Reaction Mechanisms

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In Situ NMR Spectroscopic Observation of a Catalytic Intermediate in Phosphine-Catalyzed Cyclo-Oligomerization of Isocyanates**

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Dedicated to Dr. Josef Pedain on the occasion of his 70th birthday

Polyurethanes, manufactured from aromatic and aliphatic isocyanates (**1**),[1] are an important class of high-performance materials. Aliphatic polyisocyanates are the preferred building blocks for coatings and most are based on hexamethylene diisocyanate (HDI). For the majority of applications, oligomers of HDI with significantly lower vapor pressure than that of the monomer are required. These oligomers are predominantly cyclo-oligomers, such as uretdiones **2**,[2] isocyanurates **3**,[3] and iminooxadiazinediones **4**,[4] which can be prepared by catalytic cyclo-oligomerization of monomeric isocyanates.[5] Although phosphines, including tri-*n*-butylphosphine (**5**), have been used commercially as catalysts for more than 20 years,[6] no information is available on the mechanism of the reaction. Based on the reactivity of nucleophiles towards heterocumulenes,[7] the reaction may start by the nucleophilic attack of the phosphine on the carbonyl group of the isocyanate to form a zwitterionic intermediate **A**, followed by reaction with another isocyanate moiety to result in a second zwitterionic intermediate **B** (Scheme 1). Although an intramolecular nucleophilic attack by the $^{-}O(RN)^{-}$ ion on the carbonyl group of **B** could lead to the formation of **2** and **5**, the addition of another isocyanate moiety could result in the formation of zwitterionic intermediates $\mathbf{C_1}$ and $\mathbf{C_2}$. Similarly,

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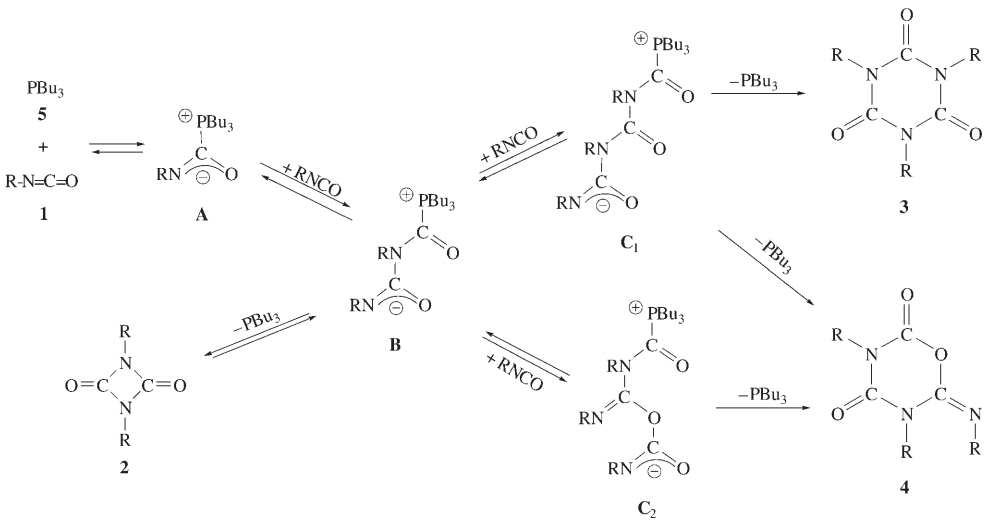
Supporting information for this article is available on the WWW under http://www.angewandte.org or from the author.



Scheme 1. Proposed mechanism of the phosphine-catalyzed oligomerization of isocyanates.

intramolecular nucleophilic attack by the $^{-}O(RN)-$ ion on the carbonyl group of $\mathbf{C_1}$ and $\mathbf{C_2}$ could lead to the formation of isocyanurates **3** or iminooxadiazinediones **4**, respectively, and the reformation of **5**. We report herein the first structural characterization of **B** by in situ spectroscopic studies.

The cyclo-oligomerization of alkyl isocyanates (RNCO: R = *n*-butyl and *n*-hexyl **1a** and **1b**, respectively) was studied by in situ IR spectroscopy in the presence of various amounts of **5** in the temperature range 20–80 °C.[8] Even in the presence of a slight excess of **5** (4.8 mmol) in relation to **1a** (4.4 mmol), only the peaks assigned to products **2a**, **3a**, and **4a** (1771; 1694; and 1791, 1719, and 1687 cm^{-1}, respectively) could be observed at 20 °C (Figure 1).[9] At the beginning of the

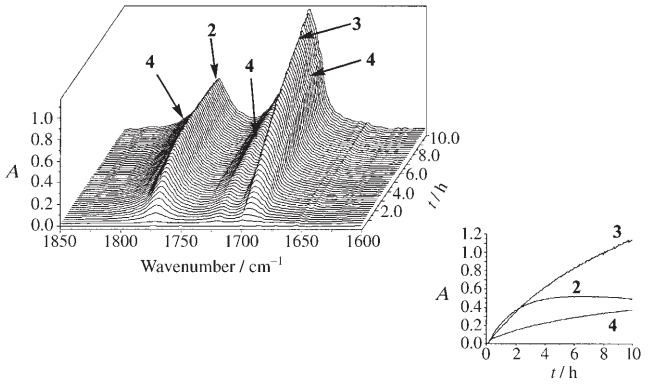


Figure 1. The IR spectra of the carbonyl region during the cyclo-oligomerization of **1a** with **5** at 20 °C.

reaction, the rate of the formation of **2a** is higher than that of **3a** and **4a**, but its concentration reaches a maximum after five hours, thus indicating that the reaction of **2a** with **1a** or yields **3a** and **4a** in almost constant ratios. When 12.2 mmol of **2a** was treated with 1.22 mmol of **5**, the formation of free isocyanates **1a**, **3a**, and **4a** was observed (Figure 2), thus providing direct evidence that the formation of **2a** is a reversible process.

As the in situ IR investigations only showed the formation of the products, we used in situ ^{1}H, ^{13}C, and ^{31}P NMR spectroscopy to confirm these results and to structurally characterize the intermediates. During the tri-*n*-butylphosphine-catalyzed cyclo-oligomerization of **1a**, we observed again the initial formation of **2a** followed by the appearance of **3a** and **4a**.[10] The concentration of **2a** goes to a maximum value, as expected, and at the end of the reaction the ratio of **2a**/**3a**/**4a** is always equal to 0.2:2:1. The in situ

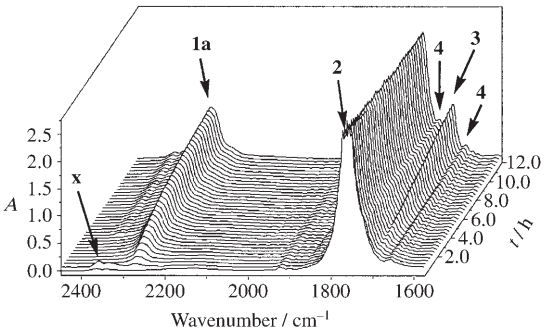


Figure 2. The IR spectra of the carbonyl region during the reaction of **2a** (12.2 mmol) with **5** (1.22 mmol) at 25 °C (the peaks marked with x are due to gaseous CO_2 in the arm of the ReactIR 1000 instrument).

NMR spectroscopic analysis of the reaction of **2a** with **5** also confirmed the formation of free **1a**, **3a**, and **4a**. On the contrary, no reaction was observed when the mixture of **3a** and **4a** was treated with **5**, thus indicating that neither the ring opening of **3** and **4** nor the interconversion between **3** and **4** occurs.[10] Similar results were obtained when **1b** was used as the monomer.

Next, we used ^{31}P NMR spectroscopy to observe the possible intermediate(s) in the reaction between **1b** and **5** in ratios of 1:1, 2:1, and 3:1, thus leading to **A**, **B**, and $\mathbf{C_1}$ and $\mathbf{C_2}$, respectively. Only one resonance at $\delta = -32.9$ ppm (linewidth (LW) = 1 Hz) was observed for **5** at 297 K (Figure 3). By lowering the temperature to 250 K, the appearance of a new, sharp peak is observed at $\delta = -54.0$ ppm (LW = 7 Hz). This peak begins to broaden when the temperature increases from 250 to 270 K (Figure 3) and finally disappears into the baseline at 275 K. It should be noted that below 250 K there is no change in the linewidth of this resonance and that there is no variation in the linewidth of free **5** over the whole temperature range studied. The observed dynamic phenomena can be explained by the fast exchange between the intermediate(s) and free isocyanate. The exact structure of the intermediate was delineated by using 99.0 % ^{13}C-labelled

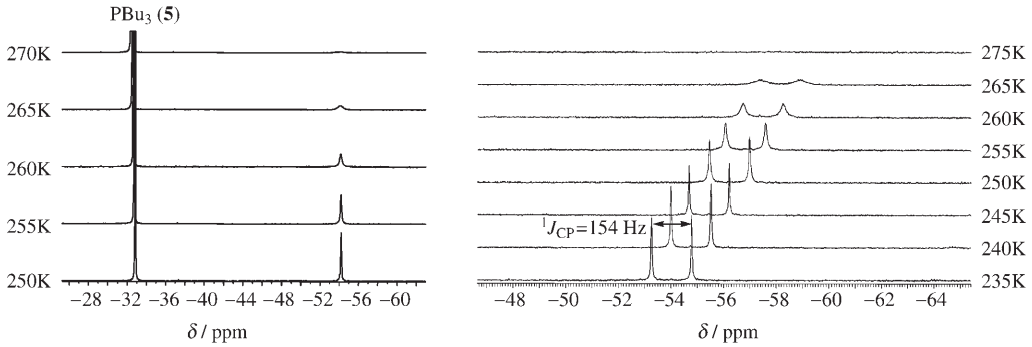


Figure 3. $^{31}P\{^1H\}$ NMR spectra at different temperatures of solutions containing: left: **1b** (3.4 mmol) and **5** (0.4 mmol); right: [^{13}C]*n*-hexyl isocyanate (3.4 mmol) and **5** (0.18 mmol).

n-hexyl isocyanate. The ^{31}P NMR spectrum shows a doublet at $\delta = -54.0$ ppm, with a coupling constant of $J = 154$ Hz, thus indicating P–C coupling over a single bond ($^1J_{PC}$; Figure 3). This observation was confirmed by a doublet of doublets at $\delta = 166.7$ ppm in the ^{13}C NMR spectrum. Besides the coupling constant exhibited by $^1J_{PC}$, a coupling constant of $^2J_{CC} = 2.5$ Hz indicates coupling to another C atom in a second -NC(O)- moiety. Accordingly, a doublet with the same $^2J_{CC}$ value appears at $\delta = 153.9$ ppm (Figure 4). The integral ratio of the

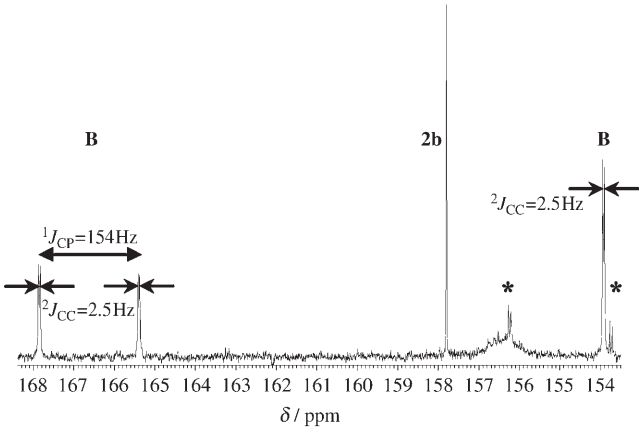


Figure 4. Part of the $^{13}C\{^1H\}$ NMR spectrum at 235 K of a solution containing [^{13}C]*n*-hexyl isocyanate (3.4 mmol) and **5** (0.18 mmol) showing the signals of **B** (* denotes an unidentified species).

peaks at $\delta = 166.7$ and 153.9 ppm is 1:1. These results confirm the presence of a P-^{13}C-N-^{13}C fragment and, thus, the formation of intermediate **B**. Finally, the temperature variation monitored by $^{13}C\{^1H\}$ spectra shows line broadening and disappearance for this intermediate at 275 K, as expected (Figure 5).

In conclusion, we have developed an understanding of the mechanism of the tri-*n*-butylphosphine-catalyzed cyclo-oligomerization of alkyl isocyanates at the molecular level and have structurally characterized one of the key catalytic intermediates for the first time. This information can be used to design new catalysts with built-in selectivity towards various oligomers. Finally, this reaction is a good example for

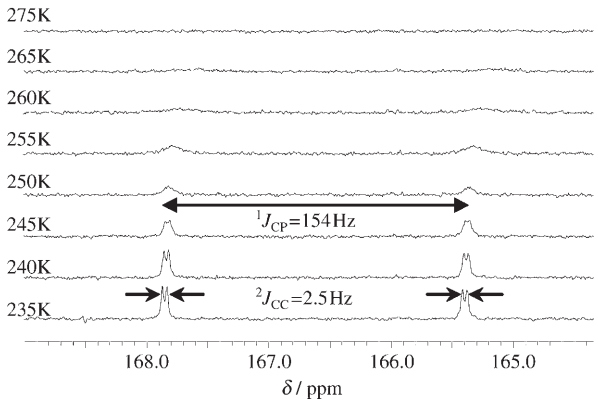


Figure 5. Temperature-dependent $^{13}C\{^1H\}$ NMR spectra for the signal of **B** at $\delta = 166.7$ ppm.

organocatalysis—a rapidly developing field of contemporary homogeneous catalysis.

Experimental Section

n-Butyl isocyanate, *n*-hexyl isocyanate, and tri-*n*-butylphosphine were purified by vacuum distillation. Preparation of [^{13}C]*n*-hexyl isocyanate: *n*-hexylamine (40.4 g, 0.4 mol) and triethylamine (121.4 g, 1.2 mol) were combined with CH_2Cl_2 (43.3 g, solvent) in a steel vessel, cooled to 0 °C, and pressurized with $^{13}CO_2$. The steel vessel containing the amine solution was connected with a lecture bottle containing 10 L of $^{13}CO_2$ (99.0 % isotopic purity, 0.45 mol; Cambridge Isotope) and occasionally shaken. The pressure dropped from 4 to 2.6 bar within 15 h and remained constant thereafter. The vessel containing the carbamate salt solution was 17 g heavier than before, thus indicating an uptake of 0.38 mol of $^{13}CO_2$. After cooling to −24 °C, the content of the steel vessel was transferred to a cooled (−20 °C) solution of $POCl_3$ (73.6 g, 0.48 mol) in CH_2Cl_2 (50 mL). The resulting yellow–orange turbid mixture was extracted with deionized water (3 × 250 mL), the organic phase was dried with sodium sulfate and distilled to yield 23.6 g of product (99.6 % pure, GC analysis; 0.18 mol, 48 % yield based on $^{13}CO_2$ uptake). B.p. 39–40 °C at 5 mbar; ^1H NMR ($CDCl_3$): $\delta = 3.3$ (t/d, $^3J_{HH} = 6.6$ Hz, $^3J_{CH} = 4.5$ Hz, 2H), 1.6 (quin, $^3J_{HH} = 7$ Hz, 2H), 1.25–1.45 (m, 6H), 0.9 (t, $^3J_{HH} = 7$ Hz, 3H); ^{13}C NMR ($CDCl_3$) intense signals at $\delta = 121.9$, 42.9 (d, $^2J_{CNC} = 3.7$ Hz), 31.2, 31.1, 26.2, 22.5, 13.9 ppm.

IR spectra were collected under nitrogen on a ReactIR 1000 instrument using a SiComp probehead.[8] A typical in situ IR experiment was performed by placing the alkyl isocyanate (**1**) onto a

thermostated (±0.5 °C) schlenk flask fitted with the IR probehead, a nitrogen inlet, a magnetic stirrer, and a septum. Tri-*n*-butylphosphine (**5**) was syringed into the schlenk flask after the data collection of the ReactIR 1000 was started.

^{1}H, ^{13}C, and ^{31}P NMR spectra were recorded on a Bruker AC 250 spectrometer. In a typical in situ NMR experiment, **1** was added into an NMR tube under nitrogen and **5** was added by syringe. The tube was immediately capped with a rubber septum and placed into the magnet for measurements at the preset temperature (±0.05 °C) using standard Bruker pulse sequences.

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[1] "Isocyanates, Organic": C. Six, F. Richter, *Ullman's Encyclopedia of Industrial Chemistry*, Wiley-VCH, **2002**.
[2] D. Liebsch, W. Altner, R. Kress (Bayer AG), DE-A 1 670 720, **1966**.
[3] M. Bock, J. Pedain, W. Uerdingen (Bayer AG), EP-A 10589, **1978**.
[4] F. Richter, J. Pedain, H. Mertes, C.-G. Dieris (Bayer AG), EP-A 798299, **1997**.
[5] H. J. Laas, R. Halpaap, J. Pedain, *J. Prakt. Chem.* **1994**, *336*, 196–198.
[6] Compounds of general formula $P(NR_2)_3$ are very selective catalysts for the formation of **2** (DE-A 3030513) but the carcinogenicity of their oxides prohibits a technical-scale application. Special aminopyridines (DE-A 3739549) selectively catalyze the formation of **2** from isophorone diisocyanate, but not for HDI or isocyanates containing exclusively NCO groups bound to a secondary carbon atom like hydrogenated methane diisocyanate or cyclohexyl isocyanate.
[7] H. Ulrich in *Organic Chemistry: A Series of Monographs* (Ed.: A. T. Blomquist), Academic Press, New York, **1967**, pp. 128–133.
[8] ReactIR 1000 Instrument, Mettler Toledo AutoChem, Inc., USA, http://www.mt.com/autochem.
[9] Compounds **2a**, **3a**, and **4a** were prepared and IR spectra (neat) were collected for the reference values.
[10] See the Supporting Information.

