

Selective Monooxidation of Light Alkanes Using Chloride and Iodate

George C. Fortman,[†] Nicholas C. Boaz,[‡] Dominik Munz,[†] Michael M. Konnick,[§] Roy A. Periana,[§] John T. Groves,^{*,‡} and T. Brent Gunnoe^{*,†}

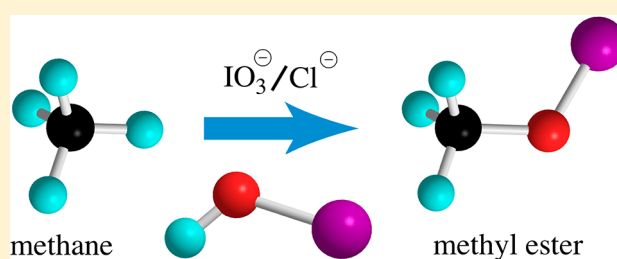
[†]Department of Chemistry, University of Virginia, Charlottesville, Virginia 22904, United States

[‡]Department of Chemistry and Princeton Institute for the Science and Technology of Materials, Princeton University, Princeton, New Jersey 08544, United States

[§]Scripps Research Institute, Jupiter, Florida 33458, United States

Supporting Information

ABSTRACT: We describe an efficient system for the direct partial oxidation of methane, ethane, and propane using iodate salts with catalytic amounts of chloride in protic solvents. In HTFA (TFA = trifluoroacetate), >20% methane conversion with >85% selectivity for MeTFA have been achieved. The addition of substoichiometric amounts of chloride is essential, and for methane the conversion increases from <1% in the absence of chloride to >20%. The reaction also proceeds in aqueous HTFA as well as acetic acid to afford methyl acetate. ¹³C labeling experiments showed that less than 2% of methane is overoxidized to ¹³CO₂ at 15% conversion of ¹³CH₄. The system is selective for higher alkanes: 30% ethane conversion with 98% selectivity for EtTFA and 19% propane conversion that is selective for mixtures of the mono- and difunctionalized TFA esters. Studies of methane conversion using a series of iodine-based reagents [I₂, ICl, ICl₃, I(TFA)₃, I₂O₄, I₂O₅, (IO₂)₂S₂O₇, (IO)₂SO₄] indicated that the chloride enhancement is not limited to iodate.



INTRODUCTION

Natural gas is a chemical feedstock and a primary fuel that accounts for nearly 25% of the world's energy.¹ A significant amount of natural gas is "stranded". However, the expense of infrastructure associated with pipelines or liquefaction often make transportation uneconomical.² The Global Gas Flaring Reduction Partnership estimates that 140 billion cubic meters of natural gas are flared or vented annually.³ New gas-to-liquid (GTL) technologies that efficiently convert alkanes from natural gas into easily transportable liquids would allow utilization of this vast hydrocarbon resource.

New chemistry is needed for the direct conversion of gaseous alkanes to liquid alcohols.⁴ The conversion of light alkanes and oxygen to alcohols is thermodynamically favorable (by ~30 kcal/mol for methane + 1/2 O₂ to give methanol), but the large activation barriers associated with breaking the strong nonpolar C–H bonds of alkanes (which have bond energies of ~100–105 kcal/mol)⁵ and the relatively lower barriers for reactions of the alcohol products make direct conversion difficult.⁶ As a result, even modern methods for alkane functionalization involve indirect and energy-intensive processes. For example, the conversion of methane to methanol by current technologies requires methane reforming to generate a mixture of carbon monoxide and dihydrogen (syngas) followed by conversion of syngas to methanol. The ethane, propane, and butane portions of natural gas can be converted to olefins by high-temperature cracking (~850 °C). Reactions that could enable the direct conversion of light alkanes from natural gas to partially oxidized

products under more moderate conditions have been highly sought.^{6–11} In particular, the preparation of monofunctionalized species (RX) at temperatures of ≤250 °C and pressures of ≤3500 kPa would allow less energy-intensive and capital-intensive GTL conversions. Radical-based chemistry provides a platform to cleave strong alkane C–H bonds; however, the oxidized products are typically more reactive than the starting alkane.⁶ Accordingly, overoxidation has been an issue for catalytic oxychlorination reactions,^{12–16} which involve passing mixtures of CH₄, HCl, and O₂ over a catalyst bed at temperatures of >350 °C.^{17,18} The direct use of halogens to produce MeX has also been developed.^{19–22}

Another option for direct alkane partial oxidation is based on the use of transition metals. Biomimetic approaches for C–H functionalization using high-valent oxo complexes have been reported.^{23–30} Another method is the use of transition metals that directly coordinate and activate C–H bonds.^{7,8,31–36} This strategy has been used to functionalize alkanes by metal-mediated alkane dehydrogenation.^{37–42} Also, electrophilic late transition metal complexes (e.g., Pt, Pd, Hg, and Au) have been shown to catalyze methane functionalization in superacidic media.^{43–47} Product inhibition and product separation have turned out to be significant challenges for these processes. Alkane functionalization using main-group metals that do not require superacids has been reported recently.⁴⁸ Metal-

Received: March 15, 2014

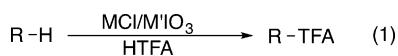
Published: May 28, 2014

mediated transformations that likely involve radicals have also been reported.^{49–51} In an alternative approach, Ag complexes catalyze conversions of alkanes to esters using ethyl diazoacetate.^{52,53}

Hypervalent iodine species^{54–56} are also capable of functionalizing nonpolar C–H bonds through electrophilic, nonradical pathways.^{21,22,57–60} I_2 ^{61–64} and KIO_3 ⁶⁴ convert methane to $MeOSO_3H$ in the superacidic medium $H_2SO_4 + SO_3$ (oleum).⁶³ Other halogen-based systems [e.g., $I(TFA)_3$, where TFA = trifluoroacetate]⁴⁴ have been demonstrated to functionalize hydrocarbons with low selectivity for esters.^{17,45,46,63} An efficient process for light-alkane C–H oxygenation has remained an elusive goal. We describe here a selective reaction of methane and higher alkanes with hypervalent iodine species mediated by catalytic quantities of chloride in weak acids such as HTFA, aqueous HTFA, and acetic acid.

RESULTS AND DISCUSSION

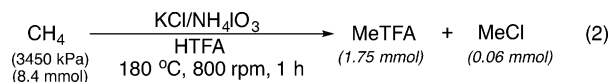
We have identified a hypervalent-iodine-based system that effectively and selectively oxidizes methane, ethane, and propane in non-superacidic media to the corresponding alcohol esters (eq 1). The reactions occur with selectivity for the monofunctionalized product. Methane is converted over a broad range of pressures (240–6900 kPa) at temperatures of ≤ 235 °C. Significantly, the system requires substoichiometric amounts of chloride to generate the active species that reacts with the alkane. In the absence of chloride, the reaction is inefficient and/or unselective. The iodate/chloride system is much more efficient than the hypervalent iodine systems without chloride such as I_2 , iodate, or $I(TFA)_3$. This suggests that the iodate/chloride process functions via a different mechanism than these systems (see below).



Yield based on RH

R = Me 24%
Et 30%
Pr 19%

Pressurizing a mixture of KCl (0.676 mmol) and NH_4IO_3 (7.70 mmol) in HTFA to 3450 kPa with methane (8.4 mmol) and heating at 180 °C for 1 h results in the formation of 1.81 mmol of MeX ($X = TFA, Cl$) in about 20% yield (eq 2). Yields are based on total methane present as determined by weighing the reactor before and after methane addition. The presence of chloride is essential to the reaction (see below), and the use of substoichiometric quantities (based on iodate or methane converted) suggests that chloride might play a catalytic role.



MeTFA was found to be relatively stable under the reaction conditions. In reactions where 0.90 mmol of ^{13}C -MeTFA, 0.676 mmol of KCl, and 7.70 mmol of NH_4IO_3 were added to 8.0 mL of HTFA with methane at 3450 kPa and the system was heated for 1 h at 180 °C, only 0.14 mmol of ^{13}C -MeTFA (15% of the starting material) was consumed (Figure 1). Gas chromatography–mass spectrometry (GC–MS) data showed that the ^{13}C -MeTFA was transformed to $^{13}CO_2$. No evidence of $^{13}CH_2X_2$ or $^{13}CHX_3$ intermediates was observed by 1H NMR analysis. In contrast, 1.81 mmol of MeTFA was produced from CH_4 during this same time period. This result highlights the

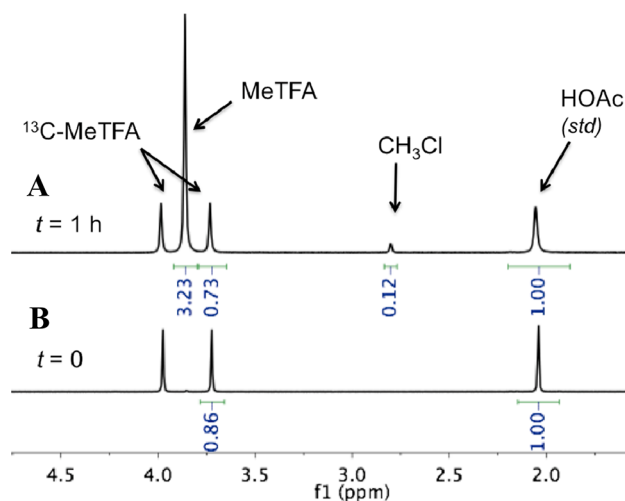


Figure 1. 1H NMR spectra resulting from the partial oxidation of methane when ^{13}C -MeTFA was added to the initial reaction mixture (bottom spectrum B). At least 85% of ^{13}C -MeTFA was retained over 1 h (top spectrum A). Conditions: 0.90 mmol of ^{13}C -MeTFA; 0.676 mmol of KCl; 7.7 mmol of NH_4IO_3 ; 8.0 mL of HTFA; $p_{CH_4/Ne} = 3450$ kPa (8.4 mmol of CH_4); 800 rpm; 180 °C; 1 h.

“protecting” ability of the electron-withdrawing TFA moiety against overoxidation. A detailed kinetic comparison of the reactivities of CH_4 and MeTFA was not possible since the concentration of CH_4 under these conditions was not known.

Carbon dioxide is formed during the course of the reaction, as observed by GC with thermal conductivity detection (GC-TCD). To determine the source of carbon dioxide (methane or HTFA), the functionalization of $^{13}CH_4$ was carried out. Reactions charged with 240 kPa (0.652 mmol) $^{13}CH_4$ converted $\sim 15\%$ of the $^{13}CH_4$ with 91% selectivity for $^{13}CH_3X$ ($X = TFA, Cl$) (eq 3). Products were confirmed through analysis of the resulting liquid and headspace by 1H and ^{13}C NMR spectroscopy (see Figure 2) and GC–MS (see

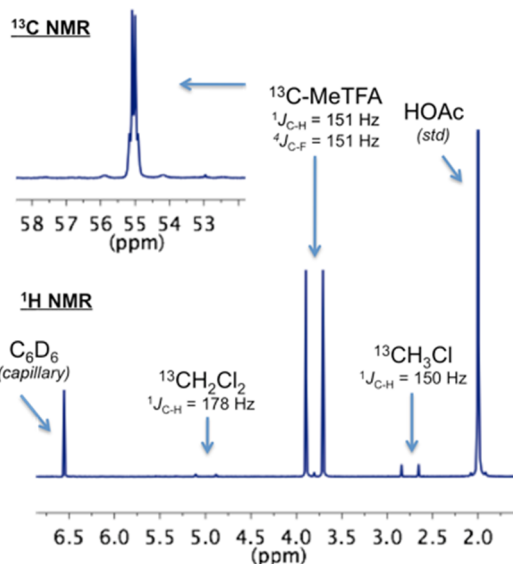
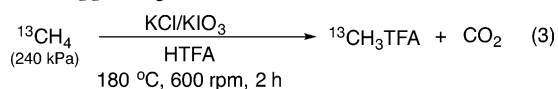


Figure 2. 1H and ^{13}C NMR spectra of a reaction mixture starting with $^{13}CH_4$. Conditions: 0.17 mM KCl; 1.13 mM KIO_3 ; 2.0 mL of HTFA; $p_{CH_4} = 240$ kPa; total pressure increased to 5520 kPa with Ar; 180 °C; 2 h; 600 rpm.

the Supporting Information). GC–MS analysis of the products from the ^{13}C -labeled methane reaction demonstrated that <2% of the methane was overoxidized to CO_2 (presumably, the remaining CO_2 originated from decarboxylation of HTFA, as this was the only other carbon source in the reaction). Mass balance of the resultant mixture of methane, MeTFA, CH_3Cl , CH_2Cl_2 , and CO_2 accounted for ~99% of the initial methane (see the Supporting Information).



The influence of the methane pressure on the conversion efficiency was probed. Although the iodate/chloride system is effective at lower pressures (<3450 kPa), the yields of MeTFA after 2 h are higher at elevated methane pressures (≥ 3450 kPa). Analysis of reactions between 240 and 5520 kPa after 2 h of reaction at 180 °C revealed that increasing the methane pressure provides increased production of the methyl ester (Figure 3). Although the conditions of the reaction make a

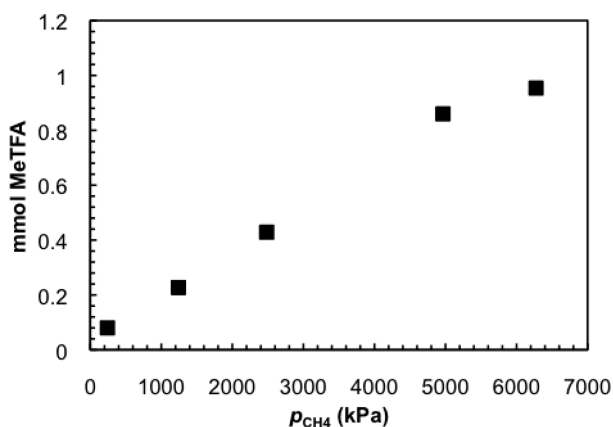


Figure 3. Production of MeTFA as a function of initial methane pressure. Conditions: 0.338 mmol of KCl; 2.26 mmol of KIO_3 ; 2.0 mL of HTFA; 180 °C; 2 h; 600 rpm.

rigorous kinetic analysis difficult, the data in Figure 3 are consistent with a reaction that is first order in methane if it is assumed that Henry's law is followed. At 6900 kPa after 2 h of reaction, the production of MeTFA was observed to reach a maximum value of ~0.5 M MeTFA with a MeTFA: CH_3Cl ratio of 130:1. For each reaction, sampling of the reactor headspace and analysis by GC-TCD revealed negligible or no CH_3Cl .

The partial oxidation of methane can also be achieved over a wide temperature range, between 100 and 235 °C (Figure 4). Reactions at 235 °C with a methane pressure of 3450 kPa, 0.676 mmol of KCl, and 7.70 mmol of NH_4IO_3 are rapid, with ~24% conversion of methane to MeTFA in 20 min.

Both chloride and iodate were observed to play a crucial role in the methane conversion (see the Supporting Information). MeTFA is not formed in substantial amounts in the absence of a chloride source (<1% conversion for "background" reactions that use iodate in the absence of chloride), and the use of another halogen (F^- , Br^- or I^-) gives only background reactions.

Exclusion of iodate results in no reaction. The use of KBrO_3 gives only small amounts of MeTFA, while a complex mixture of intractable products is formed in reactions using KClO_3 as an oxidant. The methane conversion varied with the choice of chloride and iodate sources (Figure 5; also see the Supporting

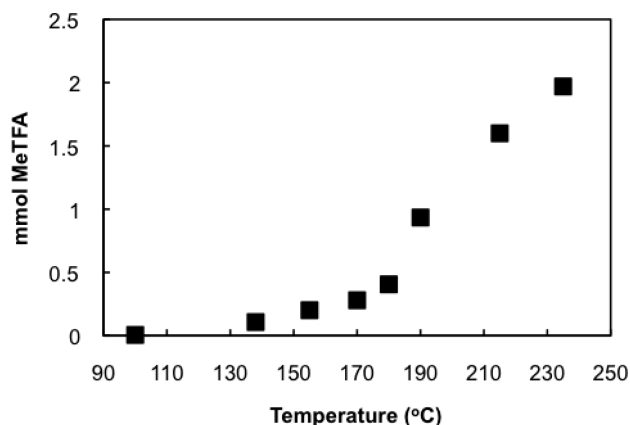


Figure 4. MeTFA production as a function of temperature. Conditions: 0.676 mmol of KCl; 7.7 mmol of NH_4IO_3 ; 8.0 mL of HTFA; $p_{\text{CH}_4/\text{Ne}} = 3450$ kPa (8.4 mmol of CH_4); 800 rpm; 20 min.

Information). Potassium chloride was found to be the optimal source of chloride. Other chloride sources, including metallic and nonmetallic sources, were found to successfully convert methane to methyl trifluoroacetate (Figure 5; also see the Supporting Information). We investigated the reactivity in the presence of sulfuryl chloride (SO_2Cl_2) and *N*-chlorosuccinimide (NCS). Both sulfuryl chloride and NCS constitute sources of elemental chlorine and are known to react by radical pathways. We did not observe reactivity comparable to that with potassium chloride (1.75 mmol of MeTFA), as MeTFA yields of only 0.08 mmol for SO_2Cl_2 and 0.18 mmol for NCS were obtained (3450 kPa CH_4 , 180 °C, 8 mL of HTFA, 0.676 mmol of NCS or 0.338 mmol of SO_2Cl_2 , 7.7 mmol of NH_4IO_3 , 1 h). For SO_2Cl_2 , 0.06 mmol of MeCl was also formed. Of the iodate sources tested, only iodic acid and silver iodate showed poor activity. Ammonium iodate surpassed other iodates by a factor of nearly 2. ^1H NMR spectroscopy indicated that the ammonium ion is not consumed during the course of the methane functionalization reaction. The effect of the potassium chloride concentration was examined (Table 1). Without the addition of KCl, only 0.02 mmol of MeTFA was formed via the background reaction. As the amount of KCl was increased, the yield of MeTFA increased. High yields of MeTFA were determined for the addition of 451, 676, and 901 mmol of KCl. Also, the amount of MeCl increased with increasing amount of KCl. Although a detailed interpretation is not possible, the formation of MeCl might occur through a pathway that involves chlorine radical.

The results of acid screening are shown in Table 2. Trifluoroacetic acid was observed to give the highest yields of the methyl ester. In contrast to chemistry that was developed around elemental iodine,^{61–64} only trace amounts of functionalized products were observed in sulfuric acid when using $\text{IO}_3^-/\text{Cl}^-$. Electrophilic functionalization of alkanes in acids weaker than H_2SO_4 and HTFA can be a challenge, but the $\text{IO}_3^-/\text{Cl}^-$ system can be performed in aqueous HTFA or even acetic acid. For example, the reaction in acetic acid led to the formation of 0.20 mmol of methyl acetate (MeOAc) after 2 h at 180 °C. Furthermore, reactions using 6.5 mL of a 1:3 (mol/mol) $\text{H}_2\text{O}/\text{HTFA}$ mixture containing 0.676 mmol of KCl and 7.7 mmol of NH_4IO_3 with methane at 3450 kPa (8.4 mmol) heated at 180 °C for 1 h resulted in the formation of 1.21 mmol of MeTFA, 0.03 mmol of MeCl, and 0.004 mmol of MeOH.

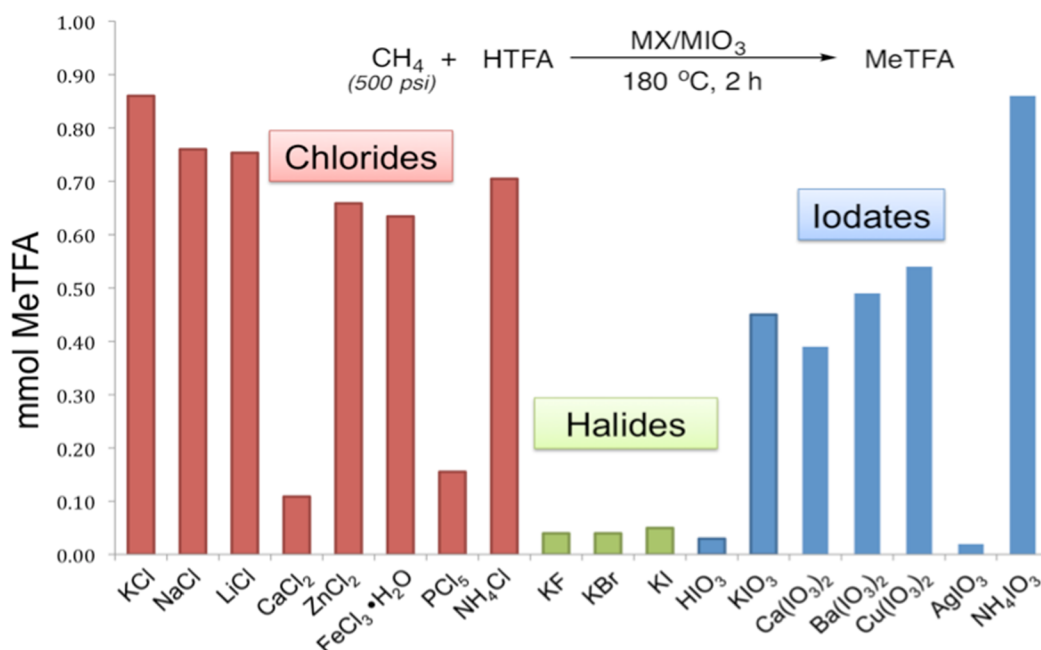


Figure 5. Comparison of halides, chloride sources, and iodate sources for the partial oxidation of methane. Conditions: 0.338 mmol of X^- ; 2.26 mmol of IO_3^- ; 2.0 mL of HTFA; $p_{CH_4/Ne} = 5520$ kPa; 180 °C; 2 h; 600 rpm. NH_4IO_3 was used as the oxidant for the reactions involving $M^{n+}Cl_n$ and KX . KCl was used in the reactions involving $M^{n+}(IO_3)_n$.

Table 1. Impact of KCl Concentration on Methane Conversion to MeX^a

KCl (μ mol)	MeTFA (mmol)	MeCl (mmol)
0	0.02	not observed
225	0.11	not observed
451	1.26	0.03
676	1.75	0.06
901	2.00	0.06

^aConditions: 7.7 mmol of NH_4IO_3 ; 8.0 mL of HTFA; $p_{CH_4/Ne} = 3450$ kPa; 180 °C; 1 h; 600 rpm.

Table 2. Comparison of Solvents for Methane Conversion to MeX^a

entry	solvent	product	yield (mmol)
1	CF_3CO_2H	MeO_2CCF_3	0.42
2	$CF_3(CF_2)_2CO_2H$	$MeO_2C(CF_2)_2CF_3$	0.38
3	CH_3CO_2H	MeO_2CCH_3	0.20
4	H_2SO_4	$MeOSO_3H$	trace
5	H_2O	$MeOH$	trace

^aConditions: 0.338 mmol of $[Cl^-]$; 2.26 mmol of NH_4IO_3 ; 2.0 mL of solvent; $p_{CH_4/Ne} = 5520$ kPa; 180 °C; 2 h; 600 rpm.

Ethane was found to react with even greater conversion and selectivity than methane (eq 4). Solutions of KCl (0.676 mmol)



with NH_4IO_3 (7.7 mmol) in 8.0 mL of HTFA placed under 2070 kPa C_2H_6 (6.7 mmol) led to the formation of 2.03 mmol of monofunctionalized EtTFA (30% yield based on ethane) with a small amount of 1,2-difunctionalized product (0.06

mmol) in 1 h at 180 °C. The resulting 1H NMR spectrum is shown in Figure 6. The selectivity for EtX ($X = TFA, Cl$)

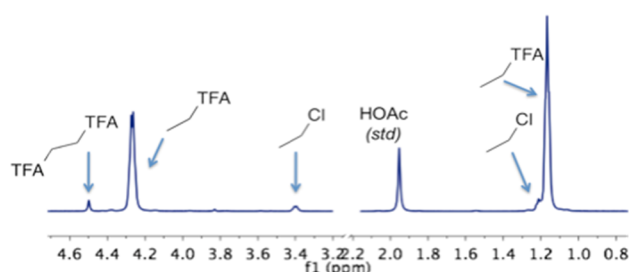
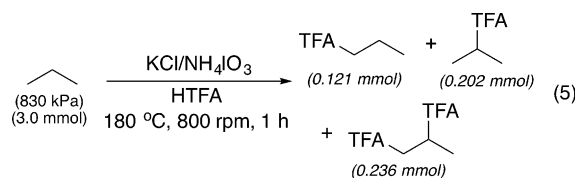


Figure 6. 1H NMR spectrum from the reaction of C_2H_6 with HTFA in the presence of NH_4IO_3 and KCl. Conditions: 0.676 mmol of KCl; 7.7 mmol of NH_4IO_3 ; 8.0 mL of HTFA; $p_{C_2H_6} = 2070$ kPa; 180 °C; 1 h; 800 rpm.

products was found to be ~97%. In an independent reaction, ethylene was converted in ~50% yield to ethylene glycol bis(trifluoroacetate) under the catalytic conditions with no observed 1,1-bis(TFA) product. Under identical conditions in the absence of KCl, only 1% of the ethane was functionalized to EtTFA. The reaction of propane (830 kPa, 3.0 mmol) with 0.676 mmol of KCl and 7.7 mmol of NH_4IO_3 in HTFA at 180 °C resulted in the production of 1-propyl (0.121 mmol), 2-propyl (0.202 mmol), and 1,2-propanediyl (0.236 mmol) trifluoroacetate products (eq 5), corresponding to 19%



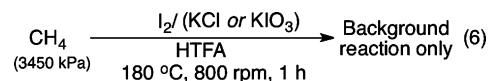
conversion based on propane. The lower conversion of propane relative to ethane is attributed to the lower pressure (830 vs 2070 kPa). The reaction is 58% selective for monofunctionalized products, which were formed in a nearly 1:2 ratio of terminal to internal oxidation. The production of any terminally functionalized alkane is rare. For example, I(III)-mediated oxidation of hexane has been reported to oxidize only the internal methylene groups.^{57,58}

Given the similarity of the $\text{IO}_3^-/\text{Cl}^-$ system to the reagents for oxychlorination, which include a chloride source (typically HCl) and an oxidant (typically O_2), the combination of chloride and iodate might be expected to functionalize alkanes by the same overall process. However, several results are inconsistent with the conclusion that the $\text{IO}_3^-/\text{Cl}^-$ chemistry proceeds by a similar pathway as catalytic oxychlorination. Oxychlorination generally requires much higher temperatures ($\geq 350^\circ\text{C}$) and yields MeCl as the initial product of CH_4 functionalization. Although the $\text{IO}_3^-/\text{Cl}^-$ -mediated methane functionalization produces small amounts of MeCl, it is a minor product in all cases, and a solution of HTFA under MeCl at 415 kPa (0.9 mmol) with 0.676 mmol of KCl and 7.7 mmol of NH_4IO_3 heated at 180°C results in only 2% conversion (0.018 mmol) of MeCl to MeTFA after 1 h. Thus, MeCl is not likely the kinetic product from the iodate/chloride reaction with methane. In addition, the dominant products for oxychlorination are typically unsaturated hydrocarbons or bis-, tris-, and even perhalogenated products.^{17,65} For example, in one patented process, oxychlorination of ethane resulted in a mixture of 12 chlorinated products, of which $<3\%$ was $\text{C}_2\text{H}_5\text{Cl}$ at 21% conversion of ethane.⁶⁵ In another example, an oxychlorination catalyst gave substantial chlorinated products for ethane functionalization, including dichloroethylenes, ethylene chloride, trichloroethylene, trichloroethane, perchloroethylene, and tetrachloroethane.¹⁷

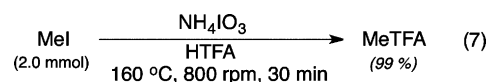
We next considered a reaction operating through the formation of iodine radicals. This scenario seems unlikely because the direct reaction of $\text{I}\cdot$ with CH_4 is highly endothermic.⁶⁶ Nonetheless, the viability of radicals as active species was probed by addition of dioxygen to the reaction mixture. Oxygen is known to react quickly with free radicals,⁶⁷ and thus, if a radical species formed in situ, a change in reactivity in the presence of O_2 would be expected. For example, Moiseev and co-workers performed the conversion of ethane to a mixture of products in HTFA using $\text{Co}(\text{TFA})_3$ in the presence of O_2 and observed significant amounts of acetic acid as a product.⁶⁸ This was proposed to be the product of a radical reaction pathway. In the case of the iodate/chloride system, reactions with methane and ethane in the absence and presence of oxygen (8 and 5 mol % relative to CH_4 and C_2H_6 , respectively) resulted in identical alkane conversions and product distributions, and no acetic acid was observed when O_2 was added to the reaction mixture for methane conversion. Although reactions in DTFA did not result in deuterium incorporation into methane or MeTFA, this could occur because functionalization of methyl intermediates is more rapid than protonation.

Another possible mechanism would be a reaction catalyzed by an I_2^+ species similar to I_2 in oleum.^{61–64} Methane functionalization occurs with several different sources of iodine (e.g., I_2 , KIO_3 , KI), but these reactions are effective in oleum ($\text{H}_2\text{SO}_4/\text{SO}_3$). The reaction of methane in HTFA with I_2 results in no conversion of CH_4 to MeTFA. Reactions of methane with KI in the presence of NH_4IO_3 result in only

background amounts of functionalized product (i.e., no enhancement relative to the use of NH_4IO_3 only). The reaction using I_2 produces no MeTFA in the presence of KCl, and only the background reaction (i.e., conversion identical to that for heating CH_4 with IO_3^-) is observed when a mixture of I_2 and KCl is used (eq 6). These results suggest that the formation of I^+ or I_2^+ as the active catalyst is not likely and that the iodate/chloride process operates by a unique mechanism.



In contrast to the observations with MeCl (see above), quantitative conversion of MeI to MeTFA was found to occur in the presence of KIO_3 in HTFA at 160°C within 30 min (eq 7). Neither I_2 nor KCl alone produced MeTFA from MeI under the same conditions. Thus, MeI is a possible intermediate in the overall catalytic production of MeTFA.



To probe viable iodine-containing species for the alkane functionalization, we attempted stoichiometric CH_4 conversion with a variety of isolable iodine compounds (Table 3). Species

Table 3. Stoichiometric Partial Oxidation of Methane Using Various Iodine Sources^a

entry	species	additive	yield of MeTFA (%) ^b
1	I_2	–	–
2	I_2	KCl	–
3	I_2	NH_4IO_3	2
4	ICl	–	–
5	ICl_3	–	5 (43 ^c)
6	$\text{I}(\text{TFA})_3$	–	7
7	$\text{I}(\text{TFA})_3$	KCl	43
8	I_2O_4	–	2 (15 ^d)
9	I_2O_4	KCl	30 (17 ^d)
10	I_2O_5	–	1 (2 ^c)
11	I_2O_5	KCl	4.1
12	$(\text{IO}_2)_2\text{S}_2\text{O}_7$	–	<1
13	$(\text{IO}_2)_2\text{S}_2\text{O}_7$	KCl	48
14	$(\text{IO})_2\text{SO}_4$	–	5.3
15	$(\text{IO})_2\text{SO}_4$	KCl	31

^aConditions: 0.4 mmol of iodine reagent; 0.1 mmol of KCl (if added); $p_{\text{CH}_4/\text{Ne}} = 3450$ kPa; 180°C ; 800 rpm; 1 h. ^bBased on moles of iodine reagent. ^cThe % yield of MeCl is given in parentheses. ^dThe % yield of MeI is given in parentheses.

of interest included ICl, ICl_3 , $\text{I}(\text{TFA})_3$, IO^+ , and IO_2^+ . UV–vis spectra of the $\text{IO}_3^-/\text{Cl}^-$ reaction mixture indicated that ICl, ICl_3 , and Cl_2 may be present in low concentrations. This likely leads to the formation of the minor product MeCl. However, the reaction of ICl with CH_4 resulted in no production of MeX, while ICl_3 predominantly generated MeCl. MeTFA was formed in low yield ($\sim 5\%$ based on I^{III}) in the ICl_3 reaction. Thus, ICl and ICl_3 are not candidates or precursors for the active I-containing species in the iodate/chloride methane functionalization.

The reaction of CH_4 in HTFA at 180°C with 0.4 mmol of $\text{I}(\text{TFA})_3$, I_2O_4 ,⁶⁹ I_2O_5 ,⁴¹ $[(\text{IO}_2)_2\text{S}_2\text{O}_7]$,⁷⁰ or $[(\text{IO})_2\text{SO}_4]$ ⁷¹ in the absence of chloride results in minimal conversion to MeTFA ($\leq 7\%$ yield; Table 3). However, for all these iodine-

based reagents except I_2O_5 , the addition of 0.1 mmol of KCl results in a dramatic increase in the yield of MeTFA (Table 3). Similar to the iodate/chloride reactions, KCl is effective in a substoichiometric quantity. The highest percent yield of MeTFA was achieved using $[(IO_2)_2S_2O_7]$, which gave a yield of nearly 50%. $I(TFA)_3$ with KCl also gave a high yield of MeTFA (43%), and the combined yield of MeTFA and MeI (47%) was high for I_2O_4 and KCl. Since MeI is converted to MeTFA using the iodate/chloride process, I_2O_4 is viable as an active intermediate. Although mechanistic details are not known at this point, we speculate that the active intermediate is an iodine oxide compound. Although $I(TFA)_3$ with KCl is active for methane conversion, its formation from iodate and chloride under the reaction conditions seems unlikely. We speculate that chloride may bind to this putative iodine oxide intermediate and enhance electrophilic alkane functionalization. The exact identity of the active iodine species is the subject of ongoing studies.

SUMMARY AND CONCLUSIONS

Light alkanes are converted to monofunctionalized esters in good yields with the use of simple chloride salts (in catalytic amounts) and with iodate as the sole oxidant in acidic media such as trifluoroacetic acid, acetic acid, or even aqueous trifluoroacetic acid. The system operates over a large range of pressures (240–6900 kPa) and temperatures (100–235 °C) and exhibits excellent selectivity for monofunctionalized products. Conversions of methane to MeTFA in excess of 20% have been achieved, and the conversion of ethane is even more efficient, with ~30% yield of EtTFA. Although propane conversion is less efficient, the ability to form monofunctionalized products selectively with some terminal activation is notable. These values for alkane conversion meet many of the established benchmarks for efficient alkane functionalization.⁷² A potential benefit of the iodate/chloride system is that iodine (the byproduct of KCl/IO_3^- oxidation reactions) can be reoxidized to iodate in basic aqueous solution with molecular oxygen. Also, iodates have been generated from iodide sources electrochemically.⁷³ The distinct reactivity imparted by chloride (compared with I_2 , IO_3^- , $I(TFA)_3$, etc. without chloride or these species with other halides) is unique and without precedent, resulting in substantial increases in efficiency for production of monofunctionalized alkanes. The exact role of chloride is unknown at this point and will be the subject of future studies, but the chloride enhancement is observed for several iodine-based reagents (Table 3). In view of the differences between classic oxychlorination and the iodate/chloride process (e.g., reaction temperature, product selectivity, and efficacy for ethane and propane), it seems unlikely that the formation of chlorine radical is the key role of chloride. It is possible that chloride bonds with the active iodine-based reagent to provide an electronic modulation for the C–H bond-breaking step and/or the C–O bond-forming step. Iodosyl chloride and iodyl chloride have been observed experimentally.⁷⁴ The presence of iodine–oxo bonds suggests a possible similarity to C–H bond breaking by metal oxo or imide complexes.^{23,75–77} However, the enhancement observed upon addition of chloride to the $I(TFA)_3$ reaction suggests that the chloride enhancement is not limited to iodine oxides. Although challenges remain, the reported iodate/chloride process functionalizes light alkanes rapidly (in 20 min under some conditions) with good conversion and selectivity over a

broad range of temperatures and pressures with an oxidant that in theory can be thermally recycled using dioxygen.

EXPERIMENTAL SECTION

General Considerations. *Caution!* Many of the reagents and reaction conditions are potentially hazardous. Proper literature should be consulted⁷⁸ and safety precautions⁷⁹ should be implemented when handling concentrated acids, strong oxidants (e.g., iodates and other iodine oxides), and mixtures of hydrocarbons and oxygen.

Unless stated otherwise, reaction mixtures were prepared in air. Trifluoroacetic acid (HTFA), trifluoroacetic anhydride (TFAA), methyl trifluoroacetate (MeTFA), acetic acid (HOAc), iodic acid, formic acid, sulfuric acid, iodine trichloride, iodine monochloride, I_2O_5 , iodomethane, chloromethane, and iodine as well as all iodates and chlorides were purchased from VWR and used as received. Methane/neon (9:1 mol/mol), ethane, and propane were purchased from GTS Welco. Trifluoroacetic acid- d_1 (DTFA), ^{13}C -methane, and ^{13}C -methanol were purchased from Cambridge Isotope Laboratories and used as received. Iodyl pyrosulfate,⁷⁰ iodosyl sulfate,⁷¹ diiodine tetroxide,⁶⁹ and tris(trifluoroacetato-O)iodine⁸⁰ were prepared according to literature procedures. 1H and ^{13}C NMR spectra were recorded on a Bruker 600, 500, or 300 MHz NMR spectrometer. NMR spectra taken in HTFA or DTFA included a capillary tube filled with C_6D_6 that was used as an internal lock reference. Chemical shifts in HTFA are reported relative to standards of HOAc (1H NMR δ 2.04) or dichloromethane (DCM) (1H NMR δ 5.03). This shift was chosen so that the products would remain at the same chemical shifts when using different standards. At least one reaction was spiked with the alternative internal standard to ensure the integrity of the standards and to ensure that the standard was not a product of the reaction (i.e., DCM was used to determine whether HOAc was a product of the reaction). GC–MS data were obtained on a Shimadzu GC-2010 instrument equipped with a Restek RT-Qbond 30 m \times 8 mm fused silica PLOT column. GC–TCD data were obtained with a Shimadzu GC-2014 instrument equipped with a 500 mL injection loop in which the sample passed through three columns in series (Hayesep T 80/100 mesh 0.5 m \times 2.0 mm, Supelco 60/80 Mesh 5 Å molecular sieve 2.0 m \times 2.1 mm, and Hayesep Q 80/100 mesh 1.5 m \times 2.0 mm). UV–vis spectra were recorded on a Varian Cary 300 Bio UV–vis spectrophotometer.

Reactions of Cl^-/IO_3^- in Acid with Alkanes. Reactions were carried out in two separate types of high-pressure reactors. Reactions consisting of a solvent volume of >2.0 mL were performed using in-house-built high-pressure reactors constructed primarily of stainless steel Swagelok parts. The reactors were equipped with Teflon liners. With liners inserted, the average reactor volume was 16.1 mL. Heating was accomplished through inductive heat transfer from tight-fitting custom aluminum blocks. Screenings of reagents and conditions were typically carried out in a custom-built Asynt Ltd. high-pressure carousel (see Figure S8 in the Supporting Information). The carousel is constructed of Hastelloy C-276 and contains nine 7 mL reaction chambers. Reactions were carried out in glass liners within the reaction chambers. Reaction temperatures were maintained through direct heat from an RTC-basic hot plate equipped with temperature control. The carousel was insulated by wrapping it in fiberglass fabric. The amounts reported for products formed for all functionalization reactions are averages of at least three independent runs.

Methane Functionalization. In a typical reaction with methane, a stir bar, 0.676 mmol of KCl, 7.7 mmol of NH_4IO_3 , and 8.0 mL of HTFA were loaded into a 16.1 mL VCO reactor containing a tight-fitting Teflon liner. After the reactor was sealed and weighed, it was purged three times with CH_4/Ne and finally charged with 90 mol % $CH_4/10$ mol % Ne to a pressure of 3450 kPa (8.4 mmol of CH_4). The reactor was weighed to quantify the amount of gas added and subsequently heated and stirred (800 rpm) for 1 h. The reactor was removed from the heating block, placed in front of a fan, and cooled to room temperature for 30 min. The reactor was reweighed to ensure that no leakage had occurred over the course of the reaction. The resultant gas was collected in a gas bag and analyzed by GC–TCD. A

standard consisting of 30 μL of HOAc and/or 30 μL of DCM was added to the reaction liquid. The mixture was stirred, and then a sample was removed for centrifugation. The products were analyzed by ^1H and ^{13}C NMR spectroscopy and GC-MS. In the reaction, 1.75 mmol of MeTFA and 0.06 mmol of MeCl were formed. ^1H NMR δ 3.85 (3H, $\text{H}_3\text{C}-\text{O}_2\text{CCF}_3$, s); ^{13}C NMR δ 50.8 ($\text{H}_3\text{C}-\text{O}_2\text{CCF}_3$, q, $^4J_{\text{C-F}} = 17$ Hz), the carbonyl carbon and CF_3 carbon overlapped with HTFA resonances.

In a typical reaction with methane in the carousel, a stir bar, 0.338 mmol of KCl, 2.26 mmol of NH_4IO_3 , and 2.0 mL of HTFA were loaded into individual glass vials. The vials were transferred into the reactor. After the reactor was sealed, it was purged three times with CH_4/Ne and finally charged with 90 mol % $\text{CH}_4/10$ mol % Ne to a pressure of 5515 kPa. The reactor was subsequently heated and stirred (600 rpm) for 2 h. The reactor was removed from the heating block, placed in front of a fan, and cooled to room temperature for 30 min. The resultant gas was collected in a calibrated gas buret to obtain the final amount of gas contained in the reactor. This gas was analyzed by GC-TCD. A standard consisting of 10 μL of HOAc and/or 10 μL of DCM was added to the reaction liquid. The mixture was stirred, and then a sample was removed for centrifugation. The products were analyzed by ^1H and ^{13}C NMR spectroscopy and GC-MS. The amount of MeTFA formed (minus a background of 0.04 mmol) was determined to be 0.86 mmol.

^{13}C -Methane Functionalization. Four carousel chambers were individually charged with a stir bar, 0.338 mmol of KCl, 2.26 mmol of KIO_3 , and 2.0 mL of HTFA. After the reactor was sealed, it was purged twice with argon and once with $^{13}\text{CH}_4$ and finally charged with $^{13}\text{CH}_4$ to a pressure of 240 kPa (0.652 mmol). The reaction mixture was heated for 2 h and stirred at 600 rpm. The reactor was cooled to room temperature over 30 min. The resultant gas was collected in a gas bag. A portion was evaluated by GC-MS to determine the amount of $^{13}\text{CO}_2$ produced (0.011 mmol). The remainder was vented directly into the sample loop of the GC-TCD instrument, and the final gas concentrations were determined through independently determined calibration curves. A standard consisting of 10 μL of HOAc was added to the reaction liquid. The mixture was stirred, and a sample was removed for centrifugation. The products were analyzed by ^1H and ^{13}C NMR spectroscopy and GC-MS. In the reaction, 80 μmol of $^{13}\text{CH}_3\text{TFA}$, 6 μmol of $^{13}\text{CH}_3\text{Cl}$, and 5 μmol of $^{13}\text{CH}_2\text{Cl}_2$ were formed. ^1H NMR δ 3.85 (3H, $^{13}\text{CH}_3\text{TFA}$, d, $^1J_{\text{C-H}} = 151$ Hz), 2.78 (3H, $^{13}\text{CH}_3\text{Cl}$, d, $^1J_{\text{C-H}} = 150$ Hz), 5.03 (2H, $^{13}\text{CH}_2\text{Cl}_2$, d, $^1J_{\text{C-H}} = 178$ Hz); ^{13}C NMR δ 50.8 ($^{13}\text{CH}_3\text{TFA}$), 25.1 ($^{13}\text{CH}_3\text{Cl}$), 53.0 ($^{13}\text{CH}_2\text{Cl}_2$).

Retention of MeTFA. In a vial, 1.0 g of $^{13}\text{CH}_3\text{OH}$ was slowly added to an equimolar amount of TFAA during continuous stirring to produce $^{13}\text{CH}_3\text{TFA}$ and HTFA. A known volume was sampled and diluted into HTFA. The sample was spiked with HOAc, and ^1H NMR spectroscopy was used to determine the concentration of $^{13}\text{CH}_3\text{TFA}$. A reaction was then set up analogous to the methane functionalization reaction in the 16.1 mL VCO reactor described above (0.667 mmol of KCl; 7.7 mmol of NH_4IO_3 ; 8.0 mL of HTFA). This mixture was then spiked with 0.9 mmol of the $^{13}\text{CH}_3\text{TFA}$ stock solution. The reactor was sealed, purged with CH_4 three times, and pressurized with 90 mol % $\text{CH}_4/10$ mol % Ne to 3450 kPa. The reaction mixture was heated (180 $^\circ\text{C}$) and stirred (800 rpm) for 1 h and then cooled to room temperature. The overpressure was vented into a gas bag, and this gas was analyzed by GC-MS. HOAc (30 μL) was added as a standard, and the reaction mixture was stirred and sampled as detailed above. ^1H NMR analysis of the liquid revealed that $\sim 85\%$ of the $^{13}\text{CH}_3\text{TFA}$ was retained and that 1.7 mmol of MeTFA was formed during the reaction. The presence of methane was found not to be crucial to the reaction, as a similar reaction run without the overpressure of methane resulted in retention of the same amount of $^{13}\text{CH}_3\text{TFA}$.

Functionalization Reactions of CH_4 and C_2H_6 with Added O_2 . In a typical reaction with methane, a stir bar, 0.676 mmol of KCl, 7.7 mmol of NH_4IO_3 and 8.0 mL of HTFA were loaded into the 16.1 mL VCO reactor that contained a tight-fitting Teflon liner. After the reactor was sealed and weighed, it was purged three times with CH_4/Ne . The reaction vessel was pressurized to 340 kPa O_2 (0.8 mmol of

O_2) and finally pressurized with 90 mol % $\text{CH}_4/10$ mol % Ne to 3450 kPa (7.6 mmol of CH_4). The reactor was subsequently heated and stirred (800 rpm) for 1 h. The reactor was removed from the heating block, placed in front of a fan, and cooled to room temperature for 30 min. The resultant gas was collected in a gas bag and analyzed by GC-TCD. A standard consisting of 30 μL of HOAc and/or 30 μL of DCM was added to the reaction liquid. The mixture was stirred, and then a sample was removed for centrifugation. The products were analyzed by ^1H and ^{13}C NMR spectroscopy and GC-MS. In the reaction, 1.73 mmol of MeTFA and 0.06 mmol of MeCl were formed. For the reaction of ethane and oxygen, the reactor was charged first with 255 kPa O_2 then filled to a final pressure of 2070 kPa with ethane. The reaction was then carried out as described above.

Methane Functionalization with Various Sources of Iodine.

Reactions in this case were carried out with various sources of iodine in different oxidation states. These reactions were carried out with and without added potassium chloride. The reactions using ICl and ICl_3 were prepared inside a glovebox. A typical reaction was performed as follows: A stir bar, 0.4 mmol of I_2O_4 , 0.1 mmol of KCl, and 6.0 mL of HTFA were loaded into the 16.1 mL VCO reactor containing a tight-fitting Teflon liner. The reactors were sealed and weighed. The reactor was attached to a high-pressure line and flushed three times with 90 mol % $\text{CH}_4/10$ mol % Ne. The reactor was then charged to 3450 kPa (8.4 mmol of CH_4) with the same gas mixture and weighed again to obtain the amount of gas added. The reactor was weighed and subsequently heated and stirred (800 rpm) for 1 h. The reactor was removed from the heating block, placed in front of a fan, and cooled to room temperature for 30 min. The resultant gas was collected in a gas bag and analyzed by GC-TCD. A standard consisting of 30 μL of HOAc and/or 30 mL of DCM was added to the reaction liquid. The mixture was stirred, and then a sample was removed for centrifugation. The products were analyzed by ^1H NMR spectroscopy and GC-MS. In the reaction, 0.238 mmol of MeTFA and 0.137 mmol of MeCl were formed. Yields for these reactions are given in terms of moles of iodine reagent. For this reaction, the yield of MeTFA is given as 30% and that of MeCl as 17%.

Methane Functionalization with SO_2Cl_2 or *N*-Chlorosuccinimide. The reactions were performed according to the methane functionalization procedure described above, except SO_2Cl_2 or NCS was used instead of KCl. For the reactions, 0.676 mmol of NCS or 0.338 mmol of SO_2Cl_2 were combined with 7.7 mmol of NH_4IO_3 in 8 mL of HTFA, and the reactor was pressurized with 3450 kPa CH_4 . The reactor was heated at 180 $^\circ\text{C}$ for 1 h and then cooled and analyzed.

Ethane Functionalization. In a typical reaction with ethane, a stir bar, 0.676 mmol of KCl, 7.7 mmol of NH_4IO_3 , and 8.0 mL of HTFA were loaded into the reactor. After the reactor was sealed, it was purged three times with ethane and finally charged with ethane to a pressure of 2070 kPa (6.7 mmol of ethane). The reactor was weighed and subsequently heated and stirred (800 rpm) for 1 h. The reactor was removed from the heating block and cooled to room temperature for 30 min. The resultant gas was collected in a gas bag and analyzed by GC-TCD. A standard consisting of 30 μL of HOAc or DCM was added to the reaction liquid. The mixture was stirred, and then a sample was removed for centrifugation. The products were analyzed by ^1H NMR spectroscopy and GC-MS. In the reaction, 2.03 mmol of EtTFA, 0.13 mmol of EtCl, and 0.06 mmol of 1,2-bis(trifluoroacetyl)ethane (glycol) were formed. ^1H NMR: 1,2-bis(trifluoroacetyl)ethane δ -4.49 (4H, 4.25, $\text{H}_2\text{C}-\text{O}_2\text{CCF}_3$); ethyl trifluoroacetate δ 4.27 (2H, $\text{CH}_3\text{H}_2\text{C}-\text{O}_2\text{CCF}_3$, q, $^3J_{\text{H-H}} = 7$ Hz), 1.18 (3H, $\text{CH}_3\text{H}_2\text{C}-\text{O}_2\text{CCF}_3$, t, $^3J_{\text{H-H}} = 7$ Hz); ethyl chloride δ -4.19 ($\text{CH}_3\text{CH}_2\text{Cl}$, br), 2.08 ($\text{CH}_3\text{CH}_2\text{Cl}$, overlap with HOAc standard).

Ethylene Functionalization. In a typical reaction with ethylene, a stir bar, 0.676 mmol of KCl, 7.7 mmol of NH_4IO_3 , and 8.0 mL of HTFA were loaded into the reactor. After the reactor was sealed, it was purged three times with ethylene and finally charged with 1379 kPa ethylene (4.3 mmol of ethylene). The reactor was weighed and subsequently heated and stirred (800 rpm) for 1 h. The reactor was removed from the heating block and cooled to room temperature for 30 min. The resultant gas was collected in a gas bag and analyzed by

GC-TCD. A standard consisting of 30 μL of DCM was added to the reaction liquid. The mixture was stirred, and then a sample was removed for centrifugation. The products were analyzed by ^1H NMR spectroscopy and GC-MS. In the reaction, 2.20 mmol of 1,2-bis(trifluoroacetyl)ethane was formed. ^1H NMR: 1,2-bis(trifluoroacetyl)ethane δ 4.49 (4H, $\text{H}_2\text{C}-\text{O}_2\text{CCF}_3$). Reactions without added chloride also led to similar reactivity. Under the same conditions, these reactions yielded 11% glycol and 21% of what is tentatively assigned as 1-trifluoroacetyl-2-iodoethane. ^1H NMR: 1-trifluoroacetyl-2-iodoethane δ 4.44 (2H, $\text{H}_2\text{C}-\text{O}_2\text{CCF}_3$, t, $^3J_{\text{H-H}} = 6.8$ Hz), 3.17 (2H, $\text{H}_2\text{C}-\text{I}$, t, $^3J_{\text{H-H}} = 6.8$ Hz)

Propane Functionalization. In a typical reaction with propane, a stir bar, 0.676 mmol of KCl, 7.7 mmol of NH_4IO_3 , and 8.0 mL of HTFA were loaded into the reactor. After the reactor was sealed, it was purged three times with propane and finally charged with 830 kPa propane (3.0 mmol of propane). The reactor was weighed and subsequently heated and stirred (800 rpm) for 2 h. The reactor was removed from the heating block and cooled to room temperature. The resultant gas was collected in a gas bag and analyzed by GC-TCD. A standard consisting of 30 μL of HOAc was added to the reaction liquid. The mixture was stirred, after which a sample was removed for centrifugation. The products were analyzed by ^1H NMR spectroscopy and GC-MS. In the reaction, 121 μmol of 1-propyl trifluoroacetate, 404 μmol of 2-propyl trifluoroacetate, and 236 μmol of 1,2-propanediyl bis(trifluoroacetate) were formed. ^1H NMR: 1-propyl trifluoroacetate δ 4.17 (2H, $\text{H}_2\text{C}-\text{O}_2\text{CCF}_3$, t, $^3J_{\text{H-H}} = 7$ Hz), 1.59 (2H, CH_2CH_3 , m), 0.79 (3H, CH_3 , t, $^3J_{\text{H-H}} = 7$ Hz); 2-propyl trifluoroacetate δ 4.17 (1H, $\text{HC}-\text{O}_2\text{CCF}_3$, h, $^3J_{\text{H-H}} = 6$ Hz), 1.18 (6H, CH_3 , d, $^3J_{\text{H-H}} = 6$ Hz); 1,2-propanediyl bis(trifluoroacetate) δ 5.27 (1H, $\text{HC}-\text{O}_2\text{CCF}_3$, m), 4.38 (1H, $\text{H}_2\text{C}-\text{O}_2\text{CCF}_3$, dd, $^2J_{\text{H-H}} = 12$ Hz, $^3J_{\text{H-H}} = 3$ Hz), 4.27 (1H, $\text{H}_2\text{C}-\text{O}_2\text{CCF}_3$, dd, $^2J_{\text{H-H}} = 12$ Hz, $^3J_{\text{H-H}} = 7$ Hz), 1.26 (3H, CH_3 , d, $^3J_{\text{H-H}} = 7$ Hz).

■ ASSOCIATED CONTENT

● Supporting Information

Supporting figures, tables, and spectra. This material is available free of charge via the Internet at <http://pubs.acs.org>.

■ AUTHOR INFORMATION

Corresponding Authors

jtgroves@princeton.edu

tbg7h@virginia.edu

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work was solely supported as part of the Center for Catalytic Hydrocarbon Functionalization, an Energy Frontier Research Center funded by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Award DE-SC0001298.

■ REFERENCES

- (1) *BP Statistical Review of World Energy 2013*; BP: London, 2013.
- (2) *Liquefied Natural Gas: Understanding the Basic Facts*; U. S. Department of Energy: Washington, DC, 2005.
- (3) The World Bank Group. World Bank Sees Warning Sign in Gas Flaring Increase. <http://www.worldbank.org/en/news/press-release/2012/07/03/world-bank-sees-warning-sign-gas-flaring-increase> (accessed Dec 12, 2013).
- (4) Olah, G. A.; Goepfert, A.; Prakash, G. K. S. *Beyond Oil and Gas: The Methanol Economy*, 2nd ed.; Wiley-VCH: Weinheim, Germany, 2009.
- (5) Luo, Y.-R. In *Comprehensive Handbook of Chemical Bond Energies*; CRC Press: Boca Raton, FL, 2007; pp 19–145.
- (6) Labinger, J. A. *J. Mol. Catal. A: Chem.* **2004**, *220*, 27–35.

(7) Cavaliere, V. N.; Wicker, B. F.; Mindiola, D. J. *Adv. Organomet. Chem.* **2012**, *60*, 1–47.

(8) Webb, J. R.; Bolaño, T.; Gunnoe, T. B. *ChemSusChem* **2011**, *4*, 37–49.

(9) Periana, R. A.; Bhalla, G.; Tenn, W. J., III; Young, K. J. H.; Liu, X. Y.; Mironov, O.; Jones, C. J.; Ziatdinov, V. R. *J. Mol. Catal. A: Chem.* **2004**, *220*, 7–25.

(10) Stahl, S. S.; Labinger, J. A.; Bercaw, J. E. *Angew. Chem., Int. Ed.* **1998**, *37*, 2180–2192.

(11) Shilov, A. E.; Shul'pin, G. B. *Chem. Rev.* **1997**, *97*, 2879–2932.

(12) Bal'zhinimaev, B. S.; Paukshtis, E. A.; Kovalev, E. V.; Suknev, A. P.; Shalygin, A. S. (Uchrezhdenie RAN Institut Kataliza im. G. K. Borenskova SO RAN). Method of Selective Catalytic Oxochlorination of Methane to Methyl Chloride. RU Patent 2446881C2, April 10, 2012.

(13) Aglulin, A. G. *Kinet. Catal.* **2009**, *50*, 427–434.

(14) Stauffer, J. E. Process for the Chlorination of Methane. World Patent 9008117A1, July 26, 1990.

(15) Rozanov, V. N.; Gvozd, E. V.; Kernerman, V. A.; Svetlanov, E. B.; Trushechkina, M. A.; Treger, Y. A. *Kinet. Catal.* **1989**, *30*, 148–154.

(16) Riegel, H.; Schindler, H. D.; Sze, M. C. (CE Lummus). Oxochlorination of Methane. U.S. Patent 4,207,268A, June 10, 1980.

(17) Joseph, W. J.; Bianchi, A. B. (Dow Chemical). Manufacture of Chlorinated Hydrocarbons. U.S. Patent 2,752,401, June 26, 1956.

(18) Podkolzin, S. G.; Stangland, E. E.; Jones, M. E.; Peringer, E.; Lercher, J. A. *J. Am. Chem. Soc.* **2007**, *129*, 2569–2576.

(19) Brickey, R. T.; Lisewsky, G. A.; Waycuilis, J. J.; York, S. D. (Marathon GTF Technology, Ltd.). Processes for converting gaseous alkanes to liquid hydrocarbons using microchannel reactor. World Patent 2011159490A1, Dec 22, 2011.

(20) Lorkovic, I. M.; Sun, S.; Gadewar, S.; Breed, A.; Macala, G. S.; Sardar, A.; Cross, S. E.; Sherman, J. H.; Stucky, G. D.; Ford, P. C. J. *Phys. Chem. A* **2006**, *110*, 8695–8700.

(21) Olah, G. A.; Gupta, B.; Felberg, J. D.; Ip, W. M.; Husain, A.; Karpeles, R.; Lammertsma, K.; Melhotra, A. K.; Trivedi, N. J. *J. Am. Chem. Soc.* **1985**, *107*, 7097–7105.

(22) Ding, K.; Metiu, H.; Stucky, G. D. *ACS Catal.* **2013**, *3*, 474–477.

(23) Gunay, A.; Theopold, K. H. *Chem. Rev.* **2010**, *110*, 1060–1081.

(24) Nelson, A. P.; DiMagno, S. G. *J. Am. Chem. Soc.* **2000**, *122*, 8569–8570.

(25) Gormisky, P. E.; White, M. C. *J. Am. Chem. Soc.* **2013**, *135*, 14052–14055.

(26) Stoian, S. A.; Xue, G.; Bominaar, E. L.; Que, L., Jr.; Münck, E. J. *Am. Chem. Soc.* **2014**, *136*, 1545–1558.

(27) Hintermair, U.; Sheehan, S. W.; Parent, A. R.; Ess, D. H.; Richens, D. T.; Vaccaro, P. H.; Brudvig, G. W.; Crabtree, R. H. *J. Am. Chem. Soc.* **2013**, *135*, 10837–10851.

(28) Liu, W.; Huang, X.; Cheng, M.-J.; Nielsen, R. J.; Goddard, W. A., III; Groves, J. T. *Science* **2012**, *337*, 1322–1325.

(29) Liu, W.; Groves, J. T. *Angew. Chem., Int. Ed.* **2013**, *52*, 6024–6027.

(30) Liu, W.; Groves, J. T. *J. Am. Chem. Soc.* **2010**, *132*, 12847–12849.

(31) *Alkane C–H Activation by Single-Site Metal Catalysis*; Pérez, P. J., Ed.; Catalysis by Metal Complexes, Vol. 38; Springer: Dordrecht, The Netherlands, 2012.

(32) *Activation and Functionalization of C–H Bonds*; Goldberg, K. I., Goldman, A. S., Eds.; ACS Symposium Series, Vol. 885; American Chemical Society: Washington, DC, 2004.

(33) Gunnoe, T. B. In *Physical Inorganic Chemistry: Reactions, Processes, and Applications*; Bakac, A., Ed.; John Wiley & Sons: Hoboken, NJ, 2010; Vol. 2, pp 495–549.

(34) Owen, J. S.; Labinger, J. A.; Bercaw, J. E. *J. Am. Chem. Soc.* **2006**, *128*, 2005–2016.

(35) Asbury, J. B.; Hang, K.; Yeston, J. S.; Cordaro, J. G.; Bergman, R. G.; Lian, T. *J. Am. Chem. Soc.* **2000**, *122*, 12870–12871.

(36) Crabtree, R. H. *Chem. Rev.* **2012**, *112*, 1536–1554.

- (37) Choi, J.; MacArthur, A. H. R.; Brookhart, M.; Goldman, A. S. *Chem. Rev.* **2011**, *111*, 1761–1779.
- (38) Crabtree, R. H.; Mihelcic, J. M.; Quirk, J. M. *J. Am. Chem. Soc.* **1979**, *101*, 7738–7740.
- (39) Dobereiner, G. E.; Yuan, J.; Schrock, R. R.; Goldman, A. S.; Hackenberg, J. D. *J. Am. Chem. Soc.* **2013**, *135*, 12572–12575.
- (40) Renkema, K. B.; Kissin, Y. V.; Goldman, A. S. *J. Am. Chem. Soc.* **2003**, *125*, 7770–7771.
- (41) Leitch, D. C.; Lam, Y. C.; Labinger, J. A.; Bercaw, J. E. *J. Am. Chem. Soc.* **2013**, *135*, 10302–10305.
- (42) Ahuja, R.; Punji, B.; Findlater, M.; Supplee, C.; Schinski, W.; Brookhart, M.; Goldman, A. S. *Nat. Chem.* **2011**, *3*, 167–171.
- (43) Chepaikin, E. G. *Russ. Chem. Rev.* **2011**, *80*, 363–396.
- (44) Jones, C. J.; Taube, D.; Ziatdinov, V. R.; Periana, R. A.; Nielsen, R. J.; Oxgaard, J.; Goddard, W. A., III. *Angew. Chem., Int. Ed.* **2004**, *43*, 4626–4629.
- (45) Periana, R. A.; Taube, D. J.; Gamble, S.; Taube, H.; Satoh, T.; Fujii, H. *Science* **1998**, *280*, 560–564.
- (46) Periana, R. A.; Taube, D. J.; Taube, H.; Evitt, E. R. (Catalytica, Inc.). Catalytic Process for Converting Lower Alkanes to Esters, Alcohols, and to Hydrocarbons. U.S. Patent 5,306,855A, April 26, 1994.
- (47) Kao, L. C.; Hutson, A. C.; Sen, A. *J. Am. Chem. Soc.* **1991**, *113*, 700–701.
- (48) Hashiguchi, B. G.; Konnick, M. M.; Bischof, S. M.; Gustafson, S. J.; Devarajan, D.; Gunsalus, N.; Ess, D. H.; Periana, R. A. *Science* **2014**, *343*, 1232–1237.
- (49) Strassner, T.; Ahrens, S.; Muehlhofer, M.; Munz, D.; Zeller, A. *Eur. J. Inorg. Chem.* **2013**, 3659–3663.
- (50) Chen, W.; Kocal, J. A.; Brandvold, T. A.; Bricker, M. L.; Bare, S. R.; Broach, R. W.; Greenlay, N.; Popp, K.; Walenga, J. T.; Yang, S. S.; Low, J. J. *Catal. Today* **2009**, *140*, 157–161.
- (51) Sen, A.; Greta, E.; Oliver, T. F. *Prepr.—Am. Chem. Soc., Div. Pet. Chem.* **1988**, *33*, 460–462.
- (52) Flores, J. A.; Komine, N.; Pal, K.; Pinter, B.; Pink, M.; Chen, C.-H.; Caulton, K. G.; Mindiola, D. J. *ACS Catal.* **2012**, *2*, 2066–2078.
- (53) Caballero, A.; Despagnet-Ayoub, E.; Díaz-Requejo, M.; Díaz-Rodríguez, A.; González-Núñez, M. E.; Mello, R.; Muñoz, B. K.; Ojo, W.-S.; Asensio, G.; Etienne, M.; Pérez, P. J. *Science* **2011**, *332*, 835–838.
- (54) Zhdankin, V. V.; Stang, P. J. *Chem. Rev.* **2008**, *108*, 5299–5358.
- (55) Richardson, R. D.; Wirth, T. *Angew. Chem., Int. Ed.* **2006**, *45*, 4402–4404.
- (56) Wirth, T. *Angew. Chem., Int. Ed.* **2005**, *44*, 3656–3665.
- (57) Dohi, T.; Kita, Y. *ChemCatChem* **2014**, *6*, 76–78.
- (58) Moteki, S. A.; Usui, A.; Zhang, T.; Solorio Alvarado, C. R.; Maruoka, K. *Angew. Chem., Int. Ed.* **2013**, *52*, 8657–8660.
- (59) Ding, K.; Zhang, A.; Stucky, G. D. *ACS Catal.* **2012**, *2*, 1049–1056.
- (60) Buddrus, J.; Plettenberg, H. *Angew. Chem., Int. Ed. Engl.* **1976**, *15*, 436.
- (61) Michalkiewicz, B.; Jarosińska, M.; Łukasiewicz, I. *Chem. Eng. J.* **2009**, *154*, 156–161.
- (62) Gang, X.; Zhu, Y.; Birch, H.; Hjuler, H. A.; Bjerrum, N. J. *Appl. Catal., A* **2004**, *261*, 91–98.
- (63) Periana, R. A.; Mirinov, O.; Taube, D. J.; Gamble, S. *Chem. Commun.* **2002**, 2376–2377.
- (64) Bjerrum, N. J.; Xiao, G.; Hjuler, H. A. (Statoil Research Centre). Process and Catalyst System for the Oxidation of Gaseous Hydrocarbons into Alcohols. World Patent 9924383A1, May 20, 1999.
- (65) Kuck, M. A. A Novel Process for the Oxychlorination of Ethane. U.S. Patent 3,987,118A, Oct 19, 1976.
- (66) Golden, D. M.; Benson, S. W. *Chem. Rev.* **1969**, *69*, 125–134.
- (67) Stewart, P. H.; Larson, C. W.; Golden, D. M. *Combust. Flame* **1989**, *75*, 25–31.
- (68) Stolarov, I. P.; Vargaftik, M. N.; Shishkin, D. I.; Moiseev, I. I. *J. Chem. Soc., Chem. Commun.* **1991**, 938–939.
- (69) Daehlie, G.; Kjekshus, A. *Acta Chem. Scand.* **1964**, *18*, 144–156.
- (70) Jansen, M.; Müller, R. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 255–256.
- (71) Dasent, W. E.; Waddington, T. C. *J. Chem. Soc.* **1960**, 3350–3356.
- (72) Conley, B. L.; Tenn, W. J., III; Young, K. J. H.; Ganesh, S. K.; Meier, S. K.; Ziatdinov, V. R.; Mironov, O.; Oxgaard, J.; Gonzales, J.; Goddard, W. A., III; Periana, R. A. *J. Mol. Catal. A: Chem.* **2006**, *251*, 8–23.
- (73) Schumacher, J. C. *Chem. Eng. Prog.* **1960**, *56*, 83–84.
- (74) Hawkins, M.; Andrews, L.; Downs, A. J.; Drury, D. J. *J. Am. Chem. Soc.* **1984**, *106*, 3076–3082.
- (75) Webb, J. R.; Burgess, S. A.; Cundari, T. R.; Gunnoe, T. B. *Dalton. Trans.* **2013**, *42*, 16646–16665.
- (76) Slaughter, L. M.; Wolczanski, P. T.; Klinckman, T. R.; Cundari, T. R. *J. Am. Chem. Soc.* **2000**, *122*, 7953–7975.
- (77) Walsh, P. J.; Hollander, F. J.; Bergman, R. G. *J. Am. Chem. Soc.* **1988**, *110*, 8729–8731.
- (78) *Handbook of Chemical Health and Safety*; American Chemical Society: Washington, DC, 2001.
- (79) American Chemical Society. Chemical Safety Practices & Recommendations. <http://www.acs.org/content/acs/en/about/governance/committees/chemicalsafety/safetypractices.html> (accessed March 15, 2014).
- (80) Hickey, D. M. B.; Leeson, P. D.; Novelli, R.; Shah, V. P.; Burpitt, B. E.; Crawford, L. P.; Davies, B. J.; Mitchell, M. B.; Pancholi, K. D.; Tuddenham, D.; Lewis, N. J.; O'Farrell, C. *J. Chem. Soc., Perkin Trans. 1* **1988**, 3103–3111.