov, A. I. *Tetrahedron* **1963**, *19*, 557–580.

(6) Topchiev, A. V. "Nitration of Hydrocarbons"; Pergamon Press: New York, 1959; pp 226–268.

(7) Bonetti, G. A.; DeSavigny, C. B.; Michalski, C.; Rosenthal, R. *Prepr., Div. Pet. Chem., Am Chem. Soc.* **1965**, *10*, 135–143.

(8) Pryor, W. A., Lightsey, J. W. *Science* (*Washington, D.C.*) **1981**, *214*, 435–437.

(9) Thomas, H. V.; Mueller, P. K.; Lyman, R. L. *Science* (*Washington, D.C.*) **1968**, *159*, 532–534.

(10) Mead, J. P. In "Free Radicals in Biology"; Pryor, W. A., Ed.; Academic Press: New York, 1976; Vol. I, pp 51–68.

(11) (a) Pryor, W. A.; Stanley, J. P.; Blair, E.; Cullen, G. B. *Arch. Environ. Health* **1976**, *31*, 201–210. (b) Pryor, W. A. In "Molecules Basis of Environmental Toxicity"; Bhatnagar, R.S., Ed.; Ann Arbor Science Publishers: Ann Arbor, MI, 1980; pp 3–36. (c) Pryor, W. A. In "Environmental Health Chemistry"; McKinney, J. D., Ed.; Ann Arbor Science Publishers: Ann Arbor, MI, 1980; pp 445–466. (d) Pryor, W. A. In "Medicinal Chemistry"; Mathieu, J., Ed.; Elsevier: Amsterdam, 1977; Vol. V, pp 331–359.

(12) Sosnovsky, G. "Free-Radical Reactions in Preparative Organic Chemistry"; MacMillan: New York, 1964; pp 255–269.

(13) Yoshida, T.; Yamamoto, F.; Namba, K. *Kogyo Kagaku Zasshi* **1970**, *73*, 519–523.

(14) Akimoto, H.; Sprung, J. L.; Pitts, J. N., Jr. *J. Am. Chem. Soc.* **1972**, *94*, 4850–4855.

0002-7863/82/1504-6685$01.25/0

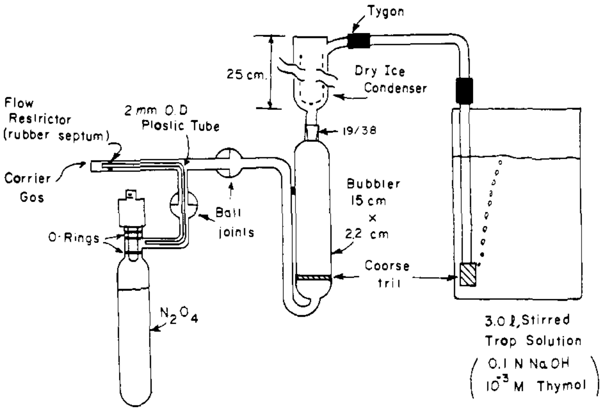

Figure 1. Apparatus used to study the nitrogen dioxide and autoxidation reaction products formed by cyclohexene and the three unsaturated fatty acid esters.

A mixture of hexane isomers (ACS reagent, Aldrich) was washed with sulfuric acid until no discoloration of the acid was observed (ca. three times). After neutralization, the hexane was predried with magnesium sulfate and distilled in the presence of calcium hydride.

Oleic (18:1), linoleic (18:2), and linolenic (18:3) acid methyl esters (ca. 99% by GC, Sigma) were used without purification. (The rate of nitrogen dioxide initiated autoxidation of these compounds was the same both before and after silica gel treatment.)

Nitrogen dioxide was generated from dinitrogen tetroxide (99.5%, Matheson). Dinitrogen tetroxide was dried overnight in glass bulbs with phosphorus pentoxide, purified by three freeze–pump–thaw cycles, and vacuum transferred to storage bulbs.

Nitrogen Dioxide Generation. Nitrogen dioxide was generated by two methods. Permeation tubes[15a] modified from a design described by O'Keeffe and Ortman[16] were used to generate concentrations of 0.5% and below, and glass bulbs with glass–Teflon valves (Figure 1) were used to generate concentrations of 1% and higher in a carrier gas stream. (The permeation tubes were stored in two 1.5-L glass vessels thermostatted at 35.0 °C; the vessels were modeled after those of Scaringelli et al.[17]) High-pressure gas cylinders or, for most cases in which air was used, an in-house, compressed air line were used as gas sources. Air from the house line was filtered, predried with indicating silica gel, and passed through activated charcoal. Prior to an experiment, all carrier gases were passed through a dry ice trap to minimize contaminants.

Reaction of Alkene with Nitrogen Dioxide in a Carrier Gas. The apparatus (Figure 1) was flushed with carrier gas; for volatile substrates, the dry ice condenser was cooled. Substrate, e.g., 1.0 mL of neat fatty acid ester or 6–8 mL of 6.6 M cyclohexene in hexane (ca. 60% cyclohexene, v/v), was placed in the bubbler, purged with carrier gas, warmed to 30 °C, exposed to NO_2, and purged again with carrier gas. The mass of nitrogen dioxide transferred was determined by weight loss from either the glass bulb (Figure 1) or the permeation tubes; the nitrogen dioxide that escaped the source but was not absorbed by reaction with alkene was trapped (Figure 1, procedure below).

Product concentrations were determined after exposure of cyclohexene as follows. After the final purging, the reaction solution was cooled to 0 °C and transferred to a 10.0-mL volumetric flask in an ice bath. The bubbler was rinsed twice with 1–2 mL aliquots of either cold anhydrous ethyl ether or a mixture of equal parts of methanol and ethyl ether, and the aliquots were added to the original reaction solution. Samples of diluted reaction solution were analyzed by GC immediately after reaction. Repeated analyses over several days showed that 2-cyclohexenyl nitrate decomposes within 24 h at room temperature in a solution containing methanol; refrigeration extends this time to 2–3 days. All other products were stable for at least 2–3 days at room temperature and for several weeks if they were refrigerated.

Trapping Nitrogen Dioxide from the Carrier Gas. The apparatus shown in Figure 1 illustrates the configuration for trapping large amounts of nitrogen dioxide with a 3-L beaker; smaller vessels, e.g., 50–100-mL flasks, were sufficient for trapping nitrogen dioxide at low nitrogen dioxide levels. The nitrogen dioxide–air stream was bubbled through the required volume of trapping solution (4.0 g of NaOH- and 0.4 g of thymol/L deionized water[18]) long enough to accumulate sufficient nitrite to be detectable by the Saltzman procedure.[15,19]

Analysis of Water Formed during the Anerobic Reaction of Alkenes with NO_2. Alkenes were purged with dry nitrogen (volatile alkenes were first frozen with dry ice) in a closed reaction system. The alkene was then exposed to 0.5–1% NO_2 for 1–3 h in a nitrogen atmosphere. After the NO_2 source was removed and residual NO_2 allowed to react (another 1–2 h), the reaction solution was transferred to a 10.0-mL volumetric flask, and the reaction vessel was rinsed with several 1–2-mL portions of absolute ethanol. This diluted solution, plus internal standard, was used for GC analysis.

Product Identification and Synthesis. 2-Cyclohexenol and 2-cyclohexenone were isolated by GC from a NO_2–cyclohexene reaction mixture and identified by comparison of their NMR spectra and GC retention times to authentic alcohol and ketone (Aldrich). (Retention times were determined by peak enhancement on spiking with knowns when the known compounds were available.)

2-Cyclohexenyl hydroperoxide was synthesized without isolation in ca. 80% yield[20] by the air autoxidation of cyclohexene initiated with 70 ppm NO_2. The hydroperoxide was quantitatively reduced by triphenylphosphine to 2-cyclohexanol[21] to identify the hydroperoxide peak and to determine its GC response factor from the known factor of the alcohol.

2-Cyclohexenyl nitrate formed in NO_2–cyclohexene reactions was identified by comparison of its retention time to that of nitrate synthesized as follows.[22,23] Silver nitrate (0.5 mol) and 3-bromocyclohexene (0.3 mol) (Fairfield Chemical) were stirred in 100 mL of anhydrous ether for 48 h at 25 °C. Solids (precipitated silver and silver bromide) were removed by filtration with added hexane through silica gel. The hexane–ether solution volume was reduced by using a rotary evaporator at 10 °C, and the concentrate (70–80% product and 20–30% 3-bromocyclohexene by GC peak area) was transferred to a vial, purged with dry nitrogen, sealed, and stored under refrigeration. Spectral analysis showed: IR (film) 3030, 1623–1626 (NO_3), 1278 (NO_3), 860–875 cm^{-1};[24,25a] NMR ($CDCl_3$) δ 5.8–6.4 (2 m, 2 vinyl H), 5.4 (br m, 1 allylic H). (A nearly identical absorption is observed for the α proton in cyclohexyl nitrite.)

2-Cyclohexenone oxime was synthesized from 2-cyclohexenone and was recrystallized from hexane. The final product had a melting point range of 86–88 °C.

1,2-Dinitrocyclohexane, a known compound, was isolated from a nitrogen dioxide–cyclohexene reaction mixture by column chromatography (5% ether–hexane, 22-mm glass column, 15 g of silica gel): IR (film) 1550, 1390 (nitro) cm^{-1};[24,25a] NMR ($CDCl_3$) δ 5.0 (br m, 2 α nitro H),[25b] 1.3–2.7 (br m, 8 H).

2-Nitrocyclohexanol was extracted into water from a reaction mixture, the water continuously extracted with ether, and the compound purified by GC. It was identified by comparison with the known compound: IR (film) 3430, 1550 (NO_2), 1375 (NO_2), 1074 (trans R,OH), 974 (cis R,OH)[2] cm^{-1}; NMR ($CDCl_3$) δ 4.5 (br m, 1 H), 4.2 (br m, 1 H), 3.5 (br s, 1 H), 1.3–2.2 (br m, 8 H).

1-Nitrocyclohexene was isolated by GC from a reaction mixture and compared with the known compound:[24,26] IR (film) 3038, 1665, 1508 (NO_2), 1333 (NO_2), 825 cm^{-1}; NMR ($CDCl_3$) δ 7.2–7.5 (br m, 1, vinyl H), 2.2–2.7 (br m, 4), 1.5–1.9 (br m, 4).

3-Nitrocyclohexene was isolated by GC from a reaction mixture and compared to the known compound:[26] IR (film) 3044, 1650, 1540 (NO_2), 1363 (NO_2) cm^{-1};[25a] NMR ($CDCl_3$) δ 5.9–6.2 (br m, 2 vinyl H), 4.9–5.0 (br m, allylic, α nitro H).

2-Nitrocyclohexyl nitrate was isolated from a reaction mixture by column chromatography and compared with the known compound:[24] IR (film) 1640 (NO_3), 1556 (NO_2), 1382 (NO_2), 1282 (NO_3) cm^{-1}; NMR ($CDCl_3$) δ 4.6 (br m, 1 α nitro H),[25b] 5.5 (br m, 1 H, the same as observed for 2-cyclohexenyl nitrate). the same as observed for 2-cyclohexenyl nitrate).

Oxidation of Unsaturated Fatty Acid Esters. The procedure for exposure to NO_2 is given above. If inhibitors were used, an aliquot of absolute ethanol solution containing inhibitor was added immediately

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(15) (a) Lightsey, J. W. Ph.D. Dissertation, Louisiana State University, 1982, p 16; (b) p 39; (c) p 113; (d) pp 65–72; (e) pp 44–46; (f) p 74.

(16) O'Keefe, A. E.; Ortman, G. C. *Anal. Chem.* **1966**, *38*, 760–763.

(17) Scaringelli, F. P.; O'Keefe, A. E.; Rosenberg, E.; Bell, J. P. *Anal. Chem.* **1970**, *42*, 871–876.

(18) Nash, T. *J. Chem. Soc. A* **1970**, 3023–3024.

(19) Saltzman, B. E. *Anal. Chem.* **1954**, *26*, 1949–1955.

(20) Van Sickle, D. F.; Mayo, F. R.; Arluck, R. M. *J. Am. Chem. Soc.* **1965**, *87*, 4824–4837.

(21) Horner, L.; Jurgleit, W. *Liebigs Ann. Chem.* **1955**, *591*, 138–152.

(22) Vogel, A. I. "A Textbook of Practical Organic Chemistry", 3rd ed.; Lowe & Brydone: London, 1956; p 307.

(23) Piotrowska, H. *Bull. Acad. Pol. Sci., Ser. Sci. Chim.* **1971**, *14*, 595–598.

(24) Brown, J. F., Jr. *J. Am. Chem. Soc.* **1955**, *77*, 6341–6351.

(25) (a) Silverstein, R. M.; Bassler, G. C. "Spectrophotometric Identification of Organic Compounds", 2nd ed.; Wiley: New York, 1967; pp 64–109; (b) p 137.

(26) Griswald, A. A.; Starcher, P. S. *J. Org. Chem.* **1966**, *31*, 357–361.

Table I. Mole Percentages of Products from the Reaction of Cyclohexene and NO_2 in the Absence of Oxygen at 30 °C

	wt % NO_2 in nitrogen									
	37.0	6.1	0.48	0.28	0.20	0.10	0.071	0.016	0.016[a]	0.0078[a]
substitution products by hydrogen abstraction										
2-cyclohexenol	1	5	12	13	15	20	25[b]	43	63	69
2-cyclohexenyl nitrate				2	3	4	5			
3-nitrocyclohexene	5	12	24	29	27	49	39	31	11	13
2-cyclohexenone oxime		7	3	1	3	<1	2		13	12
subtotal	6	24	39	45	48	73	71	74	87	94
addition products										
1-nitrocyclohexene	33	30	13	11	13	5	7	9	1	2
2-nitrocyclohexanol[c]	61	46	44	38	39	21	22	17	9	3
2-nitrocyclohexyl nitrate			1	3	<1	<1				
1,2-dinitrocyclohexane	<1	<1	3	3	<1	1			3	1
subtotal	94	76	61	55	52	27	29	26	13	6
total mol of products[d] ($\times 10^4$)	33.0	15.0	15.0	20.0	8.7	9.1	6.7	2.1	8.6	3.6
total mol of NO_2 ($\times 10^4$)	65.0	30.0	21.0	30.0	13.0	14.0	10.0	3.2	8.8	3.8
KCl (prod/NO_2)[e]	0.51	0.50	0.71	0.66	0.67	0.65	0.67	0.66	0.97	0.95

[a] Ultra high purity nitrogen (99.999%). [b] This 25% was shown to be 93% nitrite and 7% alcohol when analyzed before transesterification by methanol (eq 13). Thus, nitrite ester is stable under our conditions; see discussion in text. [c] Values shown include ketone as minor product. [d] Molar yields of products shown equals ca. 97 ± 14 mol % of the cyclohexene consumed. [e] Kinetic chain length.

following addition of substrate to the bubbler. A dry nitrogen stream was used to evaporate the ethanol and mix the inhibitor and ester before exposing the mixture to nitrogen dioxide and air. Aliquots of the reaction mixture (10–25 μL) were removed periodically to determine the concentrations of products and starting material.

Peroxide formation was followed by a modification[11a] of the iodometric method of Mair and Graupner.[27]

Ester conversions were determined by GC with methyl palmitate or methyl stearate as internal standards.

Elemental analyses for carbon-bound nitrogen[28] were performed on 4–5-mL aliquots of ester exposed to nitrogen dioxide in air. The reaction solutions were then subjected to catalytic hydrogenation (10% Pd on charcoal, 1 atm of hydrogen, 0.25% HCl in absolute EtOH,[29] optimum for nitro groups[30a]) to reduce nitro groups to more easily assayed amines and to either reduce or hydrolyze to alcohols all nitrite[2] and nitrate[30b] esters.

Reaction of Nitrogen Dioxide with 1-Naphthol. A 1.0-mL aliquot of a 4.34 mM solution of 1-naphthol in hexadecane was placed in the bubbler (Figure 1) and exposed to nitrogen dioxide in air for 7 h. Periodically, a 25-μL aliquot was added to 2.0 mL of absolute ethanol in a 1-cm quartz cell, and the absorbance of the solution was determined at 296 nm. The concentration of 1-naphthol was calculated from the absorbance at 296 nm (extinction coefficient = 5000 L/(mol·cm)) in ethanol.

Results

Reaction of Nitrogen Dioxide with Cyclohexene. Table I lists the products we have identified from reactions of NO_2 and cyclohexene in the absence of oxygen; these compounds account for 97 ± 14 mol % of the cyclohexene consumed.[31] As will be discussed below, each product can be associated with either an initial abstraction of allylic hydrogen or addition to the double bond by NO_2. The table shows the mole percentages of products grouped according to the mechanism responsible for their formation (and also in order of decreasing volatility). These data plus additional data not tabulated here[15c] are plotted in Figure 2.

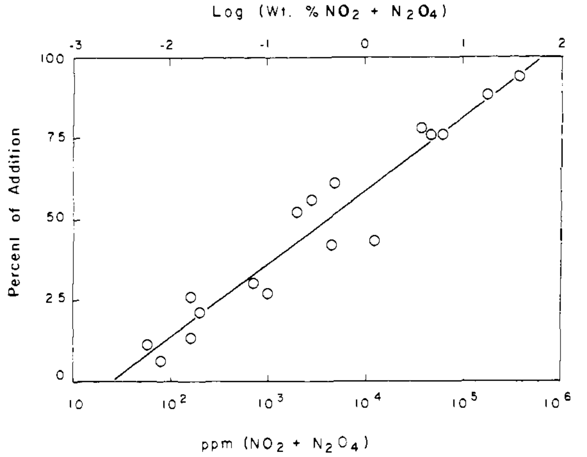

Figure 2. Mole percentage of cyclohexene reacting with nitrogen dioxide in the absence of oxygen at 30 °C by addition plotted as a function of the logarithm of the weight of nitrogen oxides in nitrogen.

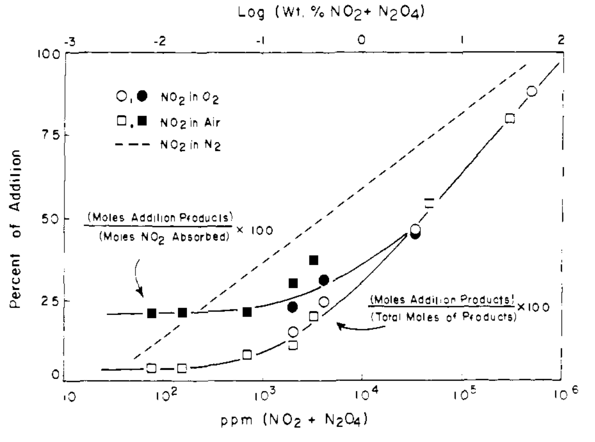

Figure 3. Mole percentage of cyclohexene reacting with nitrogen dioxide at 30 °C by addition calculated by two methods and plotted as a function of the logarithm of the weight of nitrogen oxides in air or oxygen. Open points denote the mol % of addition calculated as the ratio of addition products to the sum of all products formed. Filled points denote the mol % of addition calculated if only those products resulting from reaction with nitrogen dioxide are included (and autoxidation products are excluded). Dashed line is taken from Figure 2.

The products formed in the presence of oxygen are listed in Table II; these compounds account for 97 ± 14 mol % of the cyclohexene consumed. The weight percentage of total nitrogen oxides in the carrier gas and the identity of the carrier gas (air or oxygen) are listed across the top of the table. Figure 3 shows

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[27] Mair, R. D.; Graupner, A. J. *Anal. Chem.* **1964**, *36*, 194–204.

[28] Galbraith Labs, P. O. Box 4187, Knoxville, TN 37921.

[29] Collard, R. S.; Pryor, W. A. *Lipids* **1979**, *14*, 748–751.

[30] (a) Becker, H.; et al. "Organicum"; Addison-Wiley: Reading, MA, 1973; pp 547–583. (b) Seifert, W. K. *J. Org. Chem.* **1963**, *28*, 125–129.

[31] Cyclohexene consumption was determined by GC only for runs using high nitrogen dioxide concentrations (5–17%) and short reaction times (up to 2 h) since evaporative losses were too great for accurate analysis at long times. We assume that cyclohexene conversion is independent of NO_2 levels, although we have no data at the low levels.

Table II. Mole Percentages of Products from the Reaction of Cyclohexene and NO_2 in the Presence of Oxygen at 30 °C

	wt % NO_2 in carrier gas										
	49.0[a]	30.0[b]	4.7[b]	3.4[a]	0.42[a]	0.33[b]	0.20[a]	0.20[b]	0.071[b]	0.016[b]	0.0076[b]
substitution products by hydrogen abstraction											
2-cyclohexenol	2	9	12	11	17	23	28	26	30	24	22
2-cyclohexenyl hydroperoxide[c]	1	1	13	14	17	15	23	15	39	69	76
2-cyclohexenyl nitrate	6	2	19	31	39	40	32	48	23	3	<1
3-nitrocyclohexene	4	8	2	1	<1	2	2		<1		
subtotal	13	20	46	57	73	80	85	89	92	96	98
addition products											
1-nitrocyclohexene	18	26	8	4	1	<1	<1	1	<1		
2-nitrocyclohexanol[d]	64	48	41	33	20	13	12	7	8	4	2
2-nitrocyclohexyl nitrate	5	2	5	5	5	6	2	3			
1,2-dinitrocyclohexane	<1	4	<1	1	1	1	1				
subtotal	87	80	54	43	27	20	15	11	8	4	2
total mol of products[e] ($\times 10^4$)	105	73.0	31.0	30.0	30.0	24.0	35.0	35.0	45.0	19.0	14.0
total mol of NO_2 ($\times 10^4$)	190	130	38.0	33.0	20.0	12.0	16.0	16.0	14.0	3.1	1.6
KCL (prod/NO_2)[f]	0.55	0.56	0.82	0.91	1.5	2.0	2.2	2.2	3.2	6.1	8.8

[a] Carrier gas O_2. [b] Carrier gas air. [c] Includes yields of 2-cyclohexenone that are 5–15% of the yields of the 2-cyclohexenyl hydroperoxide shown. [d] Values shown include nitroketone and nitrohydroperoxide as minor products. [e] Molar yields of products shown equals 97 ± 14 mol % of the cyclohexene consumed. [f] Kinetic chain length.

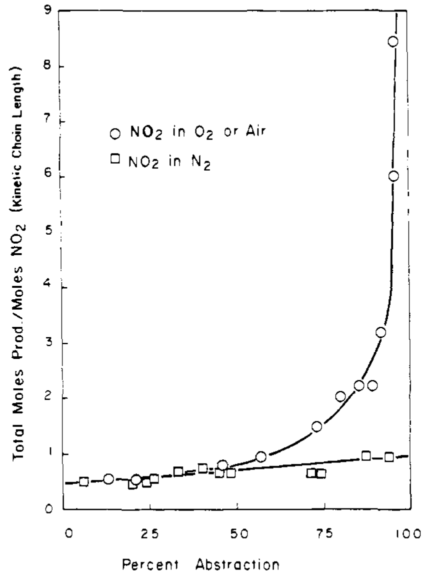

Figure 4. Kinetic chain length (KCL) of reactions initiated by nitrogen dioxide plotted as a function of the percent of reaction occurring by hydrogen abstraction.

the mole percent of addition products taken from Table II plotted vs. the logarithm of the nitrogen oxides concentration in air or oxygen as carrier gas. The percent of addition products has been calculated in two different ways in Figure 3. The open points represent the ratios of addition products to the sum of all products formed. The filled points show the same data after correction for those products due to spontaneous autoxidation.

The kinetic chain length (KCL) for our nitrogen dioxide–cyclohexene reactions is plotted as a function of the percent abstraction in Figure 4; KCL is calculated as the ratio of total moles of products formed to that of NO_2 reacted. In the absence of oxygen, the KCl increases from 0.5 when hydrogen abstraction is unimportant (high nitrogen dioxide concentrations) to 1.0 when abstraction is dominant (low nitrogen dioxide concentrations). In the presence of oxygen, the KCL also equals 0.5 when hydrogen abstraction is minor but increases to a value of about 9 at ppm levels of nitrogen dioxide. The KCL is higher in these air or oxygen runs because additional products, mainly 2-cyclohexenyl hydroperoxide, are produced by the nitrogen dioxide initiated chain autoxidation.

Table III. Water Production from Hydrogen Abstraction by Nitrogen Dioxide[a]

compound	mol of NO_2 consumed $\times 10^4$	mol of H_2O formed $\times 10^4$	molar ratio H_2O/NO_2	% abstractn[b]
1,3-cyclohexadiene	11.8	7.9	0.67	80[c]
methyl linolenate	9.8	5.5	0.56	71
	13.4	7.3	0.54	
methyl linoleate	8.7	4.3	0.50	67
	11.5	5.9	0.51	
cyclohexene	10.6	4.1	0.39	56[d]
1,5,9-cyclododecatriene	13.3	4.7	0.35	52
1-hexadecene	16.5	3.9	0.23	37
methyl oleate	13.4	3.0	0.22	36

[a] Reactions were done in a sealed vessel at 30 °C with 0.5–1% (w/w) NO_2 in nitrogen. [b] Percent hydrogen abstraction is calculated from the water/NO_2 ratio.[33] [c] Benzene was observed as a major product. [d] This value agrees qualitatively with the value obtained by the total product study (Table I).

Reaction of Nitrogen Dioxide with Alkenes in a Sealed Vessel. Table III shows the results of experiments in which we determined the percent of hydrogen abstraction occurring in reactions of nitrogen dioxide with a number of other alkenes. In these cases, hydrogen abstraction was not determined by complete product analysis; rather, an indirect, approximate method was used. This method involves the determination of the moles of water formed in eq 3 by decomposition[32] of the nitrous acid formed in eq 2. The

$$2HONO \rightarrow NO + NO_2 + H_2O \qquad (3)$$

percent abstraction[33] determined for cyclohexene by this indirect, water-analysis method is in qualitative agreement with the value determined by complete product analysis at the same nitrogen dioxide concentration. (Compare Tables I and III for 0.5 to 1% NO_2.) The compounds in Table III with doubly allylic hydrogens react more by hydrogen abstraction, and the compounds without doubly allylic hydrogens react less by abstraction relative to cyclohexene.

Nitrogen Dioxide Initiation of Unsaturated Fatty Acid Ester Oxidation. In order to determine the number of autoxidation chains started by each nitrogen dioxide, we used the standard induction period method[34] with four phenolic inhibitors: *dl-α-*

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[32] (a) Ashmore, P. G.; Tyler, B. J. *J. Chem. Soc.* **1961**, 1017–1021. (b) Asquith, P. L.; Tyler, B. J. *J. Chem. Soc. D* **1970**, 744–745.

[33] Since 50% of the nitrogen dioxide reacting by hydrogen abstraction is regenerated, the fraction of reaction occurring by hydrogen abstraction (X) was calculated by using the equation (moles water formed)/(moles NO_2 consumed) = $0.5X/(1-0.5X)$.

Table IV. Autoxidation Data for Methyl Linoleate (18:2) and Methyl Linolenate (18:3) Exposed to Nitrogen Dioxide in Air at 30.0 °C

PUFA ester	$[NO_2]$, ppm	initiatn rate,[a] M/s ($\times 10^6$)	oxidn rate,[b] M/s ($\times 10^5$)	KCL[c]
18:3	0.0	0.0	0.27	
	10.4	0.93	4.65	49
	21.6	1.94	5.95	31
	23.5	2.09	6.31	30
	45.5	4.07	8.52	21
	45.8	4.09	8.65	21
	69.2	6.19	9.54	15
	73.3	6.55	10.6	16
18:2	0.0	0.0	0.21	
	0.28	0.023	0.46	204
	0.56	0.058	0.74	128
	0.56	0.053	0.73	138
	1.4	0.12	1.05	86
	1.4	0.12	0.92	75
	1.4	0.12	0.93	78
	2.4	0.22	1.33	59
	2.6	0.22	1.33	60
	10.3	0.90	2.04	23
	23.9	2.09	2.96	14
	47.6	4.15	3.72	9
	71.5	6.24	4.61	7

[a] Initiation rate equals the product of the NO_2 delivery rate and the absorption efficiency of the esters.[15e] [b] Oxidation rate equals the rate of formation of peroxidic products. [c] KCL = (oxidation rate)/(initiation rate).

tocopherol (vitamin E), 1-naphthol, hydroquinone, and 2,4,6-trimethylphenol.[35,36] The results with methyl linoleate[15d] show that the autoxidation rate is reduced 90% and a distinct induction phase is observed with all inhibitors. The ratio of the moles of NO_2 absorbed to the moles of inhibitor used during the induction period equals the inhibitor's stoichiometric factor.[15d] We found this value for tocopherol (considered one of the most efficient phenolic inhibitors[37]) to be exactly 2.0, as expected;[35] the values determined for the other phenols range from 2.3 to 2.5.[15d] Thus, each absorbed nitrogen dioxide initiates an autoxidation kinetic chain that is stopped by one inhibitor molecule, producing an inhibitor-derived radical that then stops a second chain. The rate of disappearance of inhibitor was found to be about half the rate of absorption of nitrogen dioxide, consistent with the reaction of one inhibitor with two kinetic chains.

Table V. Autoxidation Data for Methyl Oleate (18:1) Exposed to Nitrogen Dioxide in Air at 30.0 °C

$[NO_2]$, ppm	initiatn rate, M/s $\times 10^6$	oxidatn rate,[a] M/s $\times 10^6$	oxidatn rate,[b] M/s $\times 10^6$	KCL[c]
0	0	0	0	
21.3	0.68	0.77	1.3	1.9
50.2	1.61	0.94	1.7	1.0
50.2	1.61	0.96	2.0	1.2
71.2	2.28	1.2		

[a] Calculated from the rate of hydroperoxide formation. [b] Calculated from the rate of reaction of oleate (18:1). [c] KCL = kinetic chain length = (oxidation rate)/(initiation rate).

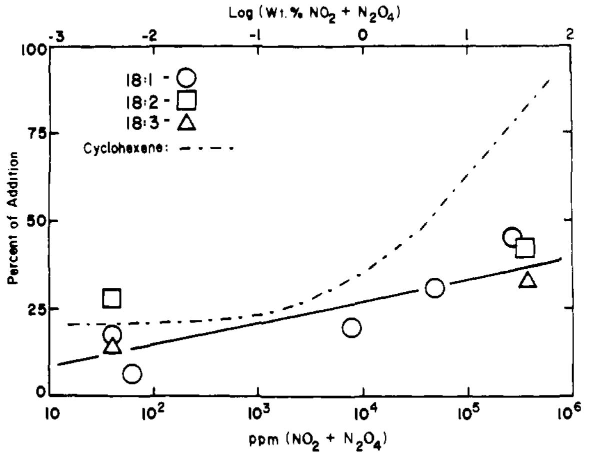

Figure 5. Percentage of initiation by addition occurring in reactions of the three unsaturated fatty acid esters at 30 °C plotted as a function of the logarithm of the weight of nitrogen oxides in air. Percentages of addition were calculated from the nitrogen incorporated in the addition step, as determined by elemental analysis.

At a carrier-gas flow of 300 mL/min through neat methyl linoleate, sufficient mixing and oxygen saturation occur in the bubbler apparatus used for cyclohexene so that both air and pure oxygen give the same rate of oxidation.[38] Autoxidation rates of the three unsaturated esters were determined as functions of the rate of initiation by nitrogen dioxide. As will be shown below, the rate of autoxidation is proportional to the square root of the rate of initiation. Autoxidation rates and KCL of linoleate were calculated from the rate of hydroperoxide formation (Table IV), since hydroperoxide yields were shown to be nearly quantitative.[15f] For methyl oleate, the KCL were calculated from the rates of substrate disappearance since hydroperoxide yields are not quantitative and nitro-containing products are also formed (Table V).

Verification of the Initiation Mechanism for Unsaturated Fatty Acid Esters by Nitrogen Incorporation. To determine the mechanism of initiation of fatty acid ester autoxidation by nitrogen dioxide, we analyzed samples of nitrogen dioxide exposed ester for carbon-bound nitrogen. Initiation by addition gives a product with a carbon-bound nitrogen atom (Scheme I, eq 1), whereas hydrogen abstraction (Scheme II) yields no initiation product containing carbon-bound nitrogen.[39]

Figure 5 shows the percent addition to the fatty acid esters plotted as a function of the gas-phase nitrogen dioxide concentration; the cyclohexene data obtained in the presence of oxygen (corrected for the influence of autoxidation products; Figure 3,

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(34) Boozer, C. E.; Hammond, G. S.; Hamilton, C. E.; Sen, J. N. *J. Am. Chem. Soc.* **1955**, *77*, 3233–3237.

(35) (a) Ingold, K. U. *Chem. Rev.* **1961**, *61*, 563–589. (b) Mahoney, L. R. *Angew. Chem., Int. Ed. Engl.* **1969**, *8*, 547–555.

(36) Direct reaction of nitrogen dioxide with inhibitor would shorten the induction period without giving any alkene oxidation products; since we intended to follow the course of reaction by the formation of oxidation products, this would give misleading results. We therefore determined the relative reactivity of nitrogen dioxide with a phenol, 1-naphthol, in an inert solvent, hexadecane. The rate of absorption and reaction of nitrogen dioxide was 2.5% of its delivery rate, 76 nmol/min at 10 ppm. Since the unsaturated fatty acid esters absorb 10 (methyl oleate) to 30 (methyl linoleate) times this amount of delivered nitrogen dioxide under the same conditions,[15e] the reaction of nitrogen dioxide with an inhibitor in competition with an ester such as methyl linoleate can be neglected.

(37) Burton, G. W.; Le Page, Y.; Gabe, E. J.; Ingold, K. U. *J. Am. Chem. Soc.* **1980**, *102*, 7791–7792.

(38) Bolland, J. L. *Proc. R. Soc. London, Ser. A.* **1946**, *186A*, 218–236.

(39) (a) Scheme II shows that allylic nitrate esters are formed (eq 16); however, these were hydrolyzed before elemental analysis was performed. (b) If nitrogen dioxide were involved in termination reactions that form carbon–nitrogen bonds, 3-nitroalkenes and 1,2-dinitroalkanes would be formed, causing addition to appear spuriously high. However, Table II shows that for cyclohexene the yield of both 3-nitrocyclohexene and 1,2-dinitrocyclohexane is about 12% at high nitrogen dioxide concentration and essentially 0% at low. Therefore, nitrogen dioxide is involved in carbon–nitrogen bond-forming termination reactions only at high NO_2 concentrations where addition is the predominant process. Furthermore, the KCL for cyclohexene is less than unity at high NO_2 levels (Figure 4, low percent abstraction), and a 12% yield of 3-nitroalkene and 1,2-dinitroalkane indicates that no more than 12% of the chains are terminated by carbon–nitrogen bond formation. (c) The fraction addition was calculated from the relation: moles NO_2 incorporated into the substrate (from elemental analysis)/total moles NO_2 that have reacted. This analysis assumes that one N atom becomes bound to carbon for each addition reaction that occurs and that any NO_2 involved in termination reactions becomes incorporated as a nitrite group.[39b] Before analysis, the workup procedure hydrolyzes and removes nitrite groups (see Experimental Section).

filled points) are also represented by a dashed line. At ppm levels of nitrogen dioxide, the percent addition determined for the unsaturated fatty acid esters is in good agreement with the results predicted by the cyclohexene data. However, at higher levels, particularly at 30–40% nitrogen dioxide, the values decrease to about half those expected on the basis of the cyclohexene data. (See the right-hand side of Figure 5.) At these high levels, nitrogen dioxide is involved in termination, and the product is primarily the nitro nitrite ester. Therefore, the elemental analysis for carbon-bound nitrogen is low by about a factor of 2 since nitro nitrite ester is hydrolyzed to nitro alcohol before analysis.[39c]

Discussion

Our product studies suggest that nitrogen dioxide adds to the double bonds of alkenes at high nitrogen dixide concentrations; these results are supported by previous investigations.[1,2] However, at low concentrations, nitrogen dioxide appears to abstract allylic hydrogen atoms in competition with the addition reaction.

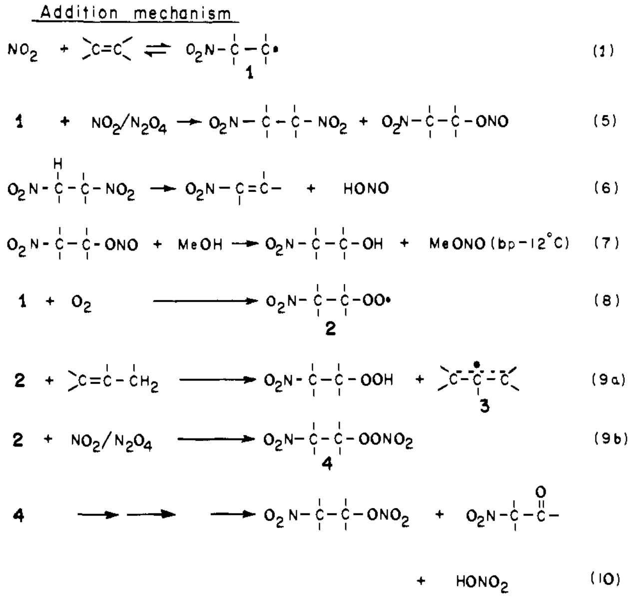
Addition Products. Nitrogen dioxide is in equilibrium with its dimer (eq 4) with an equilibrium constant, K_{eq}, equal to about

$$N_2O_4 \overset{K_{eq}}{\rightleftarrows} 2NO_2 \qquad (4)$$

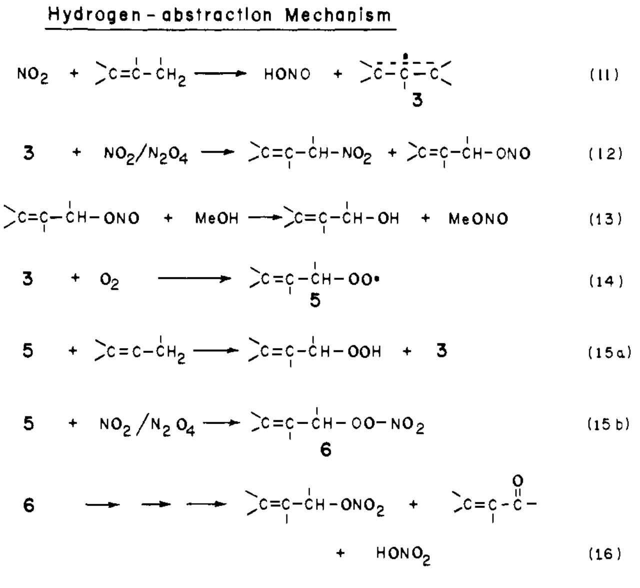
10^{-4} M.[40] Because dissociation and recombination are both rapid[41] compared with the reaction of nitrogen dioxide with alkenes,[2,42] the equilibrium is maintained during reaction; it is thought that the reaction involves the NO_2 radical.[2] Scheme I shows the reactions involved in the addition of NO_2 to olefins. The initial reaction is reversible[43,44] addition to the double bond to form the carbon-centered radical **1**. Radical **1** then reacts with more nitrogen dioxide, dinitrogen tetroxide, or oxygen (if air is present). In the absence of oxygen, radical **1** reacts with nitrogen dioxide to give a nitro nitrite and 1,2-dinitroalkane (eq 5, Scheme I) and 1-nitroalkene (eq 6). (Subsequent workup of the reaction mixture with methanol converts the nitrite ester to the nitro alcohol[2] (eq 7).) If oxygen is present, radical **1** can give peroxy radical **2** (eq 8). Radical **2** either abstracts an allylic hydrogen atom to give a 2-nitro hydroperoxide and the allyl radical **3** (eq 9a) or is trapped by nitrogen dioxide to form an alkyl peroxynitrate **4** (eq 9b).[3] Alkyl peroxynitrates are short-lived intermediates at ambient temperature and ultimately form a nitro nitrate or nitro ketone (eq 10), depending on structure and reaction conditions.[45]

Hydrogen Abstraction Products. The initial products of hydrogen abstraction by nitrogen dioxide from an alkene are nitrous acid and allyl radical **3** (Scheme II). (The nitrous acid decomposes to form water and nitrogen oxides (eq 3).[32]) The reactions of **3** (and workup with methanol) produce allylic substitution products, as shown in eq 12–16, Scheme II.

Scheme I



Scheme II



Nitrous Acid Elimination. We have assumed that 3-nitrocyclohexene, a major product, arises from hydrogen abstraction and not from elimination of nitrous acid (HONO) from 1,2-dinitrocyclohexane. One indication that it is an abstraction product is that its yield increases with the other abstraction products when the gas-phase nitrogen dioxide concentration is decreased (Table I). (In contrast, the yield of 1-nitrocyclohexene decreases with the other addition products.) Nevertheless, to test whether the elimination of HONO from 1,2-dinitrocyclohexane could be a source of 3-nitrocyclohexene, we determined the amount of both compounds in a reaction mixture (in dry ether) prior to our usual workup. Addition of wet methanol (<5% water) in the presence of residual nitrogen dioxide and nitrous acid mimics the most acidic conditions encountered during reaction or workup. Except for the conversion of the nitro nitrite to a nitro alcohol (eq 7), the relative amounts of the products were unchanged by this simulated workup procedure. (Furthermore, we showed that in the presence of the base triethylamine, both 3-nitrocyclohexene and 1,2-dinitrocyclohexane react to form more 1-nitrocyclohexene.) Thus, any elimination of nitrous acid from 1,2-diadducts will give the 1-nitro rather than the 3-nitro alkene, and 3-nitrocyclohexene must result from allylic hydrogen abstraction by nitrogen dioxide.

Dissociation of Nitrite Ester and Hydrogen Abstraction by Alkoxy Radicals. Nitrite esters appear to be formed in our system, as discussed below. Nitrite esters are known to dissociate to form alkoxy radicals in the gas phase,[46,47] as shown in eq 17. If reaction

$$RO{-}NO \rightarrow RO\cdot + NO \qquad (17)$$

17 occurs, the resulting alkoxy radicals could abstract hydrogen from cyclohexene (eq 18) to form products such as 2-nitrocyclohexanol or 2-cyclohexenol or could react with nitrogen dioxide to form the analogous nitrates (eq 19). Since nitrate and alcohol

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(40) Redmond, T. F.; Wayland, B. B. *J. Chem. Phys.* **1968**, *72*, 1626–1629.

(41) Carrington, T.; Davidson, N. *J. Chem. Phys.* **1953**, *57*, 418–424.

(42) Sprung, J. L.; Akimoto, H.; Pitts, J. N., Jr. *J. Am. Chem. Soc.* **1974**, *96*, 6549–6554.

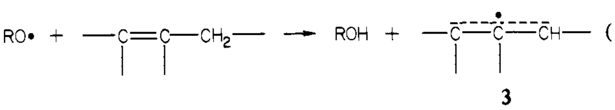
(43) Khan, N. A. *J. Chem. Phys.* **1955**, *23*, 2447–2448.

(44) Sprung, J. L.; Akimoto, H.; Pitts, J. N., Jr. *J. Am. Chem. Soc.* **1971**, *93*, 4358–4363.

(45) (a) Lachowicz, D. R.; Kreuz, K. L. *J. Org. Chem.* **1967**, *32*, 3885–3888. (b) Duynstee, E. F. J.; Hennekens, J. L. J. P.; van Raayen, W.; Voskuil, W. *Tetrahedron Lett.* **1971**, *34*, 3197–3200. (c) Kenley, R. A.; Hendry, D. G. *J. Am. Chem. Soc.* **1982**, *104*, 220–224.

(46) Gray, P. *Trans. Faraday Soc.* **1955**, *51*, 1367–1374.

(47) Slagle, I. R.; Yamada, F.; Gutman, D. *J. Am. Chem. Soc.* **1981**, *103*, 149–153.



$$RO\cdot + -C{=}C-CH_2- \rightarrow ROH + -\dot{C}\!-\!C\!-\!CH- \quad (18)$$

3

$$RO\cdot + NO_2 \rightarrow RONO_2 \quad (19)$$

cannot be formed directly in the absence of oxygen other than by reactions 18 and 19, the formation of alcohols and nitrates in the absence of oxygen indicates nitrite decomposition by reaction 17. The data of Table I show that in the absence of oxygen, nitrates amount to no more than 5% of all products; alcohol production is also minor. For example, after a reaction mixture listed in Table I for the 0.071% nitrogen dioxide run was extracted into ether (and before it was treated with methanol), the 2-cyclohexenyl nitrite:2-cyclohexenol ratio was 93:7,[48] indicating that the nitrite ester is stable under our conditions. This observation was made for a reaction in which allylic substitution (hydrogen abstraction) products were the major products. Thus, in the absence of oxygen, alkoxy radical formation from eq 17 can be neglected.

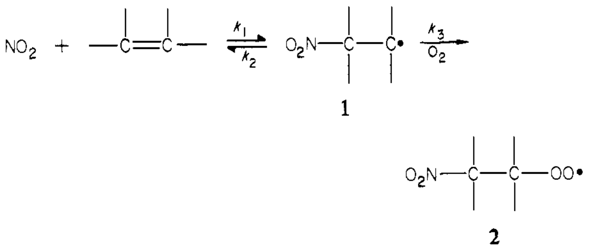
Additional evidence indicating that hydrogen abstraction by alkoxy radicals is not important in the absence of oxygen can be found by comparing the water formation data of Table III with the addition product data of Figure 2. The amount of water formed by the reaction of cyclohexene with 0.5–1% nitrogen dioxide indicates that 56% of the nitrogen dioxide that reacts does so by hydrogen abstraction to form nitrous acid; the data in Figure 2 show that about 50% addition is occurring at the same nitrogen dioxide concentrations. Thus, the data indicate that all the hydrogen abstraction in the absence of oxygen is by nitrogen dioxide to give HONO, rather than by the alkoxy radical.

In the presence of oxygen, alkoxy radicals could arise from three mechanisms: nitrite dissociation (eq 17), deoxygenation of peroxyl radicals, and/or dissociation of peroxynitrates (eq 20). We have

$$RO{-}ONO_2 \rightarrow RO\cdot + NO_3 \quad (20)$$

shown above that eq 17 is not important. Deoxygenation of peroxyl radicals by NO (produced in eq 3) also should not be important in our flow systems since NO concentrations are very low, especially at low NO$_2$ levels where we observe the largest amount of hydrogen abstraction. Finally, although peroxynitrates are formed in these systems (eq 9b and 15b), they appear to be stable at room temperature.[45c] Thus, we conclude that alkoxy radicals should not be an important hydrogen-abstracting radical either in our deaired or aerobic studies.

Rationale of the Change of Initiation Mechanism from Addition to Hydrogen Abstraction. We suggest the following explanation for the increasing amount of hydrogen abstraction observed with decreasing nitrogen dioxide concentration. Addition, the thermodynamically favored process,[44,49] is reversible (eq 1).[43,44] In contrast, hydrogen abstraction is not. (The nitrous acid formed in eq 11 either decomposes to nitrogen oxides and water (eq 3)[32] or is blown out of solution by the carrier gas.) Therefore, at high concentrations of a radical trapping species (nitrogen dioxide,[50] dinitrogen tetroxide, or oxygen), intermediate **1** reacts to give addition products. Equation 21 illustrates this with oxygen as the radical-trapping species. At low concentrations of trapping species, radical **1** is trapped more slowly and a larger fraction of



$$NO_2 + -C{=}C- \underset{k_2}{\overset{k_1}{\rightleftharpoons}} O_2N-C-C\cdot \xrightarrow[O_2]{k_3} O_2N-C-C-OO\cdot \quad (21)$$

1 **2**

1 reverts to reform the alkene; therefore, less addition occurs, and hydrogen abstraction becomes favored.

One might argue that abstraction is too slow to compete with addition. The rate constants for abstraction of an allylic hydrogen by NO$_2$ at room temperature are unknown; however, we can use the rate constant for abstraction of a benzylic hydrogen as an approximation since the allylic and benzylic hydrogens have the same BDE.[49] The activation energy for abstraction from toluene is 18.3 to 20.8 kcal/mol and log A is 7.4 in benzene or carbon tetrachloride,[13,51] giving a rate constant of 1.4 to 960 × 10^{-8} M^{-1} s^{-1} at 298 K. The rate constant for addition of NO$_2$ to an alkene is 0.05 M^{-1} s^{-1} at 298 K if one uses an average of the activation parameters given by Pitts et al.[42] Thus, the ratio of rate constants k_{add}/k_{abs} is 5×10^3 to 4×10^6, and addition is highly favored over abstraction, as our data at high NO$_2$ concentrations show. However, the very rapid reversibility of addition ($k_{rev} = 5 \times 10^4$ to 5×10^5 s^{-1})[42] and the irreversibility of hydrogen abstraction cause abstraction to be favored by about 9:1 at nitrogen dioxide concentrations below 100 ppm (Figure 2).

In support of this rationale, consider the similar situation in free radical bromination. The rate constant for allylic hydrogen abstraction by bromine atoms at 298 K is calculated to be 1.7×10^5 M^{-1} s^{-1} by using log A = 10.5 (our estimate) and the experimental activation energy of 7.2 kcal/mol.[52] The rate constant for addition of bromine atoms to a typical alkene at 298 K is calculated to be 1.1×10^9 to 3.2×10^{10} M^{-1} s^{-1} by using log A = 10.5 (our estimate) and the experimental activation energies of 0–2 kcal/mol.[53-55] The resulting rate constant ratio, k_{add}/k_{abs}, for bromine atoms is 6×10^3 to 2×10^5. Again, even though addition is greatly preferred, the rapid reversibility of addition ($k_{rev} \simeq 10^7$ s^{-1} at 298 K[56c]) and the irreversibility of abstraction (if HBr is removed) allows abstraction to predominate at low bromine concentrations.[56] For example, 3-bromocyclohexene is formed in 84% yield from cyclohexene if a nitrogen carier gas is used to maintain a low concentration of bromine and remove HBr.[56a] Our results with nitrogen dioxide and cyclohexene are essentially identical.

Explanation of the Dependence of the Product Distribution on the Oxygen Concentration. It may appear surprising at first that hydrogen abstraction predominates at low NO$_2$ concentrations in the presence of oxygen (Figure 3, open points), since oxygen should trap intermediate **1** (eq 21) and change the addition: substitution product ratio. The lack of effect of oxygen on the ratio of addition to abstraction can be rationalized in the following way. Cyclohexene readily autoxidizes at 30 °C[57] to give a 90% yield of hydrogen abstraction products such as 2-cyclohexenyl hydroperoxide, 2-cyclohexenol, and 2-cyclohexenone.[20] As the nitrogen dioxide concentration decreases and the KCL increases, the amount of product from autoxidation increases. At the lowest nitrogen dioxide levels we studied in the presence of oxygen, the

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(48) The nitrite ester and alcohol are easily separated by GC. The nitrite ester and alcohol peaks are distinguishable because the nitrite peak decreases as the alcohol peak increases in area on addition of methanol to the mixture. The nitrite ester concentration was determined by use of the 2-cyclohexenol response factor and the nitrite ester's GC-peak area.

(49) Benson, S. W. "Thermochemical Kinetics", 2nd ed.; Wiley: New York, 1976; pp 271–310.

(50) Nitrogen dioxide ($k = 1.7 \times 10^{10}$)[50a] traps alkyl radicals at 25 °C faster than does oxygen ($k = 2 \times 10^8$ to 10^9).[50b-f] (a) Glanzer, K.; Troe, J. *NBS Spec. Publ.* (*U.S.*) **1978**, No. 513, 1–43. (b) Daby, E. E.; Weinstock, B. In "Photochemical Smog and Ozone Reactions"; Gould, R. F., Ed.; American Chemical Society: Washington, DC, 1972; pp 16–57. (c) Washiba, N.; Bayes, K. D. *Int. J. Chem. Kinet.* **1976**, *8*, 777–794. (d) Hasegawa, K.; Patterson, L. K. *Photochem. Photobiol.* **1978**, *28*, 817–823. (e) Hochanadel, C. J.; Ghormley, J. A.; Boyle, J. W.; Ogren, P. J. *J. Phys. Chem.* **1977**, *81*, 3–7. (f) Ingold, K. U. *Acc. Chem. Res.* **1969**, *2*, 1–9.

(51) Saeki, K.; Yoshida, T.; Namba, K. *J. Ind. Explosives Soc. Jpn.* **1973**, *34*, 339–342.

(52) Anderson, H. R., Jr.; Scheraga, H. A.; VanArtsdalen, E. R. *J. Chem. Phys.* **1953**, *21*, 1258–1267.

(53) Thaler, W. A. In "Methods in Free-Radical Chemistry", Huyser, E. S., Ed.; Marcel Dekker: New York, 1969; Vol. 2, pp 121–227.

(54) Vaughan, W. E.; Rust, F. F.; Evans, T. W. *J. Org. Chem.* **1942**, *7*, 477–490.

(55) Rust, F. F.; Vaughan, W. E. *J. Org. Chem.* **1942**, *7*, 491–496.

(56) (a) Sixma, F. L. J.; Riem, R. H. *Proc. K. Ned. Akad. Wet., Ser. B: Phys. Sci.* **1958**, *61B*, 183. (b) McGrath, B. P.; Tedder, J. M. *Proc. Chem. Soc., London* **1961**, 80–81. (c) Estimated for the gas phase; S. W. Benson, private communication, 1981.

(57) Howard, J. A.; Ingold, K. U. *Can. J. Chem.* **1966**, *44*, 1119–1130.

Table VI. Autoxidizability Ratios[a] for the Unsaturated Fatty Acid Esters at 30.0 °C

ester	our values[b]	Howard & Ingold[c]
18:3	14	39
18:2	6	21
18:1	0.3	0.89

[a] $(k_p/(2k_t)^{1/2}) \times 10^3$ ($M^{-1/2}\ s^{-1/2}$). [b] Bubbler reactors; NO_2 initiator. [c] Well-stirred reactor; azobis(cyclohexanenitrile) initiator.[59]

KCL is about nine, and therefore about eight-ninths (89%) of the products result from autoxidation and about 11% from initiation by nitrogen dioxide. This large yield of autoxidation products explains why the percent of addition determined from total products (Figure 3, open points) approaches 10%, which is the percent of addition products expected on the basis of autoxidation products alone.[20]

The yield of autoxidation products (estimated from the KCL) can be subtracted from the total products (Figure 3, filled points) to approximate the effects of varying the nitrogen dioxide concentration on the reaction of nitrogen dioxide with cyclohexene in the absence of autoxidation. These data show that at ppm levels of nitrogen dioxide there is a slight shift toward more addition in the presence of oxygen than in its absence. Thus, there appears to be an oxygen-trapping effect, but it is small.

To rationalize this small effect of oxygen, we suggest that the rate of capture of radical **1** by oxygen may not be sufficiently rapid to prevent **1** from reverting to starting materials. The rate of trapping of **1** by oxygen depends on the rate constant ($k_3 = 2 \times 10^8$ to 10^9 $M^{-1}\ s^{-1}$),[50c-f] the concentration of **1**, and the oxygen concentration. Similarly, the rate of reversal of **1** to starting materials depends on the rate constant ($k_2 = 5 \times 10^4$ to 5×10^5 s^{-1})[42] and on the concentration of **1**. Under the steady-state conditions of autoxidation, the estimated oxygen concentration in our reaction solutions is 10^{-3} to 10^{-4} M.[58] Therefore, the ratio of the rate of reversal of **1** to starting materials to the rate of trapping of **1** by oxygen lies between 0.05 and 25, indicating that from 5% to 96% of **1** can revert to starting material even in the presence of oxygen.

Determination of the Oxidizability Ratios of the Unsaturated Fatty Acid Esters. Equation 22 relates the oxidizability ratio of a substrate, $k_p/(2k_t)^{1/2}$ to the rates of initiation and oxidation;

$$\frac{d}{dt}[\text{total peroxide}] = \frac{-d}{dt}[\text{ester}] = \frac{k_p}{(2k_t)^{1/2}}[\text{ester}](R_{\text{init}})^{1/2} \quad (22)$$

this equation requires that steady-state conditions exist, that the only important termination reactions are between peroxyl radicals, and that the KCL is large and initiation and termination reactions are insignificant compared to propagation.[59,60] Our data from Tables IV and V are plotted according to eq 22 in Figure 6 and lead to relative values for the oxidizability of the three esters in agreement with literature values: 18:3/18:2/18:1 = 40/20/1 (Table VI). However, our absolute values are all about one-third of the literature values.[59] Three rationalizations for our low values of the oxidizability ratio can be suggested. One is that our KCL are small (Tables IV, V) for the runs using high nitrogen dioxide levels, so eq 22 is not applicable over our entire study. Alternatively, our oxidizability ratios may be low because our reaction system is not completely homogeneous due to inadequate mixing. In addition, it is known[61] that nitrogen dioxide reacts with olefins to produce nitroxides, and the production of this inhibitor, which would increase the rates of termination in our system, could also lead to the reduced autoxidizability that we observe.

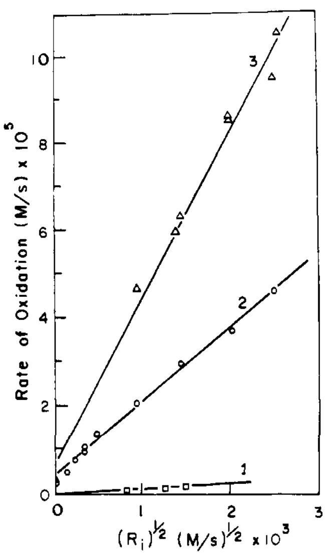

Figure 6. Rates of peroxide formation of the methyl esters oleate (curve 1), linoleate (curve 2), and linolenate (curve 3) are plotted as a function of the square root of the initiation rate by nitrogen dioxide. Taken from data in Tables IV and V.

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Registry No. Cyclohexene, 110-83-8; 1,3-cyclohexadiene, 592-57-4; methyl linolenate, 301-00-8; methyl linoleate, 112-63-0; 1,5,9-cyclododecatriene, 4904-61-4; 1-hexadecene, 629-73-2; methyl oleate, 112-62-9; 1-naphthol, 90-15-3; NO_2, 10102-44-0; H_2, 1333-74-0.

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(58) (a) Thomsen, E. S.; Gjaldbaek, J. Chr. *Acta Chem. Scand.* **1963**, *17*, 127–133. (b) Osburn, J. O.; Markovic, P. L. *Chem. Eng.* (*N. Y.*) **1969**, *76*, 105–108.

(59) Howard, J. A.; Ingold, K. U. *Can. J. Chem.* **1967**, *45*, 793–802.

(60) Reich, L.; Stivala, S. S. "Autoxidation of Hydrocarbons and Polyolefins"; Marcel Dekker: New York, 1969; pp 31–137.

(61) Estefan, R. M.; Gause, E. M.; Rowlands, J. R. *Environ. Res.* **1970**, *3*, 62–78. Pryor, W. A.; Church, D. F., unpublished results.