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Synthesis and Low Temperature Spectroscopic Observation of 1,3,5-Trioxane-2,4,6-Trione: The Cyclic Trimer of Carbon Dioxide

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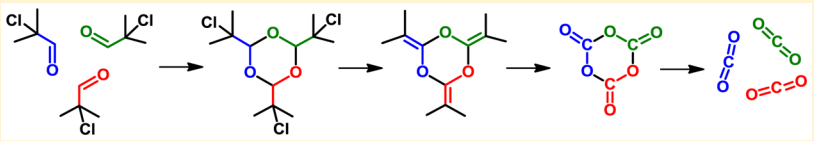
Supporting Information



ABSTRACT: 1,3,5-Trioxane-2,4,6-trione (cyclic trimer of CO_2) is the product of a four-step synthesis: chlorination of isobutyraldehyde; cyclotrimerization of 2-chloro-2-methylpropanal; dehydochlorination of 2,4,6-tris(2-chloropropan)-2-yl-1,3,5-trioxane; ozonolysis at −80 °C of 2,4,6-tri(propan-2-ylidene)-1,3,5-trioxane. This trioxane-trione is detected in solution at temperatures between −80 to −40 °C, and its conversion to CO_2 is monitored by ^{13}C NMR and FTIR. The CO_2 trimer has a half-life of approximately 40 min at −40 °C.

INTRODUCTION

As a product of combustion and respiration whose accumulation in the atmosphere has become a cause for significant concern, carbon dioxide has been the subject of much research directed at its reutilization. Various approaches toward this CO_2 reutilization goal have been described in excellent reviews over the past two decades.[1−4] Important processes involve reduction with hydrogen,[5] coupling with other small molecules,[6] incorporation into polymers[7] and artificial photosynthesis.[8] The main products include fuels, solvents, chemical intermediates and polymers. The efficiency of these commercial processes in terms of reagent usage is relatively low with respect to the fraction of CO_2 incorporated into the product; the highest being for urea (57%), and decreasing for salicylic acid (36%) and methanol (10%).[3] This could be raised to 100% if a CO_2 self-fixation chemistry could be developed. Ideally with a sufficient input of energy, CO_2 would react with itself to yield a liquid or solid product from which this energy could be extracted when needed for useful work. Such chemistry has been the subject of theoretical calculation for structures representing the linear polymer and cyclic oligomers of CO_2.[9−14] With respect to thermodynamic stability, the cyclic trimer has been described as "feasible" although energetically less stable than three CO_2 molecules by 27 kJ/mol per CO_2 unit.[10] Regarding kinetic stability of the cyclic trimer toward fragmentation to CO_2, calculated barriers for this decomposition have ranged from activation energies of 61 to 172 kJ/mol depending on the computational method with calculated half-lives ranging from days to milliseconds at ambient conditions and substantially longer at lower temperatures.[9,12,14]

The cyclic trimer of CO_2 has also been proposed as a low-energy intermediate in the transformation of CO_2 to an extended solid.[14] The formation of an orthocarbonate extended covalent structure of interconnected six-membered rings was predicted by model calculation with the finding of a stabilization energy that increased with molecular size.[10,11] Later experimental work found under extreme pressure/temperature (40 GPa/1800 K), CO_2 will transform to a metastable extended solid which has been characterized as a Phase V form of CO_2 with a sigma bonded quartz-like structure.[15] It has also been proposed that sorption of CO_2 into the isolated nanoscale confined spaces of sulfur- or nitrogen-treated porous carbon at 30 bar pressure can produce a polymeric structure of carbon dioxide[16] as has been reported for other molecules in nanoconfined spaces.[17]

The 1,3,5-trioxane-2,4,6-trione structure of the CO_2 cyclic trimer, **1**, may represent an important intermediate or product in the self-fixation of gaseous CO_2. Theoretical studies on this molecule have indicated a possibility of kinetic stability at room temperature[9] and as well as a possibility for it to be thermodynamically feasible.[10] To date, no experimental evidence has been reported for its existence. The objective of this work is to synthesize compound **1** and to make an assessment of its stability. The approach is that of a model compound synthesis where the trioxane ring is first generated from substituted aldehydes and then the peripheral carbonyl structures are incorporated at low temperature in the final step. As will be shown, compound **1** does not possess the stability for facile isolation and storage.

RESULTS

A retrosynthetic route for the synthesis of compound **1** is illustrated in Scheme 1. The three steps are an oxidative cleavage of a triolefin-trioxane, **2**, a dehydrochlorination of α-chloroaldehyde trimer, **3**, and a trimerization of two candidate

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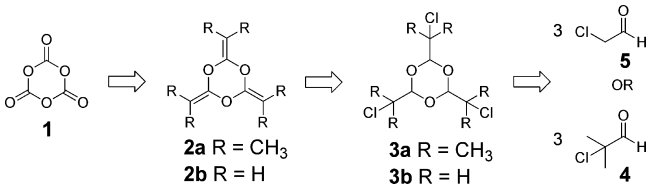
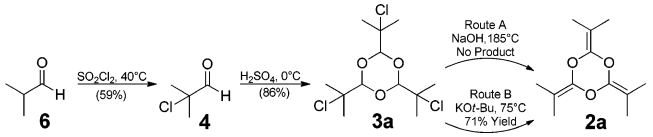
Scheme 1. Retrosynthetic Route toward the CO_2 Trimer



α-chloroaldehydes, **4** and **5**. The chemical properties of triolefin-trioxane compounds are not well-known, nor has the susceptibility of this type of olefin toward oxidative cleavage been reported. This synthesis requires that all three olefin bonds of **2** be cleaved thereby adding great importance to the yield of this reaction. Thus, both the unsubstituted 2,4,6-trismethylene-1,3,5-trioxane, **2b**, and the hexamethyl-substituted analog 2,4,6-tris-isopropylidine-1,3,5-trioxane, **2a**, were both targeted for comparative purposes as well as a strategy of having an alternative if difficulties are encountered en route to **1**. In Scheme 1 the absence or presence of methyl substituents on the exocyclic olefin structure **2** may affect the oxidative cleavage to compound **1** and will determine detectable byproducts, both of which are issues of interest.

The synthesis of the hexamethyl triolefin-trioxane **2a** is depicted in Scheme 2. Isobutyraldehyde, **6**, was chlorinated by a

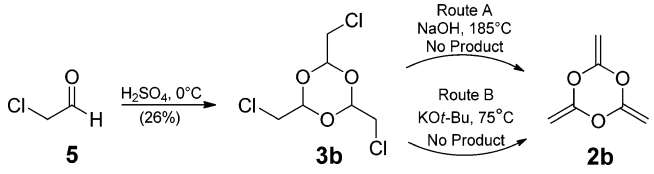
Scheme 2. Synthesis of Substituted Triolefin-Trioxane



procedure using sulfuryl chloride[18] to afford the corresponding α-chloroaldehyde, **4**. This aldehyde was then trimerized to 2,4,6-tris(1-chloro-1-methylethyl)-1,3,5-trioxane, **3a**, in good yield by a procedure using concentrated H_2SO_4[19,20] and isolated as a crystalline solid (see Supporting Information for crystal structure). The third step of dehydrohalogenating **3a** to the hexamethyl triolefin-trioxane **2a** was problematic. In our hands a patented procedure[21] for preparation of compound **2a** (Route A, reaction of **3a** with sodium hydroxide dispersed in dimethylheptanol at 185 °C) produced no yield of product. An alternate approach of using potassium *tert*-butoxide in THF (Route B) afforded **2a** in good yield. Compound **2a** prepared via Route B is a liquid while that reported from Route A was a solid with a very broad melting point (54−62 °C).[21] A thorough analysis of this product was conducted (^{1}H NMR, ^{13}C NMR, IR, UV−vis, HR-MS, elemental analysis and differential scanning calorimetry; see Experimental Section and Supporting Information for data and discussion), and these results are in good agreement with the structure assigned to compound **2a**.

Attempts to synthesize the unsubstituted triolefin-trioxane **2b** met with considerable challenges (Scheme 3). Trimerization of the commercially available aqueous solution of **5** with concentrated H_2SO_4 produced low yields (26%) of **3b** and often inconsistent results. Multiple attempts to dehydrohalogenate trioxane **3b**, using either the previously reported conditions[21] (Route A) or our modified procedure (Route B) failed to yield the desired unsubstituted triolefin-trioxane **2b**. Confident in the structure of the methyl substituted triolefin-trioxane and the reproducibility of our procedure; our focus was placed on the oxidation chemistry of **2a**.

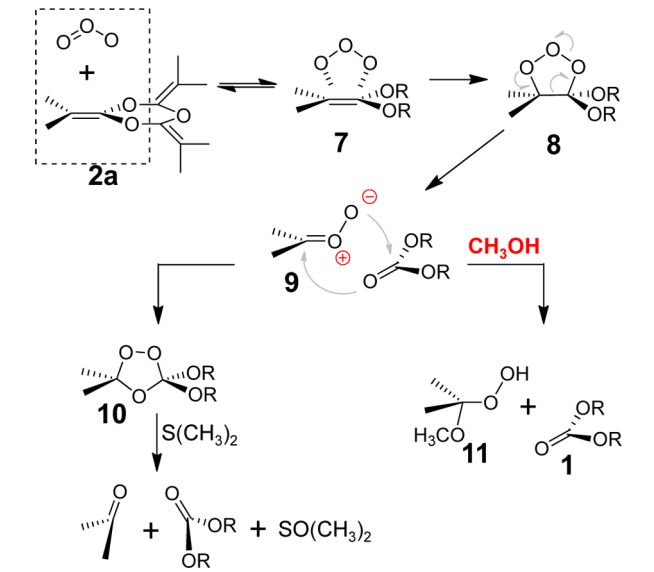
Scheme 3. Attempted Synthesis of Unsubstituted Triolefin-Trioxane



The initial approach to oxidative transformation of the **2a** olefin bonds to carbonyl bonds involved preliminary experiments to determine if the three C−C double bonds could be oxidatively cleaved in a stepwise manner. Cleavage using oxo metals such as OsO_4[22,23] or combinations of $RuCl_3$[24,25] and co-oxidants was unsuccessful as was using singlet oxygen generated from ozone and phosphine.[26] Byproducts interfered with analyses and obscured isolation of anticipated products of unknown stability.

A complete oxidation approach using ozonolysis was then explored.[27−29] The Criegee mechanism[30] for this chemistry as applied to compound **2a** is depicted in Scheme 4. Ozone and

Scheme 4. Criegee Ozonolysis Mechanism Applied to Compound 2a[a]



[a]For clarity, chemistry is represented on one of the three carbon−carbon double bonds.

the olefin bonds of **2a** initially at low temperature may or may not form a π or charge-transfer complex, **7**,[31−33] followed by formation of the primary ozonide, **8**, which breaks down to the carbonyl oxide "Criegee intermediate", **9**, and the complementary carbonyl compound. In an inert solvent these moieties recombine to form the secondary ozonide, **10**, which is sometimes sufficiently stable for isolation but which is usually reacted with a reductant to yield the desired pair of carbonyl compounds as indicated by the left route in Scheme 4. Initially, our selected reaction conditions (−78 °C, saturated solution of **2a** in CH_2Cl_2 with a flowing 5% O_3/O_2 mixture until the blue coloration of excess ozone persists followed by purging the O_3 then by the addition of $(CH_3)_2S$ to quench the reaction and warming to ambient temperature) did not result in the detection of the desired trione-trioxane product **1**. However,

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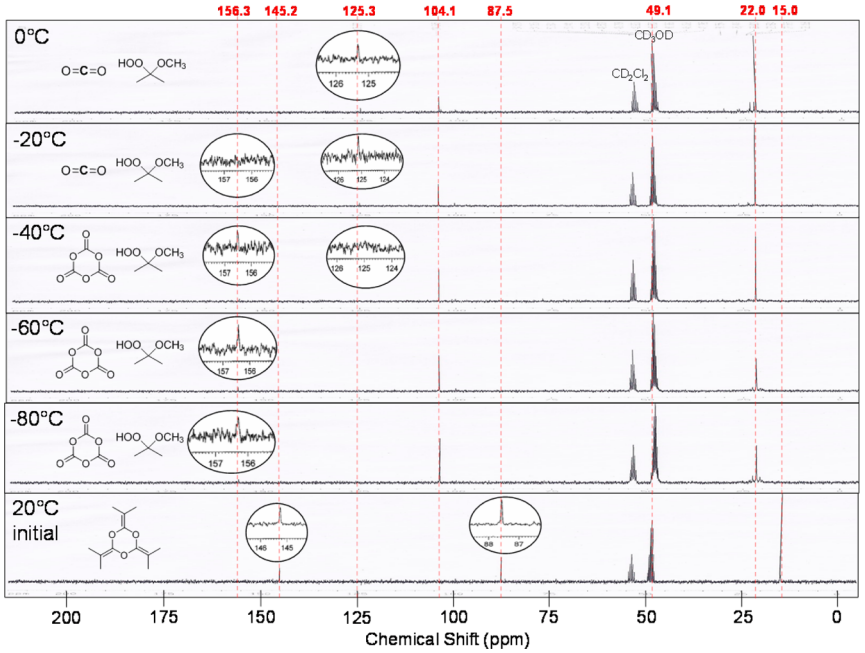

Figure 1. ^{13}C NMR spectra from the triolefin-trione−ozone reaction. The lowest spectrum is the substrate **2a** CD_2Cl_2/CD_3OD solution prior to ozone treatment. The series spectra above were recorded after the −78 °C ozone saturation and purging from this solution at successive 20 °C temperature increments from −80 to 0 °C. The compound structures for which resonances are assigned are depicted at the left of each spectra and the chemical shifts discussed in the text are indicated by the dashed lines and values at the top of this figure. Those resonances of particular importance have a magnified insert.

the resultant oxidation byproduct, $(CH_3)_2SO$, was observed consistent with the action of some ozonide intermediate on Me_2S.[34] As some secondary ozonides are known to be sufficiently stable for ambient isolation,[35] limited attempts were made to isolate an ozonide intermediate by withholding the addition of the reducing agent, but a stable and structurally characterized product was not obtained. The intramolecular constraint of three olefin bonds initially held in close proximity when the primary ozonide and the reactive carbonyl oxide are generated from one of them is conjectured to be a route to a complex product mixture.

The reaction path on the right side of Scheme 4 was then pursued. Methanol is employed as a well-known and quantitative trapping agent for the carbonyl oxide intermediate and converts it into the relatively stable 2-methoxyprop-2-yl hydroperoxide, **11**.[36] The hypothesis for using methanol in this manner is that, when the primary ozonide **8** fragments, the carbonyl oxide intermediate will incorporate the exocyclic methyl groups of **2a** (structure **9**) and not incorporate the trioxane ring structure of **2a**. In favor of this hypothesis is the reported ozonolysis of 1,1-dimethoxyethylene preferentially yielding dimethyl carbonate and the carbonate functional group's resistance to further reaction with carbonyloxides.[37] The presence of methanol is also useful in preventing the self-coupling of the acetone carbonyl oxide **9** to form dimeric and oligoperoxidic compounds.[38] As a proof of concept, the ozonolysis reaction of **2a** was carried out in a similar manner as before in a chilled (1:1) mixture of CH_2Cl_2 and CH_3OH in the absence of any reducing agent. After the reaction warmed to ambient temperature, NMR analysis of the evaporated mixture revealed hydroperoxide **11** (average of 62% over two reactions) as the dominant product. This observation indicates that the oxidative cleavage is, in fact, occurring as planned since the trapped carbonyl oxide is concomitant with the generation of the new carbonate functionality. Due to the lack of any other observable product, it seems possible that the trione-trioxane **1** is formed but subsequently degrades. If this is the case, further support for its existence was needed.

To obtain evidence for the existence of the trione-trioxane **1**, a variable temperature ^{13}C NMR experiment was conducted. A solution of **2a** dissolved in a 1:1 CD_2Cl_2:CD_3OD mixture was prepared in an NMR cell, and an initial spectrum is obtained. This solution is then cooled to −78 °C, and a 5% O_3/O_2 stream was passed into this solution until the blue coloration of excess ozone was observed. The cell was then purged with oxygen and quickly transferred into a precooled NMR probe at −80 °C. Spectra were acquired at progressive temperatures of −80, −60, −40, −20, and 0 °C. These spectra are presented in Figure 1 with expansions of important resonances depicted in inserts. The initial 20 °C spectrum displayed the three resonances of triolefin-trione **2a** at chemical shifts of 15.0 ($-CH_3$), 87.5 ($=\underline{C}(CH_3)_2$) and 145.2 ($=C(O)_2$) ppm. After cooling and completion of the ozone treatment, these resonances disappeared, and the three resonances attributable to the hydroperoxide compound **11** appeared at 22.0 ($-CH_3$), 49.1 ($-OCH_3$, obscured by the CD_3OD) and 104.1 (C-OOH) ppm in excellent agreement with those previously reported for this compound.[39] At this −80 °C temperature an additional new resonance appeared at 156 ppm which we assign to the carbon in the structure of **1**. This chemical shift is consistent with that of other cyclic carbonates.[40] This resonance persisted on warming to −60 and −40 °C, but on further temperature increase, it was rapidly displaced by another resonance at 125 ppm. This new signal is consistent with dissolved CO_2 in chlorinated solvents and was subsequently verified at the end of this experiment by introduction of CO_2 and observed growth of this signal. The observation of these coupled signals indicates that a carbonate type structure, presumably the trione-trioxane

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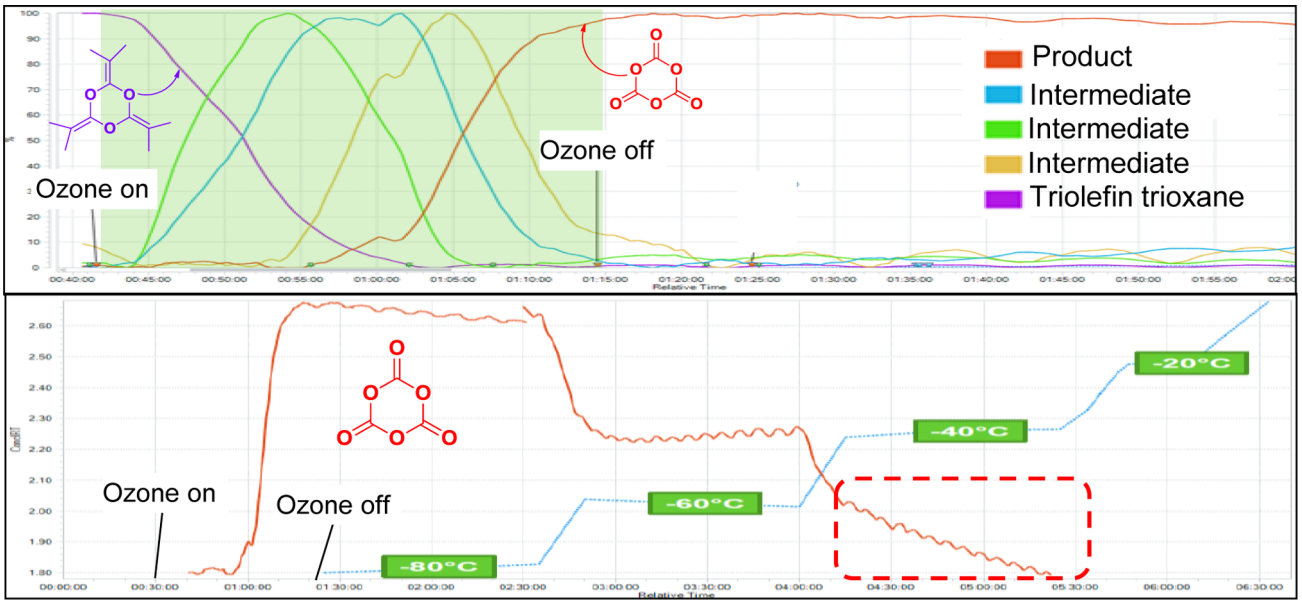

Figure 2. FTIR trend lines for in situ monitoring of (above) ozonolysis conversion of compound **2a** to compound **1** at −80 °C in 1:1 CH_2Cl_2:CH_3OH and of (below) stability of compound **1** during 20 °C stepped interval warming from −80 to 0 °C.

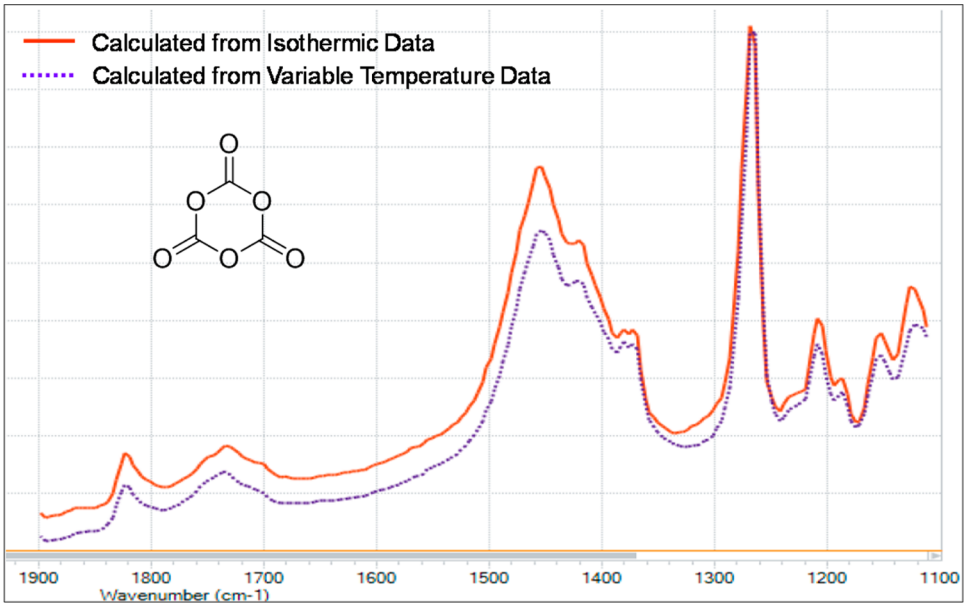

Figure 3. Infrared spectrum of trione-trioxane **1** derived from in situ −80 °C ozonolysis reaction spectra and from thermal stability−variable temperature spectra.

1, was present at low temperatures then decomposes to its monomeric form as CO_2 gas.[41,42] As further support for assignment of the 156 ppm resonance to the carbon nucleus in compound **1**, SCF GIAO magnetic shielding tensor calculations were carried out on this compound, CO_2 and TMS. The calculated chemical shifts relative to TMS are 150.2 and 123.9 ppm respectively which are in reasonably good agreement with the 156 and 125 experimental values.

To complement this NMR evidence for the existence and stability of this trione-trioxane, compound **1**, an in situ FTIR experiment was conducted under essentially the same conditions. Instead of an NMR cell, the reaction was conducted in a 25 mL flask which was fitted with an ozone inlet and the ATR probe of a ReactIR reaction monitoring system. With the capability of generating several spectra per minute, this method is better suited for quantitative kinetic analysis, but it does require sophisticated software for spectral deconvolution and tracking of the time dependent profiles of species in the reaction medium. Control spectra of the CH_2Cl_2 and CH_3OH solvents, the triolefin-trioxane **2a** and O_3 reagents and the hydroperoxide **11** and CO_2 byproducts were input to the software, and the reaction is monitored by repetitive recording of FTIR spectra in real time. The composite spectra are deconvoluted for individual species, and the corresponding trend lines depict the quantities of reactants, intermediates and products as a function of time. The upper half of Figure 2 presents trend lines for the in situ −80 °C ozonolysis of **2a**, depicting this reagent, intermediates and the trione-trioxane product **1**. Three distinct intermediates appear to form and are consumed during the course of this reaction. The product once

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formed has an indefinite stability at −80 °C. In the lower half of Figure 2 this product is monitored as a function of time for 1.5 h intervals at −80, −60, and −40 °C. Once the temperature and baseline have stabilized, the decomposition of **1** in the −40 °C interval is readily apparent and is accompanied by the generation of CO_2. This is in good agreement with the NMR experiment of Figure 1. From the slope of the trend line in this region (indicated by the dashed window in Figure 2), a half-life of 40 min is estimated at this temperature which is in reasonable agreement with a range of half-lives calculated by various theoretical methods.[9]

The infrared spectrum of the trione-trioxane **1** was deconvoluted from the accumulated spectra during the ozonolysis reaction and from the postreaction spectra as the temperature was increased to assess the thermal stability of this compound. As presented in Figure 3, these spectra duplicate each other closely. Assignment of the major bands may be correlated with the anhydride and carbonate functional groups experimentally observed for molecules of closely related structure and with calculated from the MP2 and DFT(B3LYP) levels of theory.

Experimentally, infrared bands characteristic of the cyclic anhydride functional group as part of a six membered ring (a doublet of comparable intensity derived from the symmetric and asymmetric C═O stretching modes in the 1750 to 1850 cm^{-1} range and a single C−O band in the 1160−1260 cm^{-1} range)[43] are consistent with those observed. As a closely related structure, pyran-2,4,6-trione (acetonedicarboxylic anhydride, 3-oxoglutaric anhydride) displays such bands at 1810, 1740, and 1245 cm^{-1},[44] which are in relatively close conformity with the 1821, 1733, and 1272 cm^{-1} bands in Figure 3. The carbonate group displays C═O and C−O bands in a similar range although less sensitive to ring strain and with a different intensity ratio between the symmetric and antisymmetric C═O bands.[43] The broad bands in the 1380−450 cm^{-1} range are difficult to assign as most model compounds have C−H bands in that range. However, in ring systems containing carboxyl groups and an absence of C−H bonds, such bands are observed and correlated with out-of-plane deformations.[43] While the functional group character of compound **1** combines structural elements of both anhydride and carbonate, its infrared spectrum more resembles the anhydride. Vibrational calculations for compound **1** have been reported at the MP2(FC)/6-31G* level with a scaling factor of 0.94.[9] Infrared frequencies calculated for the C═O symmetric and asymmetric stretching modes are 1991 cm^{-1} (corrected to 1872 cm^{-1}; relative intensity 0) and 1918 cm^{-1} (corrected to 1803 cm^{-1}; relative intensity 89) respectively, and those for the C−O symmetric and asymmetric ring stretching modes are 1302 cm^{-1} (corrected to 1224 cm^{-1}; relative intensity 100) and 1043 cm^{-1} (corrected to 980 cm-1; relative intensity 3) respectively. Comparable infrared frequency calculation at the BL3YP/6-31G* level without a scaling factor have been reported as 2015 cm^{-1} (relative intensity 26), 1931 cm^{-1} (relative intensity 764) and 1286 cm^{-1} (relative intensity 742) for the respective C═O symmetric and C═O asymmetric and C−O ring stretching modes.[13] These calculated band frequencies, when corrected by a scaling factor, correlate with those of the experimentally observed bands centered at 1821, 1733, and 1272 cm^{-1} in Figure 3. The 1821 and 1733 cm^{-1} bands display weak unresolved satellite bands. This feature has been observed in a study of 5- and 6-membered lactone compounds comparing experimental and MP2 and DFT calculated spectra and was attributed to a Fermi-resonance interaction between the C═O vibration and overtone or combination bands.[45]

As final evidence in this study for the formation of **1** from **2a** and its subsequent decomposition into CO_2, quantitative yield measurements of the hydroperoxide byproduct **11** from the ozonolysis and of the CO_2 evolved during the postreaction warming were conducted. The yield measurement for compound **11** was conducted on a 200 mg scale following the ozonolysis procedure of the NMR and IR experiments and produced a 67% yield. A small quantity of residual mixed impurities was also observed which may be due an incomplete trapping of the carbonyl oxide **9** in Scheme 4 or to some decomposition or side reaction of this hydroperoxide byproduct **11**. Measurement of the yield of CO_2 evolved from **1** after warming to room temperature was conducted by two procedures utilizing infrared spectroscopy and the reaction conditions employed above in the measurement of compound **11**. The first procedure utilized an infrared solution cell with CaF_2 windows to quantify the CO_2 band intensity at 2339 cm^{-1}. Immediately after the ozonolysis of **1** was completed and warmed to near room temperature, a measured aliquot of the reaction mixture was transferred to fill the IR solution cell and the spectrum recorded. An analytical solution of CO_2 in the 1:1 CH_2Cl_2:CH_3OH solvent was then prepared with a CO_2 concentration having a comparable 2339 cm^{-1} band intensity in its IR spectrum. The CO_2 yield derived from **1** was then determined from a proportionality between the integrated intensities of this band in the ozonolysis reaction and analytical spectra. This method resulted in a 37% yield based on quantity of **2a** and on assumptions of quantitative conversions of the ozonolysis and of the CO_2 evolution reactions. There was also the possibility of CO_2 escape from the solution IR cell during transfer and measurement of the condensed phase reaction mixture. A second procedure was conducted using a gas IR cell with an attached cylindrical well in which the ozonolysis reaction and subsequent warming of the product were conducted. After completion of the ozonolysis, the reaction solution was cooled from −78 °C to −195 °C, the cell was evacuated to remove the O_3/O_2 from the headspace and then slowly warmed to 20 °C while monitoring gas phase species in the isolated cell. This procedure was repeated with a quantitatively prepared CO_2/CH_2Cl_2:CH_3OH solution (volume and CO_2 concentration calculated for a 100% yield from **2a**) placed in the cylindrical well. The yield of CO_2 measured in the gas phase for the ozonolysis reaction was 61% relative to that measured from the CO_2/CH_2Cl_2:CH_3OH analytical solution. This 61% yield of CO_2 appears to complement the above 67% yield of the hydroperoxide byproduct **11**. On the basis of these measurements, a 64% yield is supported for the formation of the trione-trioxane **1** in Scheme 4.

■ DISCUSSION

While the self-condensation of CO_2 into larger molecules is attractive for the perspective of a high efficiency in CO_2 utilization and perhaps energy storage, the kinetic stability of such compounds is a key issue. For the case of the 2,4,6-trione-1,3,6-trioxane **1**, the result of this work indicates that its preparation from CO_2 would be very tedious and would require maintenance of low temperatures, high pressures and a yet to be defined catalyst. This molecule has received significant theoretical analyses, and estimates of its kinetic stability or half-life are useful information even if variable. Older calculation methods appear to significantly overestimate these paremeters,[9]

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while those based on density functional theory are low (41 ms/298 °K) and to be regarded as lower limits.[12] Half-life calculation based on CCSD coupled cluster theory (~100 s/298 °K)[14] is in reasonable good agreement with the 40 min/233 °K experimental value.

A comparison of this kinetic stability of **1** with known compounds of related structure is worthy of comment. Molecules composed of multiple CO_2 units are known for the oligo-carbonate series $(CH_3)_3CO-[C(O)O]_n-C(CH_3)_3$, n = 1, 2, 3. All are stable at ambient conditions and have progressively decreasing decomposition temperatures: n = 1 (>200 °C);[46] n = 2 (100 °C);[47] n = 3 (65 °C).[48] For polymer analogs of undefined end groups claims are made of subambient stability both theoretically[9,13] and experimentally.[16] While a kinetic instability increases with an increasing $-[C(O)O]_n-$ chain length, a chain length of three units can be considered stable at ambient conditions. However, at such a short chain length end group effects play a role, and it has been reported that changing the *tert*-butyl to the isopropyl end group diminished stability and precluded purification.[48] Ring strain may also play a role in the stability of **1**. Calculation has optimized the conformation of **1** as planar with small departures (4°) of the O−C−O and C−O−C bond angles from 120°[14] which would indicate the ring strain is relatively modest as expected. By comparison, the CO_2 cyclic dimer, 1,3-dioxetanedione has a half-life that is shorter than that for **1** by 7 orders of magnitude.[14] Another structural feature of interest with respect to stability is the orientation of the bonding between CO_2 units. If one CO_2 unit is reversed as is the case in 1,2-dioxetanedione where the connecting linkages of the CO_2 units are C−C and O−O bonds, the half-life is reported to increase by many orders in magnitude compared with the 1,3-dioxetanedione structure.[14] In a linear structure the CO_2 unit orientation reversal has been realized in di-*tert*-butylperoxyoxalate, $(CH_3)_3C-O-OC(O)-C(O)O-O-C(CH_3)_3$, where C−C and O−O bonds are important determinants of compound stability. This compound, while not as stable as the linear tricarbonate analog above, has a half-life of over 400 s at 60 °C[49] which is significantly greater than that of **1**. The stability of reverse CO_2 orientation (head-to-head and tail-to-tail placements) in poly(carbon dioxide) has been investigated for thermodynamic stability relative to the head-to-tail placement with the latter more stable by 160 kJ/mol.[50] Finally, the kinetic stability gains by successively replacing a C=O moiety by a CH_2 group in the 1,3,5-trione-trioxane structure of **1** have been calculated with the result of a half-life increase of 10^4 with each substitution.[12] The trends described in this paragraph, from the perspective of increasing kinetic stability of molecular adducts derived from CO_2 additions, appear to indicate that C−C bond formation between a CO_2 unit and a small nonpolar coreactant would be advantageous.

CONCLUSION

The work reported here provides substantial evidence for the existence and kinetic stability of 2,4,6-trione-1,3,5-trioxane **1** prepared in a model compound synthesis for the cyclic trimer of carbon dioxide. This compound is synthesized in four steps: chlorination of isobutyraldehyde **6**; trimerization of chloro-isobutyraldehyde **4**; dehydrochlorination of chloro-isobutyl-trioxane **3a**; and ozonolysis of the hexamethyl triolefin-trioxane **2a** to the trione-trioxane **1**. During the ozonolysis reaction, it is critical that methanol be present to trap the carbonyl oxide intermediate **9** and to prevent side reactions. Analysis of **1** during its formation and decomposition to CO_2 by both ^{13}C NMR and in situ mid-FTIR spectroscopy is consistent with assigned spectral features. The FTIR spectral features are interpreted to indicate that **1** is more related to a cyclic anhydride than to a cyclic carbonate. Its yield from the ozonolysis of **2a** is 64% as derived from yield measurements of the hydroperoxide byproduct **11** and of the CO_2 decomposition product. Compound **1** has a half-life of 40 min at −40 °C in 1:1 CH_3OH:CH_2Cl_2 solution, is stable at ambient pressures and decomposes quantitatively to carbon dioxide above −40 °C.

EXPERIMENTAL SECTION

General Information. All reactions were conducted in oven-dried glassware under an inert atmosphere of dry argon unless otherwise specified. Solvents were refluxed and distilled over Na/benzophenone ketyl or CaH_2 prior to use. All commercial reagents were used as received without further purification. Ozonolysis was performed using an LG-7 CD Laboratory Ozone Generator by Ozone Engineering. Analytical TLC was done using precoated silica gel 60 F254 plates and visualized with either UV light (254 nm), $KMnO_4$ or Cerium Molybdate staining solution. NMR spectra were recorded at 300 MHz for ^1H NMR and at 75.4 MHz for ^{13}C NMR. All chemical shifts for ^1H and ^{13}C NMR spectroscopy were referenced to residual signals from $CDCl_3$ (^1H) 7.26 ppm and (^{13}C) 77.2 ppm or from CD_2Cl_2 (^{13}C) 53.8 ppm. FTIR spectra were obtained in transmission with sample supported on a NaCl plate under a nitrogen purge of 40 cm^3min^{-1} and in ATR reflection with sample supported on a diamond window. The ozonolysis reaction was monitored by real time in situ FTIR spectra were obtained with a Mettler-Toledo ReactIR 15 using a silver halide fiber optic probe assembly containing a silicon or diamond ATR sensor at the tip of the probe. Mass spectral analyses of parent ion were conducted with an ESI-TOF instrument. Elemental analysis was performed by a commercial contractor. Compounds **3a**, **3b**, **4** and **11** were prepared using known procedures. Compound **2a** was prepared using a modified procedure.

Synthetic Procedures. *2,4,6-Tris(chloromethyl)-1,3,5-trioxane (**3b**).*[51] In an atmosphere of air, chloroacetaldehyde (≥45% in H_2O) (1.95g, 25.0 mmol) was added to a round-bottom flask equipped with a stir bar and cooled to 0 °C via ice bath. Conc. H_2SO_4 was added dropwise with vigorous stirring until precipitation occurs. The suspension was then poured over ice (ca. 50 mL). The suspension was then vacuum filtered and washed liberally with water. The material was then resuspended in a 2:1 mixture of ethanol and ice cold water followed by vacuum filtration to remove any colored material. The material was then dried on high vacuum to give a white powder (0.23 g, 26%). mp 85−86 °C (Lit.[51] 86 °C); ^1H NMR ($CDCl_3$, 300 MHz) δ = 3.61 (d, J = 4.71 Hz, 6 H), 5.16 (t, J = 4.71 Hz, 3 H) ppm; ^{13}C NMR ($CDCl_3$, 75 MHz) δ = 43.2, 99.8 ppm; IR ν_{max} (solid) 1127, 1024, 760 cm^{-1}. X-ray crystal structure (Tables S1−S6, Supporting Information).

*2-Chloro-2-methylpropanal (**4**).*[18] Isobutyraldehyde (23.2 g, 0.32 mmol) was added to a two-neck round-bottom flask equipped with a magnetic stir bar, pressure equalizing funnel and reflux condenser. Sulfuryl chloride (33.8 g, 0.32 mmol) was then transferred to the addition funnel and added dropwise at a rate to maintain an external oil bath temperature below 40 °C. The evolved gases were vented through a trap containing water (ca. 50 mL). Once the sulfuryl chloride was added, the reaction was heated to 45 °C with stirring for 1.5 h then stirred at RT for an additional 2.5 h. The addition funnel and reflux condenser were replaced with a stopper and a distillation head fitted with a receiving flask. The crude material was distilled under a vacuum (95 °C, 115 mmHg). A second distillation was necessary to achieve the pure material as a colorless liquid (12.48 g, 37%). ^1H NMR ($CDCl_3$, 300 MHz) δ = 1.56−1.87 (m, 6 H), 9.42 (s, 1 H) ppm; ^{13}C NMR ($CDCl_3$, 75 MHz) δ = 25.8, 69.3, 194.9 ppm.

*2,4,6-Tris(2-chloropropan-2-yl)-1,3,5-trioxane (**3a**).*[18] In an atmosphere of air, aldehyde **4** (20.0 g, 0.18 mol) was added to a round-bottom flask equipped with a stir bar. Conc. H_2SO_4 was added

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dropwise with vigorous stirring until precipitation occurs. The suspension was then poured into ice cold water (ca. 50 mL). Large chunks of material were finely pulverized with a large glass stir rod. The suspension was then vacuum filtered and washed liberally with water. The material was then resuspended in a 2:1 mixture of ethanol and ice cold water followed by vacuum filtration to remove any colored material. The material was then dried on high vacuum to give a white powder (12.2 g, 61%). mp 106−108 °C (Lit.[18] 106−107 °C); ^{1}H NMR ($CDCl_3$, 300 MHz) δ = 1.54−1.63 (m, 18 H), 4.86−4.90 (m, 3 H) ppm; ^{13}C NMR ($CDCl_3$, 75 MHz) δ = 26.7, 67.2, 103.0 ppm; IR ν_{max} (solid) 1154, 1122, 1107 cm^{-1}. X-ray crystal structures (Tables S7−S12, Supporting Information).

*2,4,6-Tri(propan-2-ylidene)-1,3,5-trioxane (**2a**).* A 100 mL Schlenk flask equipped with a magnetic stir bar was charged with KO*t*-Bu (10.48 g, 93.8 mmol) in a glovebox under an atmosphere of dry argon. The flask was then removed from the glovebox and connected to a Schlenk line under argon. Dry THF (35 mL) was then added via syringe, this mixture was then cooled to 0 °C via ice bath and a solution of trioxane **3a** (4.97 g, 15.6 mmol) dissolved in dry THF (10 mL) was added slowly to the cooled reaction mixture. After stirring 15 min at 0 °C, the ice bath was removed and the mixture warmed to room temperature. The flask was then fitted with a reflux condenser and heated to 75 °C for 18 h. The mixture was then cooled to room temperature, and the THF removed under a vacuum. Et_2O (20 mL) was then added, and the resultant suspension was vacuum filtered over a bed of Celite, washing with Et_2O (20 mL). The solvent was then removed under a vacuum, and the crude product was purified by vacuum distillation (10 mmHg at 185 °C) to yield the title compound as a colorless liquid (2.32 g, 71%). ^{1}H NMR ($CDCl_3$, 300 MHz) δ = 1.63 (s, 18 H,) ppm; ^{13}C NMR ($CDCl_3$, 75 MHz) δ = 15.0, 86.9, 144.7 ppm; IR ν_{max} (liquid) 2991, 2919, 2863, 1726, 1284, 1212 cm^{-1}; UV (CH_3CN) λ_{max} = 210 nm (ε = 1.57 × 10^4 L/mol·cm); HRMS (ESI) *m*/*z* calcd for $C_{12}H_{18}O_3$ $[M + H]^+$ 211.1334, found 211.1342. Anal. Calcd for $C_{12}H_{18}O_3$: C, 68.54; H, 8.68; O, 22.83. Found: C, 68.48; H; 8.76. Note: in an earlier published procedure[21] for compounds **2a** and **2b** difficulties were encountered in both obtaining the products and reproducing characterization data (see Supporting Information for detailed discussion and data).

*2-Hydroperoxy-2-methoxypropane (**11**).*[39] Compound **11** was synthesized by ozonolysis of 2,3-dimethylbutene according to literature procedure.[39] ^{1}H NMR ($CDCl_3$, 300 MHz) δ = ppm 1.35 (s, 6 H), 3.27 (s, 3 H), 8.83 (s, 1 H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ = ppm 22.0, 49.1, 105.2.

Variable Temperature ^{13}C NMR of 2a-Ozonolysis Reaction. A solution of triolefin-trioxane **2a** (30.0 mg, 0.143 mmol) in 0.5 mL 1:1 CD_2Cl_2:andCD_3OD solvent mixture was prepared in a 5 mm NMR cell and cooled to −78 °C with a dry ice−acetone bath in a tall Dewar flask with a viewing window feature. A 5% O_3/O_2 mixture from the ozone generator (10 V coronal discharge) was delivered to the cold solution through a long syringe needle such that the bubbling rate was rapid but not excessive. The ozone was delivered until the solution just developed a pale blue color. The NMR cell was then purged of any excess O_3 with pure O_2 until the solution was again colorless. The cell was then rapidly transferred to the NMR precooled to −80 °C. Two acquisitions were taken at 20 deg. temperature intervals starting at −80 °C and warming to −20 °C with a scan count of 64 and a delay time of 30 s.

Variable Temperature IR of In Situ 2a-Ozonolysis Reaction. Control experiments for individual spectra of solvents, reagents, and byproducts were first conducted using a Mettler-Toledo ReactIR 15 system with the ATR silicon probe to record spectra of CH_2Cl_2; CH_3OH, 1:1 CH_2Cl_2:CH_3OH mixture, **2a**/1:1 CH_2Cl_2:CH_3OH; O_3/1:1 CH_2Cl_2:CH_3OH, **11**/1:1 CH_2Cl_2:CH_3OH. The ozonolysis reaction was conducted in a 25 mL round-bottom flask with necks to accommodate the ReactIR fiber optic probe and the ozone dispersion tube. A solution of the triolefin-trioxane **2a** (599.7 mg, 2.80 mmol) dissolved in 10 mL (1:1 CH_2Cl_2:CH_3OH) was introduced to the reaction flask and cooled under Ar atmosphere to −80 °C by an acetone bath regulated by the feedback control of a refrigerated cooling coil. The ozone generator was then set to deliver 5% O_3/O_2 at a modest bubbling rate. The experiment was initiated with IR spectral reaction monitoring of the ozonolysis reaction. Within the first hour the triolefin-trioxane reagent **2a** was consumed, and the bath temperature was successively raised in 20 °C intervals for 1.5 h periods to generate the data displayed in Figure 2.

Byproduct 11 Yield from 2a-Ozonolysis Reaction. A solution of **2a** (210 mg, 1.01 mmol) in 20 mL 1:1 CH_2Cl_2:CH_3OH solvent mixture was cooled to −78 °C and treated with 5% O_3/O_2 via dispersion tube until a persistent blue coloration was observed (15 min). After warming to 20 °C, solvents were removed by rotary evaporation to yield **11** (215 mg, 2.03 mmol, 67%).

Byproduct CO_2 Yield from 2a-Ozonolysis Reaction. Two IR transmission spectroscopy based techniques were used: a solution measurement and a gas phase measurement. The first procedure utilized an infrared solution cell with CaF_2 windows to quantify the CO_2 band intensity at 2339 cm^{-1}. Immediately after the ozonolysis of **2a** as described above was completed and warmed to near room temperature, a measured aliquot of the reaction mixture was transferred by syringe to fill the IR solution cell, and the spectrum was recorded. An analytical solution of CO_2 in the 1:1 CH_2Cl_2:CH_3OH solvent was then prepared via transfer of CO_2 from a calibrated bulb to provide a solution spectrum with a comparable 2339 cm^{-1} band intensity. This method resulted in a 37% CO_2 yield based on quantity of **2a** and on assumptions of quantitative conversions of the ozonolysis and of the CO_2 evolution reactions. There was also the possibility of CO_2 escape from the solution IR cell during transfer and measurement of the condensed phase reaction mixture. A second procedure was conducted using a gas IR cell with an attached cylindrical well in which the ozonolysis reaction and subsequent warming of the product were conducted. After completion of the ozonolysis, the reaction solution was cooled from −78 °C to −195 °C, the cell was evacuated to remove the O_3/O_2 from the headspace and slowly warmed to 20 °C while monitoring gas phase species. This procedure was repeated with an analytically prepared CO_2/1:1 CH_2Cl_2:CH_3OH solution (volume and CO_2 concentration calculated for a 100% yield from **2a**) placed in the cylindrical well, frozen, evacuated and subsequently warmed to 20 °C in the isolated cell. The yield of CO_2 measured in the gas phase for the ozonolysis reaction was 61% relative to that measured from the CO_2/CH_2Cl_2:CH_3OH analytical solution.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.6b00647.

Crystal data. (CIF)
Crystal data. (CIF)
Discussion of synthesis of compounds **2a** and **2b**; NMR, IR and UV spectra of compound **2a**; DSC thermogram for compound **2a**; and crystal structure data for compounds **3a** and **3b**. (PDF)

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Notes

The authors declare no competing financial interest.

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