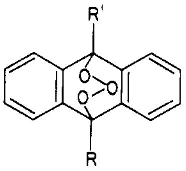
Pd(II)-Mediated Oxidation of Olefins Using the Transannular Ozonides of 9-*tert*-Butylanthracenes as an Oxygen Atom Source

Akira Matsuura, Yoshikatsu Ito, and Teruo Matsuura*

Department of Synthetic Chemistry, Faculty of Engineering, Kyoto University, Kyoto 606, Japan

Received June 25, 1985

Much attention has been given to oxygen atom transfer reactions using a transition-metal complex and some oxygen atom donors such as alkylhydroperoxides, peroxy acids, and iodosobenzene, in relation to their importance in biological monooxygenation processes.[1] Recently we found that the transannular primary ozonide **1b** obtained from 9-*tert*-butyl-10-methylanthracene has exceptional thermostability[2] and that the epoxidation of olefins with this ozonide in dichloromethane proceeds at reflux temperature.[3] We report here that this type of primary ozonide (**1a** and **1b**) can transfer an oxygen atom in the presence of a Pd(II) salt to styrenes and stilbene to afford acetophenone derivatives and stilbene oxide, respectively. This finding adds a further example to the utilization of primary ozonides for oxygen transfer reactions, i.e., the epoxidation of alkenes by intermediates formed during the ozonation of alkynes[4] and the oxidation of 1,3-diphenylisobenzofuran by the transannular ozonide **1c** of 9,10-dimethylanthracene at low temperature.[5]



1a, R=H; R'=*t*-Bu
1b, R=CH$_3$; R'=*t*-Bu
1c, R=R'=CH$_3$

Results and Discussion

Ozonide **1a** was prepared by the ozonation of the corresponding anthracene in acetone at −78 °C in 55% yield, according to the procedure for the preparation of **1b**.[2] Although **1a** was obtained as crystals of mp 93–94 °C, it was thermally unstable in a solution even at room temperature like the known ozonide **1c** ($\Delta H_{30\,°C} = 24.5$ kcal/mol).[6] The thermal decomposition of **1a** to anthraquinone was monitored by UV spectroscopy at temperatures ranging from 19 to 39 °C, giving the following Arrhenius equation:

$$\log k = (13.8 \pm 0.5) - (23800 \pm 170)/2.303RT$$

The activation energy ($E_a = 23.9 \pm 0.1$ kcal/mol, $\log A = 13.8 \pm 0.6$) of thermal decomposition of **1a** is smaller than that obtained for **1b** ($E_a = 28.6 \pm 0.5$ kcal/mol, $\log A = 14.6 \pm 0.3$).[2]

Oxidation of olefinic substrates with **1a** and **1b** in the presence of Pd(II) salt was carried out in acetonitrile under a nitrogen atmosphere. The results are summarized in Table I for styrenes and Table II for stilbene. Acetophenone and stilbene oxide are the respective major products. Whereas the simple reaction of **1b** with Pd(OAc)$_2$ without an olefin produced 10-(*tert*-butylperoxy)-10-methylanthrone (**4**) in 86% yield (entry 2), the addition of styrene to this reaction system gave 10-hydroxy-10-methylanthrone (**2b**) in 49–98% yield along with its monooxygenated product. Replacement of Pd(OAc)$_2$ by Pd(OCOCF$_3$)$_2$ did not alter the reaction course, giving a similar result (entry 10). In both cases, the addition of 2,6-di-*tert*-butyl-4-methylphenol, a radical scavenger, gave no effect (entry 8, 11), indicating that no radical process is involved in this reaction. The involvement of a peroxidic radical intermediate such as **8** (see below) is also eliminated, since the thermal decomposition of **1b** with styrene in the absence of Pd(OAc)$_2$ resulted in no oxygenation but only polymerization of styrene. In the absence of **1b** acetophenone was formed from styrene in 9% yield (entry 3), most probably via direct oxidation of olefin with Pd(II). It should be noted that oxidation of styrene with **1b** and Pd(OAc)$_2$ did not give any styrene oxide. Isobutene was trapped in 11% yield from the reaction mixture with styrene, **1b** and Pd(OAc)$_2$.

The reaction of styrenes with the less stable ozonide **1a** in the presence of Pd(OAc)$_2$ gave 10-hydroxyanthrone (**2a**) in 40–55% yield and the corresponding acetophenone in 39–55% yield in addition to anthraquinone (**3**) in 22–43% yield (entry 13–15). Simple thermolysis of **1a** in dichloromethane afforded anthraquinone (**3**) in 72% yield.

The reaction rate and the yield of the corresponding acetophenone increase in the order, *p*-methoxystyrene > styrene > *p*-chlorostyrene. The result suggests that a positive charge is developed at the α-carbon atom in the transition state of the reaction.[8]

The oxidation of styrenes by Pd(II) salts and trioxides **1a** and **1b** may be interpreted by a mechanism (Scheme I, pathway A) similar to that suggested by Mimoun et al. to account for the oxidation of terminal olefins with the peroxidic complexes RCOOPdOO-*t*-Bu.[8] The palladium complex **6** appears to be the most likely active intermediate in this reaction. Although attempts to isolate such a species from the reaction mixture failed, we observed an interesting finding in the oxidation of styrene using 10-hydroperoxy-10-methylanthrone (**5**) as an oxygen source. Oxidation of styrene with **5** in the presence of Pd(OAc)$_2$ gave acetophenone in 60% and **2b** in 79% yield. This reaction is thought to occur in two distinct steps, since the reaction of **5** with Pd(OAc)$_2$ and no styrene derivative gave a yellow-orange solid complex which is believed to have structure **6** and the oxidation of *p*-methoxystyrene with this complex gave *p*-methoxyacetophenone (85%) and **2b** (87%).

The reaction of *trans*- and *cis*-stilbene with ozonide **1b** gave stereospecifically *trans*-stilbene oxide in 5–32% yield together with 10-hydroxy-10-methylanthrone (**2b**) in 16–41% and 10-(*tert*-butylperoxy)-10-methylanthrone (**4**)

---

(1) (a) Patai, S. "The Chemistry of Functional Groups, Peroxide"; Wiley-Interscience: New York, 1983. (b) Lindsay, J. R.; Sleath, P. R. *J. Chem. Soc., Perkin Trans. 2* **1982**, 1009. (c) Franklin, C. C.; VanAtta, R. B.; Fan Tai, A.; Valentine, J. S. *J. Am. Chem. Soc.* **1984**, *106*, 814. (d) Powell, M. F.; Pai, E. F.; Bruice, T. C. *J. Am. Chem. Soc.* **1984**, *106*, 3277. (e) Nagata, R.; Matsuura, T.; Saito, I. *Tetrahedron Lett.* **1984**, *25*, 2691. (f) Nishinaga, A.; Yamazaki, S.; Nogusa, H.; Shimoyama, T.; Matsuura, T. *Nippon Kagaku Kaishi* **1985**, 378 and references cited therein.

(2) Ito, Y.; Matsuura, A.; Otani, R.; Matsuura, T.; Fukuyama, K.; Katsube, Y. *J. Am. Chem. Soc.* **1983**, *105*, 5699.

(3) Ito, Y.; Matsuura, A.; Matsuura, T. *Tetrahedron Lett.* **1984**, *25*, 1491.

(4) Keay, R. E.; Hamilton, G. A. *J. Am. Chem. Soc.* **1976**, *98*, 6578.

(5) Wassermann, H. H.; Murray, R. W. "Singlet Oxygen"; Academic Press: New York, 1979; p 106.

(6) Gobert, F.; Altenburger-Combrisson, S.; Albouy, J. *Org. Magn. Reson.* **1979**, *12*, 202.

(7) (a) Smidt, J. S.; Hapner, W.; Jira, R.; Sieber, R.; Sedlmeier, J.; Sabel, A. *Angew. Chem., Int. Ed. Engl.* **1962**, *1*, 80. (b) Backvall, J. E.; Akermark, B.; Ljunggren, S. O. *J. Am. Chem. Soc.* **1979**, *101*, 2411.

(8) (a) Mimoun, H.; Charpentier, R.; Mitscher, A.; Fischer, J.; Weiss, R. *J. Am. Chem. Soc.* **1980**, *102*, 1047. (b) Roussel, M.; Mimoun, H. *J. Org. Chem.* **1980**, *45*, 5387.

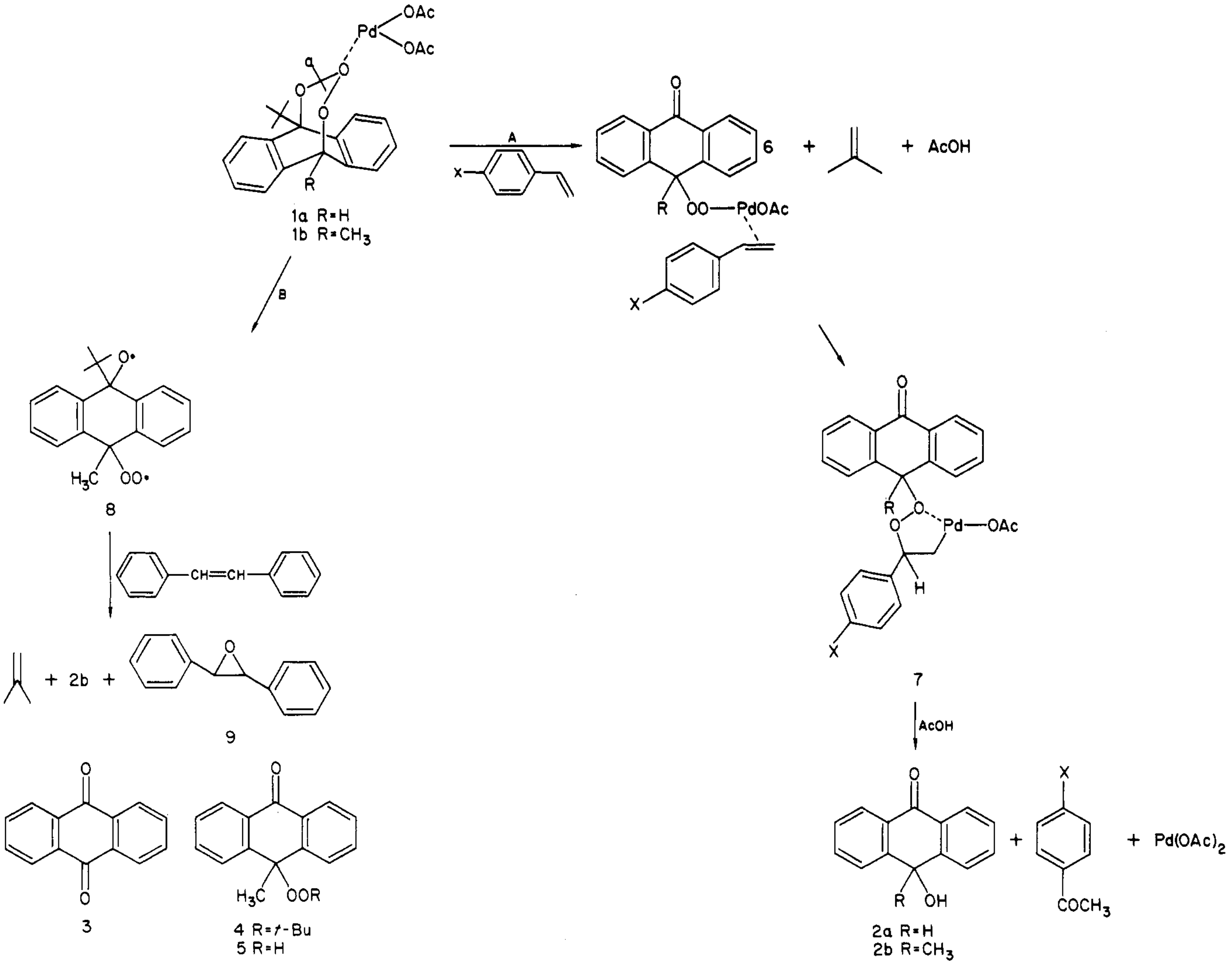
0022-3263/85/1950-5002$01.50/0

Table I. Oxidation of Styrenes by Pd(II) Salts and Ozonides 1a and 1b[a]

entry	ozonide, mmol	$Pd(OAc)_2$, mmol	X in p-X-$(C_6H_4)CH=CH_2$[b]	time, h	convsn of ozonide, %	isolated yield, % 2	3	4	correspacetophenone
1	**1b** (0.34)			71	27			70	
2	**1b** (0.5)	0.5		71	40			86	
3		0.5	H	74					9
4	**1b** (0.5)	1.0	OCH_3	72	100	96			93
5	**1b** (0.34)	0.34	OCH_3	70	100	93			90
6	**1b** (0.5)	1.0	H	69	96	87			84
7	**1b** (0.5)	0.5	H	72	100	82		9	77
8	**1b** (0.17)	0.17	H + BMP[c]	72	100	87			75
9	**1b** (0.5)	0.05	H	70	57	49		40	45
10	**1b** (0.67)	$Pd(OCOCF_3)_2$ 0.67	H	47	100	98			96
11	**1b** (0.5)	$Pd(OCOCF_3)_2$ 0.5	H + BMP[c]	48	100	95			95
12	**1b** (0.5)	0.5	Cl	70	87	73		14	66
13	**1a** (0.8)	0.8	OCH_3	1	100	55	31		55
14	**1a** (0.65)	0.65	H	2	100	45	22		45
15	**1a** (0.9)	0.9	Cl	2	100	40	43		39
16	**5** (0.6)	0.6	H	72	100	79			67

[a] Reactions were carried out at room temperature. [b] 5 molar amounts of styrene derivatives to trioxides **1a** and **1b** were used. [c] 10 molar amounts of 2,6-di-*tert*-4-methylphenol (BMP) were added.

Scheme I



in 49–68% yield (Table II), indicating the same stereospecificity as that in the epoxidation of stilbene by the thermolysis of **1b** in dichloromethane.[3] Since *cis*-stilbene oxide underwent no change under the reaction conditions, the initial formation of *cis*-stilbene oxide is improbable in the formation of *trans*-stilbene oxide from *cis*-stilbene. Replacement of $Pd(OAc)_2$ by $Pd(OCOCF_3)_2$ increased the yield of *trans*-stilbene oxide (entry 19, 22). In both cases the addition of a radical scavenger decreased the yield of *trans*-stilbene oxide (entry 20, 23), indicating involvement of a radical process in the epoxidation of stilbene. Considering similarities between the thermal[3] and Pd(II) salt assisted reaction of ozonide **1b** with stilbene in the product ratio and the radical nature, the latter reaction most probably involves a peroxy radical intermediate such as **8** in pathway B of Scheme I. The following facts also

Table II. Oxidation of Stilbene by Pd(II) Salts and Ozonides 1a and 1b[a]

entry	ozonide, mmol	$Pd(OAc)_2$, mmol	stilbene[b]	time, h	convsn of ozonide, %	isolated yield, % 2	3	4	epoxide 9
17	**1b** (0.5)	1.0	*trans*-stilbene	72	70	16		68	14
18	**1b** (0.34)	0.68	*trans*-stilbene + BMP[c]	72	80	30		40	
19	**1b** (0.5)	$Pd(OCOCF_3)_2$ 0.5	*trans*-stilbene	71	75	37		55	32
20	**1b** (0.68)	$Pd(OCOCF_3)_2$ 0.68	*trans*-stilbene + BMP[c]	71	70	20		47	5
21	**1b** (0.68)	1.36	*cis*-stilbene	72	79	30		54	5
22	**1b** (0.5)	$Pd(OCOCF_3)_2$ 0.5	*cis*-stilbene	71	73	41		49	25
23	**1b** (0.5)	$Pd(OCOCF_3)_2$ 0.5	*cis*-stilbene + BMP[c]	71	70	45		30	3
24	**1a** (0.7)	$Pd(OCOCF_3)_2$ 0.7	*trans*-stilbene	2	100		81		

[a] Reactions were carried out at room temperature. [b] Five molar amounts of stilbene to trioxides **1a** and **1b** were used. [c] Ten molar amounts of 2,6-di-*tert*-butyl-4-methylphenol (BMP) were added.

support the radical mechanism: (i) stilbene underwent no reaction with the peroxidic palladium complexes RCOOPdOO-*t*-Bu[8] and with the yellow complex obtained from hydroperoxide **5** and $Pd(OAc)_2$ (see above) and (ii) both *cis*- and *trans*-stilbenes undergo stereospecific epoxidation to give *trans*-stilbene oxide by the α-acyloin-sensitized photooxygenation in which a peroxidic radical intermediate is considered to participate.[9]

The reaction of *trans*-stilbene with the less stable ozonide **1a**, with or without added $Pd(OCOCF_3)_2$, gave only anthraquinone (**3**) in 81% and 79% yield, respectively, and no *trans*-stilbene oxide or **2a**. This suggests that the lifetime of a peroxy radical intermediate may be too short to react with *trans*-stilbene.

In summary, there may be two pathways, heterolysis (Scheme I, pathway A) and homolysis (pathway B), for the cleavage of peroxide bond (bond a) of the transannular ozonides **1a** and **1b** in the presence of Pd(II) salt depending upon the nature of the olefinic substrate.

Experimental Section

All melting points are uncorrected. The NMR, IR, UV, and mass spectra were measured by Varian T-60 and FT-80A (or JNM-GX 400), JASCO IRA-1, Shimadzu UV-240, and JEOL-JES-DX 300 spectrometers, respectively. HPLC analyses were performed with a JASCO Twinkle chromatograph equipped with Shimadzu chromatopac C-R1B, by using silica gel column (ss-05) and *n*-hexane–ethyl acetate eluent.

Preparation of Transannular Ozonide (1a) of 9-*tert*-Butylanthracene. 9-*tert*-Butylanthracene was prepared according to the Parish's procedure.[10] Through a solution containing 1 g of 9-*tert*-butylanthracene in 10 mL of acetone was bubbled an ozone–oxygen stream (1.5 g of O_3/h) at −78 °C until the starting material was consumed. After excess ozone was swept with N_2 at the same temperature, the solvent was evaporated at 0 °C under reduced pressure. Colorless crystals were filtered below 0 °C, washed with acetone, and recrystallized from acetone–*n*-hexane to give 0.657 g (55 %) of **1a**.

1a: mp 93–94 °C dec (from *n*-hexane–acetone) ^1H NMR ($CDCl_3$, at −20 °C) δ 1.48 (s, 3 H), 1.52 (s, 3 H), 1.84 (s, 3 H), 6.23 (s, 1 H), 7.20–8.05 (m, 8 H); mass spectrum, m/z (relative intensity) 282 (10), 267 (19), 251 (19), 225 (59), 208 (29), 193 (100), 57 (31); IR (Nujol) 1415, 1390, 940, 905, 715, 680, 670 cm^{-1}; UV ($CHCl_3$) 242 nm (ϵ 654); high-resolution mass spectrum calcd for $C_{18}H_{18}O_3$ 282.12565, found 282.12645. Anal. Calcd for $C_{18}H_{18}O_3$: C, 76.57; H, 6.42. Found: C, 76.58; H, 6.35.

Thermolysis of 1a. A solution of **1a** (480 mg, 1.7 mmol) in CH_2Cl_2 (20 mL) under N_2 was stirred at room temperature for 5 h. After the solvent was evaporated under reduced pressure, the residue was submitted to preparative TLC on silica gel to give 254 mg (75%) of anthraquinone (**3**).

General Procedure for the Oxidation of Olefins by Pd(II) Salts and Ozonides 1a and 1b. Under N_2, CH_3CN, which was dried twice over P_2O_5 and freshly distilled, was added to a vessel containing an ozonide, $Pd(OAc)_2$ or $Pd(OCOCF_3)_2$, and an olefin. After the mixture was stirred at room temperature for about 70 h, the solvent was evaporated under reduced pressure. The residue was submitted to preparative TLC on silica gel, eluting with benzene.

Reaction of Styrene with 1a and $Pd(OAc)_2$. A solution of **1a** (184 mg, 0.65 mmol), $Pd(OAc)_2$ (146 mg, 0.65 mmol), and styrene (340 mg, 3.25 mmol) in CH_3CN (10 mL) under N_2 was stirred at room temperature for 2 h. Acetophenone (35 mg, 45%), 10-hydroxyanthrone (**2a**)[11] (62 mg, 45%), and anthraquinone (**3**) (30 mg, 22%) (identified by NMR and IR) were obtained (Table I, entry 14).

Reaction of Styrene with 1b and $Pd(OAc)_2$. A solution of **1b**[2] (150 mg, 0.5 mmol), $Pd(OAc)_2$ (114 mg, 0.5 mmol), and styrene (260 mg, 2.5 mmol) in CH_3CN (10 mL) under N_2 afforded acetophenone (47 mg, 77%), 10-hydroxy-10-methylanthrone (**2b**) (93 mg, 82 %), and anthraquinone (**3**) (9 mg, 9%) (Table I, entry 7).

2: ^1H NMR ($CDCl_3$) δ 1.65 (s, 3 H), 2.83 (br s, 1 H), 7.13–8.12 (m, 8 H); IR (Nujol) 1660, 1605 cm^{-1}. Anal. Calcd for $C_{15}H_{12}O_2$: C, 80.33; H, 5.39. Found: C, 80.43; H, 5.36.

Reaction of *p*-Methoxystyrene with the Complex Obtained in the Reaction of 10-Hydroperoxy-10-methylanthrone (5)[12] with $Pd(OAc)_2$. Under N_2, $Pd(OAc)_2$ (287 mg, 1.2 mmol) was added to a solution of **5** (307 mg, 1.2 mmol) in CH_3CN (10 mL), and the mixture was stirred at room temperature for 5 h. A yellow-orange complex (410 mg) depositing from the reaction mixture was filtered and washed with CH_3CN. Complex: mp > 250 °C; ^1H NMR (Me_2SO-d_6) δ 1.57 (s, 3 H), 2.00 (s, 3 H), 7.23–8.26 (m, 8 H). Anal. Calcd for $C_{17}H_{14}O_5Pd \cdot 2H_2O$: C, 46.32; H, 4.11. Found: C, 45.61; H, 2.99.

To a solution of the complex (200 mg) in dry CH_3CN (10 mL) was added *p*-methoxystyrene (0.4 mL), and the mixture was stirred at room temperature for 43 h. The reaction mixture was concentrated under reduced pressure. The residue was submitted to preparative TLC on silica gel with benzene as eluent to give *p*-methoxyacetophenone (63 mg, 83%) and **2b** (96 mg, 87%). *trans*-Stilbene showed no reactivity to this complex.

Reaction of Styrene with $Pd(OAc)_2$ and 10-Hydroperoxy-10-methylanthrone (5).[12] Under N_2 a solution of **5** (150 mg, 0.6 mmol), $Pd(OAc)_2$ (140 mg, 0.6 mmol), and styrene (325 mg, 3 mmol) gave acetophenone (50 mg, 67%) and **2b** (110 mg, 79%) (Table I, entry 16).

Determination of Activation Parameters. The reaction was carried out at 19–39 °C in $CHCl_3$ with **1a** (1.4×10^{-3} M) and measuring the absorbance change at 250 and 300 nm. The A_∞ value was obtained after allowing the reaction to continue for 300 min to verify that the absorbance was no longer changing. The observed rate constant was obtained from the slope of the first-order plot of $\ln [(A_0 - A_\infty)/A_t - A_\infty)]$ vs. time. All k_{obsd} values were determined from slopes of the first-order plots of $\ln [a_0/(a_0 - a_t)]$ vs. time. Activation energies were calculated from Arrhenius plots of the rate constants.

Analysis of Acetophenone Derivatives and 10-Hydroxy-10-methylanthrone (1b). Acetophenone and **1b** were analyzed by high-pressure liquid chromatography with phenyl benzoate as an internal standard.

---

[9] (a) Shimizu, N.; Bartlett, P. D. *J. Am. Chem. Soc.* **1976**, *98*, 4193. (b) Sawaki, Y.; Ogata, Y. *J. Am. Chem. Soc.* **1981**, *103*, 2049.

[10] Parish, R. C.; Stork, L. M. *J. Org. Chem.* **1966**, *31*, 4265.

[11] Meyer, H. *Justus Liebigs Ann. Chem.* **1911**, *379*, 47.

[12] Julian, P. L.; Cole, W.; Diemer, G. *J. Am. Chem. Soc.* **1945**, *67*, 1721.