

## SCOPE AND LIMITATIONS OF THE FLASH VACUUM THERMOLYSIS APPROACH TO SMALL [n]PARACYCLOPHANES

L. W. JENNESKENS, W. H. DE WOLF and F. BICKELHAUPT\*

Scheikundig Laboratorium, Vrije Universiteit, DeBoelelaan 1083, 1081 HV Amsterdam, The Netherlands

(Received in USA 17 June 1985)

**Abstract**—Flash vacuum thermolysis (FVT) of 3-methylene-6-spirocyclohexa-1,4-dienes (**2**) was investigated as a synthetic approach to small [n]paracyclophanes **1** (**1a**,  $n = 8$ ; **1b**,  $n = 7$ ; **1c**,  $n = 6$ ). The method was found to be preparatively attractive for **1a** (80% yield), less so for **1b** (7% useful yield), and not at all for **1c** which was too unstable to survive the conditions of its formation. Besides **1**, *p*-alkylstyrenes (**3**) and 2-methylbenzocycloalkenes (**4**) were obtained; the total recovery of monomeric products was good (60–85%). The temperature dependence of the product formation furnished useful information on the mechanisms of formation and decomposition of **1** under the conditions of FVT.

The systematic investigation of the chemical properties of [n]paracyclophanes **1**<sup>1</sup> with short bridges ( $n \leq 8$ ) is of great interest. It is, however, somewhat hampered by the lack of efficient syntheses on a larger scale.

Relatively, the situation is best for [8]paracyclophane (**1a**), the oldest and least strained member of the group. Several approaches to **1a** are known; they have recently been reviewed by Hopf and co-workers<sup>2a</sup> who concluded that an adaptation of the original multistep synthesis of Cram and Knox<sup>2b</sup> is still the preferred one. Three approaches to [7]paracyclophane (**1b**) have been reported, but all give rather low yields.<sup>1a,3</sup> [6]Paracyclophane (**1c**)<sup>4</sup> and some derivatives<sup>5</sup> are available by a number of routes, and the unstable [5]paracyclophane (**1d**) has recently been prepared by photolysis of the corresponding 1,4-pentamethylene Dewar benzene in low yield.<sup>6</sup>

In an attempt to make **1** more readily available, we reinvestigated the pyrolytic approach from 3-methylene-6-spirocyclohexa-1,4-dienes **2**. We had previously shown that **2a** and **b** can be converted to **1a** and **b**, respectively, by flow pyrolysis (filled pyrex tube, 0.1 mbar N<sub>2</sub>, ca 500°).<sup>3b</sup> However, the yields were not satisfactory (**1a**, 20%; **1b**, 15%) and varied from run to run; the main product was invariably about 70% polymer which was mostly deposited directly behind the hot zone. Presumably, catalytic wall effects were responsible for the low and variable yield of low molecular weight products. Therefore, it seemed worthwhile to investigate if better results could be obtained by flash vacuum thermolysis (FVT), as wall effects and secondary reactions are of minor importance under these conditions.<sup>7</sup>

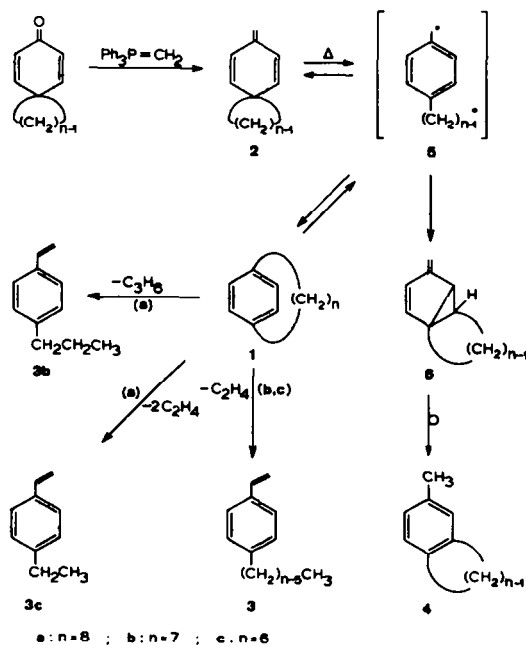
We here report that this goal was fully achieved for **1a**; in the case of **1b**, we were only partially successful, while **1c** could not be prepared by this method. Apart from the preparative aspects, interesting insight was obtained into the mechanisms of formation and thermal decomposition of small [n]paracyclophanes **1**.

### RESULTS

The starting materials **2a–c** for FVT were conveniently prepared from the corresponding spirocyclohexadienones<sup>8</sup> by a Wittig reaction with

triphenylmethylenephosphorane (Scheme 1) in 60–70% yield.<sup>3b,9</sup> FVT of **2a–c** was performed at 0.04 mbar in an alumina tube (Experimental). The pyrolysate was collected on a cold finger and analyzed by preparative GLC and weighing of the products which were identified by their spectral data and by comparison with authentic samples. The product composition was found to depend on the thermolysis temperature (Table 1, Scheme 1).

From Table 1, it can be seen that the ease of thermolysis decreases in the sequence **2a** > **2b** > **2c**. In the same direction, the yield of **1** decreases strongly, while the number and amount of by-products increases. The total recovery was surprisingly constant within each series, but varied in a characteristic way depending on the starting material: **2a** gave ca 80%, **2b** ca 60%, and **2c** ca 85% recovery.



Scheme 1.

Table 1. Products from flash vacuum thermolysis (%)

Educt	T (°)	Products			
		1	2	3	4
2a	500	73	7	0	0
	550	80	0	0	0
	600	ca 80	0	0	0
	750	33	0	{27 <sup>b</sup> 14 <sup>c</sup> }	6
2b	500	15	28	5 <sup>b</sup>	13
	550	19	14	8 <sup>b</sup>	19
	600	7	0	40 <sup>b</sup>	13
2c	500	0	85	0	0
	550	0	77	8 <sup>c</sup>	0
	600	0	37	47 <sup>c</sup>	2
1a	700	88	0	{0.7 <sup>b</sup> 1 <sup>c</sup> }	6
	750	65	0	{12 <sup>b</sup> 9 <sup>c</sup> }	11
1b	700	0	0	73 <sup>b</sup>	21

\* Trace.

<sup>b</sup> 3b.<sup>c</sup> 3c.

It was of interest to study also the behaviour of 1a and b under FVT conditions in order to be able to interpret the formation of the by-products, the *p*-alkylstyrenes 3 and the 2-methylbenzocycloalkenes 4; the pyrolysis of 1c has been reported previously.<sup>4c,9</sup> In line with the observation that the formation of 3 and 4 becomes more prominent in the higher temperature range (up to 600°), somewhat higher temperatures (700–750°) were required for 1a and b. Nevertheless, products 3 and 4 were the same as in the thermolysis of 2a and b, respectively; the total recovery was ca 95%.

It should be pointed out that 2b and 1b gave only *p*-n-propylstyrene (3b), and 2c only *p*-ethylstyrene (3c). In contrast, 2a and 1a did not yield *p*-n-butylstyrene (3a), but the lower homologues 3b and c.

## DISCUSSION

The results of Table 1 indicate that FVT is indeed superior to flow pyrolysis with a filled pyrex tube and nitrogen as a carrier gas (0.1 mbar). The recovery of monomeric products (60–85%) is much higher than in flow pyrolysis (ca 20%<sup>3b</sup>), and the formation of white polymer is greatly reduced. Both wall effects and the pressure in the gas phase are responsible for the observed differences. This was illustrated by an experiment with the FVT apparatus, but at the higher pressure of 1 mbar. Under these circumstances, the total recovery for 2a at 550° dropped from 80 to 60%, and much more polymer was formed.

Our primary goal had been to improve the synthesis of 1. Clearly, this was not achieved for 1c; although 1c is obviously formed (*vide infra*), it is too strained and unstable to survive under the reaction conditions. The preparation of the next higher homologue 1b has been slightly improved, the yield being 19% at 550° as compared to 10–15% on flow pyrolysis.<sup>3b</sup> A particular difficulty resides in the fact that 1b is not easy to separate from unreacted 2b even by preparative GLC. Therefore, thermolysis at 550° (14% 2b recovered) is not really practical. The preferred thermolysis temperature is 600°. Although the yield of 2b is only 7%, it can be easily separated from the "by-products" 3b (40%) and

4b (13%) by simple column chromatography. The FVT approach to 1b is therefore far from satisfactory; still we feel that it is not inferior to other methods if one considers the accessibility of starting materials and the ease of thermolysis as such.

For 1a FVT is a really attractive alternative to previous methods. The starting material 2a is relatively easily available, the reaction can be performed on a multigram scale, and 1a is formed at 550° in 80% yield without by-products.

An interesting spin-off of this investigation is the mechanistic interpretation of the product formation which is based on products analysis and on thermochemical data presented in Table 2; they were obtained mostly from MNDO<sup>10</sup> calculations and/or from group increments<sup>11</sup> as noted in the footnotes of Table 2.

The obvious first step in the thermolysis of 2 is cleavage of one of its spiro bonds to give the diradical 5 (Scheme 1). In this process, any conformational strain in 2 is released in 5. This is reflected in an increasing enthalpy difference between 2 and 5 in the sequence a < b < c and one may expect that the activation barriers will show the same trend as the ground state enthalpies. Consequently, one predicts increasing reactivity in the order 2c < 2b < 2a, which is experimentally confirmed by the amount of unreacted 2 at a given temperature (Table 1).

Diradical 5 has several options for further reaction. Intramolecular combination of the two radical subunits will be kinetically favoured at the positions of highest spin density. For the benzyl radical subunit, this is expected<sup>14</sup> to be the benzylic carbon atom, and radical recombination should lead to 1. However, the resulting specific compounds differ tremendously in absolute and relative thermodynamic stability. While 1a is much more stable than 2a, the situation is approximately balanced for 1b and 2b, but quite unfavourable for 1c (Table 2). As a consequence, one would expect that 5 may revert to 2 rather than proceed to 1 in the sequence a < b < c, and the thermolytic stability of 2c may in part be due to this kinetic effect rather than to inherent unreactivity. On the other hand, (re)conversion of 1 to 5 is predicted to occur in the order a < b < c, in agreement with the high temperature FVT behaviour of 1a and b (Table 1); for 1c, it has already been demonstrated that the isomerization to 2c<sup>4c,9</sup> (and to 3c<sup>9</sup>) occurs under even milder conditions (400°<sup>4c</sup> or 520°<sup>9</sup> depending on the reaction conditions).

The formation of 4 may be rationalized by two pathways. Initially, we considered the possibility that

Table 2. Estimated heats of formation  $\Delta H_f^\circ$  (kcal mol<sup>-1</sup>)

Compound	n	1	2 <sup>a</sup>	3 <sup>b</sup>	6 <sup>a</sup>
a	8	-0.2 <sup>a</sup>	23.1	53.6	47.2
b	7	21.4 <sup>a</sup>	24.5	58.5	49.2
c	6	39.1 <sup>a</sup>	23.1	63.5	50.7

<sup>a</sup> Calculated from group increments.<sup>11</sup><sup>b</sup> Calculated from the equation

$$\Delta H_f^\circ(5) = \Delta H_f^\circ(p\text{-CH}_2\text{C}_6\text{H}_4(\text{CH})_{n-2}\text{CH}_3) +$$

$$D(\text{C}_6\text{H}_5\text{CH}_2\text{—H}) + D(\text{RCH}_2\text{—H}) - 2\Delta H_f^\circ(\text{H}).$$

<sup>c</sup> From Ref. 12 (MM calculations).<sup>d</sup> From Ref. 13 (MNDO calculations).

the aliphatic radical part of **5** attacks the *ortho*-position of the benzyl radical in analogy to the *para*-attack leading to **2**; both positions have considerable spin density.<sup>14</sup> This *ortho*-addition should be followed by aromatization to  $\alpha$ -methyl[n-1]metacyclophane and by valence isomerization of the latter to **4**. The isomerization of strained *para*- and *meta*cyclophanes to the *ortho*-isomers has indeed been observed, but recent evidence seems to indicate that such isomerizations may be (acid?, wall?) catalyzed rather than being valence isomerizations proper.<sup>9</sup> As long as this situation has not been fully clarified, we prefer a second pathway, initiated by the conversion of **5** to **6** by attack of the aliphatic radical at the *meta*-position of the benzyl radical of **5**, followed by aromatization of **6** to **4** (Scheme 1). Although *meta*-attack might seem less plausible because there is little spin density at this position, it is in fact at least as favourable as the attack of an alkyl radical on an unactivated aromatic ring; in **5**, this attack is further aided by spin pairing and by intramolecularity. The thermochemical considerations (Table 2) show that the formation of **6** from **5** is exothermic and should be increasingly favoured going from **a** to **c**; while this trend is experimentally observed for **4a** and **b** (see entries for **2a** vs **2b**, and **1a** vs **1b**; Table 1), this is not the case for **4c**. We have no satisfactory explanation at the moment. Obviously, ground state stability cannot be the only factor, as the process is discernible for **2a** and **c** only at higher temperatures and thus has a rather high enthalpy of activation. In any case, the postulate of **5** as a precursor of **4** is strongly supported by the formation of **4a** and **b** from **1a** and **b**, respectively.

Simple as they look at first sight, the *p*-alkylstyrenes **3b** and **c** are mechanistically the most intriguing products. Before discussing their genesis we note two interesting aspects. First, the conversion of **2** to **3** involves the translocation of (at least) one carbon atom from one side of the benzene-ring-to-be to the other. This is most easily rationalized by invoking the intermediacy and fragmentation of **1**,<sup>3b,9</sup> this postulate is supported by the independent transformation of **1** to **3** at higher temperatures (Table 1). The second, challenging observation is that in all three cases (**a**–**c**) investigated, products **3** are not isomeric with the starting material, contrary to **1** and **4**. The formation of **3** formally involves either loss of one molecule of ethylene if one pyrolyses **1b**, **2b** or **2c**, or the loss of two molecules of ethylene or of the elements of propene (or trimethylene), respectively, from **1a** or **2a**. In the present investigation, the identity of the lost fragments has not been established; previously, we have shown that in the flow pyrolysis of **1c** (*vide supra*), **3c** and ethylene are formed simultaneously.<sup>9</sup>

We wish to comment only briefly on the mode of formation of **3** as it has not been investigated in detail. We feel that for several reasons, concerted processes are not likely; at least, they cannot be identical for **2a** on the one hand and **2b** and **c** on the other, since the fragmentation patterns are different. Similarly, an intermolecular course of the reaction, e.g. by radical chain mechanisms cannot be important. In general, they are considered less likely under the low pressure conditions of FVT;<sup>7</sup> we found that increasing the pressure leads only to increased amounts of polymer (cf. the reaction of **2a** at 1 mbar/550°; mentioned in Results). We therefore propose that cleavage of the

strained oligomethylene bridge of **1** occurs not only at its weakest point; i.e. the benzylic carbon–carbon bond to furnish the diradical **5**, but also at one of the other carbon–carbon bonds of the bridge, e.g. the homobenzylic bond to furnish an isomeric diradical **8**. We shall discuss such possibilities in future papers.

## EXPERIMENTAL

<sup>1</sup>H-NMR spectra were recorded on a Bruker WH-90 spectrometer at a frequency of 90 MHz and are reported in  $\delta$  units with TMS as internal reference. All compounds were analyzed by GCMS, using a Finnigan 4000 mass spectrometer; exact mass measurements were performed with a Varian CH-5 DF mass spectrometer at an ionization potential of 70 eV.

Compounds **2a**–**c** were synthesized from their corresponding spirocyclohexadienones<sup>8</sup> (ca 25 mmol) as described.<sup>9</sup> Products were purified by column chromatography (Al<sub>2</sub>O<sub>3</sub>, *n*-pentane).

**3-Methylenespiro[5,7]trideca-1,4-diene (2a)**. Yield 60%. <sup>1</sup>H-NMR (CDCl<sub>3</sub>)  $\delta$  6.20 and 5.78 (AB system, J(AB) = 10 Hz, 4H), 4.83 (bs, 2H), 1.85–1.55 (m, 14H); MS *m/e* (rel. intensity) 188 (25, **2a**<sup>+</sup>), 104 (100); exact mass 188.1563 (calc for C<sub>14</sub>H<sub>20</sub>, 188.1565).

**3-Methylenespiro[5,6]dodeca-1,4-diene (2b)**. Yield 60%. <sup>1</sup>H-NMR (CDCl<sub>3</sub>)  $\delta$  6.20 and 5.78 (AB system, J(AB) = 10 Hz, 4H), 4.83 (bs, 2H), 1.85–1.55 (m, 12H); MS *m/e* (rel. intensity) 174 (15, **2b**<sup>+</sup>), 104 (100); exact mass 174.1408 (calc for C<sub>13</sub>H<sub>18</sub>, 174.1408).

**3-Methylenespiro[5,5]undeca-1,4-diene (2c)**. Yield 70%. <sup>1</sup>H-NMR (CDCl<sub>3</sub>)  $\delta$  6.20 and 5.78 (AB system, J(AB) = 10 Hz, 4H), 4.83 (bs, 2H), 1.85–1.55 (m, 10H); MS *m/e* (rel. intensity) 160 (28, **2c**<sup>+</sup>), 104 (100); exact mass 160.1240 (calc for C<sub>12</sub>H<sub>16</sub>, 160.1252).

*Flash vacuum thermolysis (FVT)*. The FVT apparatus was modelled after the design of Brown,<sup>7a</sup> with modifications by Verlaak.<sup>7b</sup> In our experiments, a 28 cm aluminum oxide tube was used at a pressure of 0.04 mbar. In a typical run, 2 (0.5 mmol) was vaporized into the hot zone at a rate of 100 mg h<sup>-1</sup>, using a sublimation furnace (Büchi GKR 50) to heat the sample bulb (40–50°). The pyrolysate was trapped on a cold finger cooled with dry ice and acetone (–70°). After pyrolysis, the pyrolysate was collected from the cold finger by washing with diethyl ether. The solvent was evaporated at reduced pressure. Products were isolated by preparative GC (5% Carbowax on Chromosorb W, length 1.5 m at 110° (**2a**); 100° (**2b**), 80° (**2c**), respectively). The products were identified on the basis of their spectral data. For preparative purposes, a pyrolysis rate of ca 1 g h<sup>-1</sup> was used.

[**8**]Paracyclophane (**1a**). Its spectral data were in agreement with reported data.<sup>2</sup>

[**7**]Paracyclophane (**1b**). Its spectral data were in agreement with reported data.<sup>3</sup>

*p*-Propylstyrene (**3b**). <sup>1</sup>H-NMR (CDCl<sub>3</sub>)  $\delta$  7.22 and 7.01 (AB system, J(AB) = 8 Hz, 4H), 6.73, 5.72 and 5.20 (ABC system, J(AC) = 18 Hz, J(BC) = 10 Hz and J(AB) = 1 Hz, 3H), 2.61 (t, J = 7 Hz, 2H), 1.60 (m, 2H), 0.96 (t, J = 7 Hz, 3H); MS *m/e* (rel. intensity) 146 (31, **3b**<sup>+</sup>), 117 (100); exact mass 146.1097 (calc for C<sub>11</sub>H<sub>14</sub>, 146.1095).

*p*-Ethylstyrene (**3c**). <sup>1</sup>H-NMR (CDCl<sub>3</sub>)  $\delta$  7.20 and 7.00 (AB system, J(AB) = 8 Hz, 4H), 6.72, 5.72 and 5.23 (ABC system, J(AC) = 18 Hz, J(BC) = 10 Hz and J(AB) = 1 Hz, 3H), 2.65 (q, J = 7 Hz, 2H), 1.20 (t, J = 7 Hz, 3H); MS *m/e* (rel. intensity) 132 (84, **3c**<sup>+</sup>), 117 (100); exact mass 132.0930 (calc for C<sub>10</sub>H<sub>12</sub>, 132.0939).

6,7,8,9,10,11 - Hexahydro - 2 - methyl - 5H - benzocyclononene (**4a**). <sup>1</sup>H-NMR (CDCl<sub>3</sub>)  $\delta$  6.98–6.92 (m, 3H), 2.29 (s, 3H), 2.73 (m, 4H), 1.87–1.13 (m, 10H); MS *m/e* (rel. intensity) 188 (91, **4a**<sup>+</sup>), 145 (92), 119 (100); exact mass 188.1563 (calc for C<sub>14</sub>H<sub>20</sub>, 188.1565).

5,6,7,8,9,10 - Hexahydro - 2 - methylbenzocyclooctene (**4b**). <sup>1</sup>H-NMR (CDCl<sub>3</sub>)  $\delta$  6.96–6.92 (m, 3H), 2.73 (m, 4H), 2.30 (s,

3H), 1.87–1.13 (m, 8H); MS *m/e* (rel. intensity) 174 (100, 4b<sup>+</sup>), 145 (71), 131 (98); exact mass 174.1400 (calc for C<sub>13</sub>H<sub>18</sub>, 174.1408).

6,7,8,9-Tetrahydro-2-methyl-5H-benzocycloheptene (4c). Its spectral data were in agreement with reported data.<sup>15</sup>

*Acknowledgements*—We would like to thank D. Schaddenhorst for experimental contributions. This investigation was supported by the Netherlands Foundation for Chemical Research (SON) with financial aid (L.W.J.) from the Netherlands Organization for the Advancement of Pure Research (ZWO).

#### REFERENCES

- <sup>1</sup>P. M. Keehn and S. M. Rosenfeld, *Cyclophanes I*. Academic Press, New York (1983); <sup>2</sup>A. Greenberg and J. F. Liebman, *Strained Organic Molecules*. Academic Press, New York (1978).
- <sup>2</sup>K. L. Noble, H. Hopf and L. Ernst, *Chem. Ber.* **117**, 455 (1984); <sup>3</sup>D. J. Cram and G. R. Knox, *J. Am. Chem. Soc.* **83**, 2204 (1961).
- <sup>3</sup>A. D. Wolf, V. V. Kane, R. H. Levine and M. Jones, Jr., *Ibid.* **95**, 1680 (1973); <sup>4</sup>J. W. Van Straten, W. H. De Wolf and F. Bickelhaupt, *Recl. Trav. Chim. Pays-Bas* **96**, 88 (1977); <sup>5</sup>P. G. Gassman, T. F. Bailey and R. C. Hoye, *J. Org. Chem.* **45**, 2923 (1980).
- <sup>4</sup>V. V. Kane, A. D. Wolf and M. Jones, Jr., *J. Am. Chem. Soc.* **96**, 2643 (1974); <sup>5</sup>S. L. Kammula, L. D. Iroff, M. Jones, Jr., J. W. Van Straten, W. H. De Wolf and F. Bickelhaupt, *Ibid.* **99**, 5815 (1977); <sup>6</sup>Y. Tobe, K. Ueda, K. Kakiuchi and Y. Odaira, *Chem. Lett.* 1645 (1983).
- <sup>5</sup>J. Liebe, C. Wolff and W. Tochtermann, *Tetrahedron Lett.* **23**, 171 (1982); <sup>6</sup>C. Wolff, J. Liebe and W. Tochtermann, *Ibid.* **23**, 1143 (1982); <sup>7</sup>Y. Tobe, K. Kakiuchi, Y. Odaira, T. Hosaki, Y. Kai and N. Kasai, *J. Am. Chem. Soc.* **105**, 1376 (1983).
- <sup>6</sup>L. W. Jenneskens, F. J. J. De Kanter, P. A. Kraakman, L. A. M. Turkenburg, W. E. Koolhaas, W. H. De Wolf, F. Bickelhaupt, Y. Tobe, K. Kakiuchi and Y. Odaira, *Ibid.* **107**, 3716 (1985).
- <sup>7</sup>R. F. C. Brown, *Pyrolytic Methods in Organic Chemistry*. Academic Press, New York (1980). <sup>8</sup>J. M. J. Verlaak, Thesis, Catholic University of Nijmegen (1983).
- <sup>8</sup>V. V. Kane, *Synth. Commun.* **6**, 237 (1976).
- <sup>9</sup>J. W. Van Straten, L. A. M. Turkenburg, W. H. De Wolf and F. Bickelhaupt, *Recl. Trav. Chim. Pays-Bas* **104**, 89 (1985).
- <sup>10</sup>M. J. S. Dewar and W. Thiel, *J. Am. Chem. Soc.* **99**, 4899 (1977).
- <sup>11</sup>S. W. Benson, *Thermochemical Kinetics*. Wiley, New York (1968).
- <sup>12</sup>L. Carballeira, J. Casado, E. Gonzalez and M. A. Rios, *J. Chem. Phys.* **77**, 5655 (1982). These MM calculations give values for  $\Delta H_f^\circ$  which are generally lower than those obtained from MNDO calculations<sup>13</sup> by about 5–8 kcal mol<sup>-1</sup>; however, these differences do not influence the qualitative discussion in our text.
- <sup>13</sup>H. Schmidt, A. Schweig, W. Thiel and M. Jones, Jr., *Chem. Ber.* **111**, 1958 (1978).