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1-diphenylphosphinonaphthyl-8-triphenylstibonium triflate ([2][OTf]) was prepared in excellent yield by treating 1-lithio-8diphenylphosphinonaphthalene with dibromotriphenylstiborane followed by halide abstraction with AgOTf. This antimony(V) cation was found to be stable toward oxygen and water, and exhibited exceptional Lewis acidity. The Lewis acidity of [2][OTf] was exploited in the catalytic reductive coupling of a variety of aldehydes into symmetric ethers of type L in good to excellent yields under mild conditions using Et₃SiH as the reductant. Additionally, [2][OTf] was found to selectively catalyze the Aldol condensation reaction to afford α - β unsaturated aldehydes (**M**) when aldehydes with 2 α hydrogen atoms were used. Finally, [2][OTf] catalyzed the cyclotrimerization of aliphatic and aromatic aldehydes to afford the industrially-useful 1,3,5 trioxanes (**N**) in good yields, and with great selectivity. This phosphine-stibonium motif represents one of the first catalytic systems of its kind that is able to catalyze these reactions with aldehydes in a controlled, efficient manner. The mechanism of these processes has been explored both experimentally and theoretically. In both cases the Lewis acidic nature of the antimony(V) cation was found to promote these reactions.

Introduction

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The development of novel main group element-derived catalysts has entered into a renaissance in recent years.¹ While group 13 Lewis acids represent a well-established area of catalysis,² the emergence of group 15 reagents as catalysts has recently garnered much attention. In particular, Stephan^{3, 4} and Radosevich⁵ have utilized P(III) Lewis acids in a number of catalytic transformations, and more recently, Gabbaï and co-workers have investigated Sb(III) and Sb(V) species in sensing and catalytic applications.^{6, 7} Indeed, Gutmann and Olah have demonstrated that antimony-based Lewis acids rival traditional boron complexes.⁸ On the other hand, the corrosive nature of antimony halides such as SbCl₃ and SbCl₅,⁹ has led several groups to develop novel antimony(V) derivatives decorated by organic substituents. These Lewis acids have been shown to exhibit greater stability toward air and water.

Lewis acidic systems are also involved in several important organic and biochemical transformations, including organic substrates containing carbonyl moieties.¹⁰ For example, the synthesis of aliphatic or aromatic ethers, which are found in many useful natural products,¹¹ are valuable building blocks for fine chemicals, polymers and dyes,¹² relies primarily on the Williamson synthesis whereby an alkoxide is coupled to an alkyl halide/sulfonate under basic conditions.^{13, 14} However the large amount of chemical waste, specifically the salt byproduct,¹⁵ has been associated with environmental soil and ground water contamination.¹⁶ Alternative methodologies that involve the direct reductive homocoupling of aldehydes was recently reported using organosilicon reagents such as Et₃SiH, PhSiH₃, polymethosihydrosilane, (PMHS) and Me₃SiH. tetramethyldisiloxane (TMDS) as reducing agents in the presence of Lewis acid catalysts, including BiBr₃,¹⁷ I₂,¹⁸ Triflic acid,¹⁹ Cu(OTf)₂,²⁰ In(OTf)₃.²¹ However, these methods suffer from poor selectivity, substrate scope, and the catalysts are sensitive to air and moisture. The only example to date of such chemistry with antimony utilized Sbl₃,²² however the reaction was not catalytic in antimony, and the expensive reducing agent PhSiH₃ was needed.

Another important chemical transformation that involves the carbonyl moiety is the Aldol condensation reaction, used widely for the formation of C–C bonds.²³ The products of Aldol condensation reactions, α - β unsaturated carbonyl derivatives, are present in numerous biologically active compounds,²⁴ and find important applications in the fields of pharmaceutical, fragrance, plasticizer, detergent and cosmetic chemistry.²⁵ Typically, these reactions are performed under basic or acidic conditions²⁶ that are not environmentally friendly, owing to the higher concentration of corrosive by-products generated. More environmentally benign alternatives have been described in the literature including the use of pyrrolidine or benzoic acid,²⁷ or (p-dimethylamino)benzoate as cocatalyst for aliphatic aldehydes, ²⁸ diphenylboron perchlorate (Ph₂BClO₄), ²⁹ support,³⁰ secondary-amines immobilized on silica

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heteropolyacids,³¹ chlorinated silica gel,³² a solid Lewis basic catalyst containing aminopropyl-trimethoxysilanefunctionalized chitosan,³³ lysine,³⁴ and Et₃N-LiClO₄ activated by microwave irradiation.³⁵ In general, these synthetic methodologies are applicable to only a small range of systems that tolerate only very specific functional groups. Ideally, a selective, inexpensive, and effective catalyst with a broad substrate scope is still needed.

Additionally, the cyclotrimerization of aldehydes to form the correpsonding 1,3,5-trioxanes has become a highly-studied transformation as trioxanes play an important role in many industrial applications including stabilizers in color photography, burning regulators in fumigants, flavoring materials, carriers for scents, repellents, deodorants, and insecticides.³⁶ To date, there is a paucity of reports that describe the synthesis of these materials, and although moderate to high yields have been achieved,³⁷ there is much room for optimization as the selectivities of these systems are poor.³⁸ Recently, Findlater et al., demonstrated that FeCl₃ could selectively catalyze the Aldol condensation or cyclotrimerization of aldehydes under discrete, mild conditions.³⁹ Inspired by these recent results, we questioned if we could exploit the high Lewis acidity and relative stability of tetraaryl antimony(V) stibonium cations for the selective and catalytic transformations of aldehydes described above.

The use of naphthalene and acenaphthalene scaffolds for supporting group 15 moieties through peri-substitution continues to be an area of active investigation as these architectures position the main group elements in close proximity allowing for applications in molecular and anion exchange as well as catalysis.^{3, 40} Herein, we report the synthesis of an unknown phosphino-stibonium salt that is perisubstitued on a naphthalene framework ([**2**][OTf] = [Sb]⁺TfO⁻, Figure 1), and describe the ability of this cation to selectively catalyze the conversion of aldehydes into: symmetrical ethers L, (Figure 1, *Pathway II*), α - β unsaturated aldehydes M, (Figure 1, *Pathway III*).



Figure 1: Multiple transformation of aldehydes selectively catalyzed by the phosphiniostibonium cation [2][OTf].

The ability of $[2]^{+}$ to selectively catalyze these three independent transformation represents an important contribution to main group element-mediated catalysis and in particular to antimony chemistry.

Results and Discussion

Synthesis, Structures, and Properties

Two stibonium salts ([2][OTf] and [4][OTf]) were synthesized for this study using the straightforward protocol described in Scheme 1. The phosphino-stibonium salt, [2][OTf], was prepared in excellent yield (70%) by lithium-iodide exchange starting from the known compound, 1-iodo-8-(diphenylphosphino)naphthalene (1), followed by addition of dibromotriphenylstiborane to the in situ-generated lithium reagent. In a second step, the bromide counter anion was exchanged for triflate using silver(I) triflate. As a control study, the tetraarylstibonium cation [4][OTf] was prepared to determine if the diphenylphosphino substituent in $[2]^{\dagger}$ was necessary for the catalytic activity observed (vide infra). Similar to [2]⁺, [4][OTf] was prepared by lithium-bromide exchange starting from 1-bromonaphthalene followed by treatment with (Ph₃P)₃SbBr₂ followed by bromide abstraction with AgOTf. Both salts are highly soluble in polar organic solvents (i.e. chloroform, dichloromethane, and acetonitrile) and are completely insoluble in apolar hydrocarbons and ethers such as pentane and diethyl ether.



Scheme 1. Synthesis of stibonium salts [2][OTf] and [4][OTf].

phosphine-stibonium salt [2][OTf] The was fullv characterized by multinuclear NMR spectroscopy, DFT computational analyses, and single-crystal XRD, and the identity of [4][OTf] was confirmed by ¹H and ¹³C NMR spectroscopy (CDCl₃) as well as by elemental analysis (see ESI). Prior to the anion exchange step, intermediate [2][Br] was isolated, and a minor difference in the identity of [2][OTf] and [2][Br] could be observed by ¹H NMR (Figure 2, CDCl₃). Specifically, the ortho-protons of the diphenylphosphino moiety were shifted upfield by approximately 0.15 ppm in [2][OTf] when compared to [2][Br]. In addition, a small downfield shift was observed in the ³¹P NMR of [2][OTf] (-36.1 ppm) when compared to [2][Br] (-38.5 ppm). This small difference may be due to a weak interaction between the triflate anion and the cationic antimony center in solution.

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Figure 2: ¹H NMR spectra comparing [2][OTf] (top) to [2][Br] (bottom)

The most striking feature of the single crystal XRD structure of [2][OTf] (Figure 3), was the P1–Sb1 distance of 2.9138(11) Å which is well within the sum of the Van der Waals radii. This indicated to us that there is a strong interaction between the phosphorus and antimony centers owing to the high Lewis acidity of the cationic antimony atom. In agreement with this assessment, we note that the P1-Sb1-C21 angle of 170.18(14)° is consistent with donation of the phosphorus atom lone pair into a low-lying Sb1–C21 σ^* orbital. In addition, we noticed that the triflate counter ion is weakly coordinated to the P1-Sb1 unit as evidenced by the Sb1-O1 distance (2.812 Å), the O1-Sb1-C31 angle (166.8°), the P1-O1 distance (3.661 Å), and the O1-P1-C51 angle (158.6°). Even though it is clear that the cationic antimony center engages the oxygen atom of the triflate anion in a stronger interaction, the P1-O1 distance is and the O1-P1-C51 angle are consistent with a weak interaction between the anion and phosphorus atom. While we are uncertain if these unusual interactions persist in solution, they may be the source of the observed upfield chemical shift in the ¹H NMR of compound [2][OTf] when compared to [2][Br]. Despite our best efforts, single crystals of [2][Br] and [4][OTf] that were suitable for an X-ray diffraction could not be obtained to compare with to [2][OTf].



Figure 3: XRD Crystal structure of [2][OTf] (50% thermal ellipsoids, phenyl substituents have been drawn as thin lines for clarity). Pertinent metrical parameters are provided in the text.

To better understand the solid state structure, an natural bond order (NBO) analysis⁴¹ was performed on the crystal structure geometry of [**2**][OTf] (see ESI for full computational details). In agreement with the crystal structure, a donor acceptor interaction between a phosphorus lone pair and a

Sb– $C_{Ph} \sigma^*$ orbital (Figure 4A) was found in the NBQ output file. The energy of this interaction was best in a to be the state of the st approximately 23 kcal mol⁻¹ by using the NBO deletion protocol.⁴² We also found multiple interactions between the triflate oxygen O1 and the cation [2]⁺. Surprisingly, the two filled O1 p orbitals behave as donor orbitals to vacant σ^* Sb-CPh and P-CPh acceptor orbitals (Figure 4B and 4C). Collectively, these interactions were estimated to be approximately 10.6 kcal mol⁻¹ (NBO deletion) with the O1–Sb and the O1-P interactions accounting for ca. 9.3 and 1.3 kcal mol⁻¹, respectively. Close inspection of the natural charges on the P and Sb centers (0.97 and 1.89, respectively) indicates that the positive charge of the cation may be delocalized over the two group 15 elements. We ascribe this phenomenon to the differing catalytic properties of $[2]^+$ when compared to $[4]^+$ (vide infra).



Figure 4. NBO plots (isovalue 0.03) of A: $lp(P) \rightarrow \sigma^*(Sb-C_{Ph})$, B and C: four representative $lp(O) \rightarrow \sigma^*(Sb-C_{Ph})$ and $lp(O) \rightarrow \sigma^*(P-C_{Ph})$ donor-acceptor interactions.

Catalytic Activity Studies

We have explored the ability of the stibonium cations $[2]^+$ and $[4]^+$ to catalyze the reductive coupling of aldehydes (Figure 1, *Pathway I*), the Aldol condensation of aldehydes (Figure 1, *Pathway II*), and the cyclotrimerization of aldehydes(Figure 1, *Pathway III*). In general, it was found that cation $[2]^+$ was a superior catalyst when compared to $[4]^+$ in *Pathway I* and exhibited greater catalytic activity and selectivity. In contrast, both cations were found to be excellent catalysts for *Pathways II* and *III* (see ESI for specific results regarding cation $[4]^+$).

We initially explored the ability of $[2]^*$ or $[4]^*$ to catalyze the hydrosylilation of aldehydes with Et₃SiH, and used benzaldehyde as a model substrate. During the course of our work, Gabbaï and coworkers demonstrated that the bifunctional dication 1,2-[(Ph₂MeSb)₂C₆H₄]²⁺ catalyzed the hydrosilylation of benzaldehyde and 4-fluorobenzaldehyde, however they also showed that the monofunctional analogue [Ph₃SbMe]⁺ exhibited no catalytic activity.⁷ Interestingly, when 5 mol% of [2]⁺ was used as a catalyst, we did not observe the expected hydrosylilated species, benzyloxytriethylsilane (Ph-

 CH_2 -O-SiEt₃, **5**, *vide infra*), but instead found that dibenzyl ether (L₈) along with the symmetric siloxane ((Et₃Si)₂O) were the only products (Scheme 2). We have extended this reactivity to include a wide substrate scope including aliphatic, aromatic, and haloaromatic aldehydes (Table 1). For all cases, we found excellent catalytic activity and selectivity for the conversion of these aldehydes into the corresponding symmetric ethers (L). This method also allowed for the synthesis of the unknown ether, 3,3'-oxybis(methylene)-bis(fluorobenzene) (L₁₂) in good isolated yield.

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Scheme 2: Reductive coupling of benzaldehyde to afford ether L_8 catalyzed by $[\mathbf{2}]^*$ in $CH_2CI_2.$

From these results we have observed that $[2]^{\dagger}$ is a potent catalyst for both aliphatic and aromatic aldehydes, however longer reactions times were required to convert aromatic aldehydes into the corresponding ethers (Table 1, entries 8-15). The activity and the selectivity of this reaction suffered when aldehydes with aromatic substituents featuring strongly electron-withdrawing groups were used (Table 1, entries 9, 13, and 14). Indeed, pentafluorobenzaldehyde (entry 9) resulted in much lower selectivity for the formation of ether L₉ (50 %), and also required higher temperatures (70 °C) and longer reaction times. similar to ptrifluoromethylbenzaldehyde (entry 13) and pnitrobenzaldehyde (entry 14). Interestingly, when reactions with aliphatic aldehydes were heated, the selectivity for the formation of ethers L was lost and mixtures of unidentified products were observed by ¹H and ¹³C NMR. This loss of selectivity was not observed when reactions with aromatic aldehydes were heated. Catalyst [4][OTf] was also found to catalyze the reaction shown in Scheme 2 (ESI, Table S1). For butyraldehyde (entry 1, Table 1 and S1) [4]⁺ was found to catalyze the conversion to L_1 much faster than $[2]^+$. However, when bulkier aliphatic or aromatic aldehydes were used the selectivity of [4]⁺ for the conversion to the corresponding ethers L was found to be much lower (< 20%).

To further understand how the stibonium cation catalyzed the reaction shown in Scheme 2, we probed the interaction of various aldehydes with $[2]^+$ using ¹H NMR spectroscopy (CDCl₃). Unfortunately, when an excess benzaldehyde was treated with $[2]^+$ (3 mol%), we were unable to observe the formation of any intermediates in solution even when heating to 70 °C. In contrast, when a 3:1 solution of butyraldehyde:[2][OTf] in CDCl₃ was heated to 70 °C, the formation of an orange color and an upfield shift of the resonances corresponding to $[2]^+$ were observed (Figure 5). We attribute the observed upfield shift with lone-pair donation from the Lewis basic oxygen atom of the aldehyde into a Sb-C_{Ph} σ^* orbital that is localized on the Lewis acidic

Table 1. Substrate scope for t	he reductive	coupling of	aldehydes	toesiversymmetrie
ethers L.			DOI: 10.10	39/C6DT02121E

	$\mathbf{R}^{\mathbf{O}}$ + $\mathbf{E}t_3\mathbf{SiH}$ –	[2][OTf] 5mol% RT	→ R ^O L	∕ R + (Et ₃ S	i) ₂ O
Entry	aldehyde (R)	Time (h)	Product	Selectivity (%)	Yield ^{b(c)} (%)
1	$CH_2CH_2CH_3$	1	L1	100	100 ^e
2	(CH ₂) ₈ CH ₃	1	L ₂	100	100(90)
3	CH_2CH_2Ph	2	L ₃	100	100(90)
4	ⁱ Pr	1	L_4	100	100 ^e
5	CH(CH ₂ CH ₃) ₂	2	Ls	100	100(90)
6	cyclohexyl	1	L_6	100	100(90)
7	CH(Ph)₂	1	L ₇	80	90(70)
8	Ph	12	L ₈	100	100(90)
9	C_6F_5	48 ^d	L ₉	50	50 ^e
10	$2-Br-C_6H_4$	12	L ₁₀	100	100(50)
11	$3-Br-C_6H_4$	12	L ₁₁	100	100(50)
12	3-F-C ₆ H ₄	12	L ₁₂ (New)	100	100(70)
13	$4-CF_3-C_6H_4$	12 ^d	L ₁₃	100	100(90)
14	4-NO ₂ -C ₆ H ₄	24 ^d	L ₁₄	100	100(80)
15	$4-CH_3-C_6H_4$	12	L ₁₅	100	100(90)

(a) Reactions conditions: Aldehyde:Et₃SiH (1:3), RT, [2][OTf] (3 mol%), CH₂Cl₂. Yields: (b) Based on ¹H NMR (c) Isolated Yield after purification (in parenthesis), (d) reactions heated to 70° C. (e) Final products were compared with literature values but not isolated.





Figure 5: ¹H NMR spectra showing the interaction of butyraldehyde and stibonium salt [2][OTf] when mixed at 70°C in CDCl₃ (3:1 ratio).

When the solution shown in Figure 5 was heated for 12 hours, the butyraldehyde was found to disappear concomitant with the appearance of new peaks that corresponded to an olefin-containing product. The identity of this new compound was verified to be (*E*)-2-ethyl-2-hexenal by heating a solution of butyraldehyde in CDCl₃ to 70 °C for 12 hours in the

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presence of 3 mol% of $[2]^+$ (Figure 6). The conversion of butyraldehyde into (*E*)-2-ethyl-2-hexenal demonstrated that without the reducing agent Et₃SiH present, $[2]^+$ could also catalyze the Aldol condensation of aldehydes according to Figure 1, *Pathway II*.



Figure 6: ¹H NMR spectra showing the conversion of butyraldehyde into (*E*)-2-ethylhexenal, (M_1) over a period of 12h, using 3 mol% [**2**][OTf] in CDCl₃ at 70°C.

Substrate scope studies revealed that these reactions were limited to aldehydes with two α -hydrogen atoms, and suggested to us that steric bulk at the α -position may impede the formation of the intermediate β -hydroxy aldehyde Aldol product. Additionally, under our experimental conditions dehydration to the corresponding α , β -unsaturated aldehydes (**M**) as shown in Table 2 was observed exclusively. We were able to further optimize this reaction, and found that with lower catalyst loading (0.5 mol%) the same activity and selectivity for the formation of **M** was observed (Table 2). Importantly, after these reactions were completed, we were able to recycle the stibonium salt by the addition of hexanes to the reaction mixture which resulted in the precipitation of the catalyst and allowed for separation by decanting the supernatant solution.

The observed selectivity for the formation of the α , β unsaturated aldehydes over the β -hydroxy aldehydes is highly desired, and our catalytic system surpasses the majority of known systems reported in the literature which typically suffer from the production of mixtures of products.³⁸ Surprisingly, no difference in catalytic activity or selectivity was observed when these Aldol condensation reactions were catalyzed with **[4]**[OTf]. Indeed, when carried out under identical conditions to that of **[2]**⁺, Aldol condensation reactions catalyzed by **[4]**⁺ gave identical results. While we currently have no explanation for this observation, we believe that the highly Lewis acidic nature of the antimony(V) cationic center in these catalysts precludes any disparate reactivity between **[2]**⁺ and **[4]**⁺ that may arise due to the Ph₂P moiety in **[2]**⁺.

Previous reports have found that water plays important role in Aldol condensation reactions, and can serve to either

speed up the reaction or to improve selectivity, ^{14, 43} context, we have also found that water plays an important role the Aldol condensation reaction catalyzed by $[2]^{\dagger}$. Specifically, we believe that the water acts as a Lewis base in this reaction. Indeed, when these reactions were carried out under identical conditions, but in the presence of molecular sieves, the formation of the Aldol condensation product was suppressed from 100 to 6% (see ESI, Figure S4). These findings corroborated the need for water in the reaction, and from a mechanistic standpoint, suggested that water may act as a Lewis base in these reactions (vide infra). While it may also be possible that exogenous water may serve as a source of protons which may in fact catalyze Pathway II, we find this unlikely given the presence of the Lewis basic phosphino group in $[2]^{+}$. With that said, we have not been able to rule out this possibility at this time.

Table 2. Substrate scope for the Aldol condensation reactions catalyzed by [2][OTf] to give α , β -unsaturated aldehydes M.

2	O [2][OTf] 0.5 mol% 70 °C	0= R_1	M	Aldol pro intermed	OH OH liate
Entry	aldehyde (R)	Time (h)	Product	Selectivity (%)	Yield (%) ^{b/c}
1	CH ₂ CH ₂ CH ₃	24	M_1	100	100 (90)
2	(CH ₂) ₈ CH ₃	24	M_2	100	100 (90)
3	CH_2CH_2Ph	24	M_3	100	100 (90)
4	CH_2Ph	24	M ₄	100	100 (90)

(a) Reactions conditions: aldehyde, [2][OTf] (0.5 mol%) 70 °C, CH₂Cl₂. Yields:(b) Based on ¹H NMR, (c) isolated yield after column chromatography in parenthesis.

Inspired by recent work from Findlater *et al.*,³⁹ that demonstrated the ability of the Lewis acid FeCl₃ to catalyze the cyclotrimerization of aldehydes to give 1,3,5-trioxanes, we next questioned if our stibonium cations could similarly serve as catalysts for this transformation. Given that judicious water in the solvent favors the Aldol condensation reaction (*Pathway II*), whereas the presence of a reducing silane favors the formation of the symmetric ethers (*Pathway II*), we hypothesized that the removal of both the solvent and the reducing agent in these reactions may enhance the interaction of the aldehyde with the [Sb]⁺ center, and thus increase the electrophilic character of the acyl carbon.

Indeed, we found that treating the aldehydes shown in Table 3 (entries 1–7) with 1 mol% of [2][OTf] without solvent or Et_3SiH at-10°C resulted in the formation of the 1,3,5-trioxanes (**M**) according to the reaction shown in Table 3. In comparison to previous work from Findlater *et al.*,³⁹ water does not play an important role in this reaction, however the

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reversibility of the process is strongly temperature dependent, analogous with the previous finding that utilized $FeCI_3$ as the catalyst.³⁹ We further optimized this reaction and found that as low as 0.5 mol% loading of $[2]^+$ in an inert solvent such as hexamethyldisiloxane could catalyze the formation of trioxanes **N** at -10 °C (Table 3). We also found that higher temperatures favored the reverse reaction, and if the reaction was carried out at room temperature the conversion to **N** was negligible even in the presence of 5 mol% of $[2]^+$.

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Table 3. Substrate scope for the cyclotrimerization of aldehydes catalyzed by [2][OTf] to give 1,3,5-trioxanes N.

	3 R ₁	[2][OT 0.5 mo -10 °C	$ \begin{array}{c} f\\ f\\ c\\ c\\ R_1 \end{array} $	R ₁ D R ₁	
Entry	aldehyde (R)	Time (h)	Product	Selectivity (%)	Yield ^b (%)
1	$CH_2CH_2CH_3$	12 ^c	N ₁	100	90
2	(CH ₂) ₈ CH ₃	12	N ₂	100	90
3	CH₂Ph	12	N ₃	100	90
4	CH_2CH_2Ph	12	N 4	100	90
5	CH(CH ₂ CH ₃) ₂	12 ^c	N ₅ (New)	100	50
6	cyclohexyl	2 ^c	N ₆	100	90
7	CH(Ph) ₂	12 ^c	N ₇	90	70

(a) Reactions conditions: Aldehyde, [2][OTf] (0.5 mol%) , (Me₃Si)₂O, -10°C; (b) Isolated Yield after purification. (c) No solvent was used.

Even though the reaction can be performed under solvent free conditions, the solubility of $[2]^+$ in some of the viscous aldehydes (entries 1, 5, 6, and 7) was low and necessitated the addition of ~ 50 uL of $(Me_3Si)_2O$. The reaction is limited to aldehydes with 1 or 2 α -hydrogen atoms, but despite this limitation, we utilized this methodology to prepare the unknown trioxane, 2,4,6-tri(isopentyl)-1,3,5-trioxane (N_5). Similar to the Aldol condensation reaction, $[4]^+$ was also found to exhibit similar catalytic activity for the formation of the trioxanes N when compared to the phosphine-substituted cation $[2]^+$.

Computational Mechanistic Studies

To gain a further understanding into these reactions catalyzed by $[2]^+$, we have optimized the geometries of proposed intermediates that could potentially form in each reaction using density functional (DFT) methods. For these reactions, we propose three distinct catalytic pathways for each reaction that all stem from a single intermediate (denoted as A_c). Indeed, it was found that the interaction of the aldehyde oxygen atom with the cationic Sb(V) center (A_c),

was favorable by -6.2 kcal/mol (Scheme 5.) These calculations are in agreement with a recent review Prom 10 av s 3^{10} which claims that σ -donation from the aldehyde oxygen atom to the Lewis acidic atom is the most common mode of activation seen in main group Lewis acid catalysis.

Pathway I: This pathway details the proposed catalytic cycle for the formation of the symmetric ethers L (Scheme 3). The formation of intermediate Ac results in a more polarized C=O double bond and facilitates the addition of a Si-H bond across the C=O bond to give intermediate L_a which spontaneously releases $[2]^{+}$ to give hydrosylilated product L_{h} . The formation of L_b , was calculated to be exothermic by -32.1 Kcal/mol. Unfortunately we have not been able to observe L_b, however we have independently synthesized the hydrosylilated compound benzyloxytriethylsilane (5, see Figure 7a for ¹³C and ²⁹Si NMR, CDCl₃),⁴⁴ to determine if our experimental conditions resulted in the immediate conversion to ether L in the presence of another activated aldehyde species (A_c) as shown in Scheme 5. Interestingly when Et₃SiH was added to **5** in, the presence of $[2]^{\dagger}$ (5 mol%), no reaction was observed even upon heating. This suggested that the formation of intermediates of type A_c is critical to these reactions. Additional supportive evidence showed that the addition of benzaldehyde and Et_3SiH to **5** in the absence of $[2]^+$ did not afford dibenzyl ether (L₈).

To confirm that the hydrosilylated products (L_b) react with activated aldehyde complexes (A_c), we next treated **5** with benzaldehyde (**A**) and [**2**]⁺ (5 mol%) in the absence of Et₃SiH (Figure 7). This reaction was monitored by ¹³C and ²⁹Si NMR (CDCl₃). After a period of 12 h, the appearance of a new species (*****) was observed by ¹³C NMR (Fig 7b) with a peak at 105 ppm that is characteristic of a hemiacetal. The conversion of 5 into a new species was also observed in the ²⁹Si NMR with the disappearance the hydrosilylated product (21 ppm) and the appearance of a new signal at 9.8 ppm. This new signal was attributed to the formation of the siloxane (Et₃Si)₂O, which may have formed by hydrolysis of a silyl-hemiacetal precursor. The addition of a slight excess of Et₃SiH to this reaction resulted in the immediate formation of **L**₈ and (Et₃Si)₂O as shown by the crude ¹³C and ²⁹Si NMR (Figure 7c).

These results clearly demonstrated that once the hydrosylilated product L_b is formed, it may react immediately with A_c to form the hemiacetal L_d through L_c . However under our experimental conditions, we suggest that L_d is rapidly reduced by Et₃SiH to form the final symmetric ether L. Indeed, our computational studies revealed that this final reduction was exothermic by more than 30 kcal/mol (-40.5 for L_d, and -72.7 kcal/mol for L). The large exothermic nature of these steps may explain why we are unable to observe or isolate the hydrosilylated compounds L_b or hemiacetal derivatives L_d using our method. Importantly, we are currently investigating the potential for this methodology to be expanded toward the of unsymmetric ethers preparation starting from hydrosilylated compounds of type L_b and aldehydes.

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Scheme 3: Proposed mechanism for the catalytic transformation of aldehydes into symmetric ethers (*Pathway I*), α-β unsaturated aldehydes (*Pathway II*), and 1,3,5 -trioxanes (*Pathway III*). Numbers correspond to calculated DFT energies (kcal/mol).



Figure 7: ¹³C and ²⁹Si NMR spectra of: (a) benzyloxytriethylsilane (5), (b) the reaction of 5 with benzaldehyde (A) and [2][OTf] (5 mol%), and (c) the formation of dibenzyl ether (L₈) and hexaethyldisiloxane (S) upon addition of Et₃SiH. Spectra recorded at RT, CDCl₃.

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Pathway II: This pathway details the proposed catalytic cycle for the formation of the Aldol condensation products M (Scheme 3). In this pathway, we propose that the activated species A_c is isomerized to the enol derivative M_a in the presence water. Even though formation of the enol is uphill by 7.2 kcal/mol, we believe it to be largely favored over complete deprotonation of the aldehyde to give the enolate M_b as this species was calculated to be 32.6 kcal/mol higher in energy. The endothermic formation of enol $\boldsymbol{\mathsf{M}}_{\mathsf{a}}$ is also consistent with the need to heat these reactions (vide supra). Regardless M_a is sufficiently nucleophilic to add to another equivalent of the aldehyde in an exothermic reaction (-12.5 kcal/mol) to give the Aldol product M_c . Unlike A_c , M_c is more susceptible to tautomerization in the presence of water and is isomerized to M_d by an energetically favored process (-5.3 kcal/mol). We also calculated that the enol \mathbf{M}_{d} is enthalpically favored over the enolate M_e (-5.3 versus 19.1 kcal/mol) analogous to the M_a/M_b equilibrium. Instead, it was found that deprotonation of M_d by water favored elimination of the β -hydroxy substituent to give the α , β -unsaturated condensation product M. Our calculations also favored the formation of compound **M** over **M**_e by more than 30 kcal/mol.

Given that our calculations predicted that the formation of enol M_a was only slightly endothermic, we questioned if this enol could be used in a cross Aldol condensation reaction. To address this question, we treated butyraldehyde, an aldehyde with enolizable protons, with benzaldehyde, an aldehyde with no α -protons, in the presence of $[2]^+$ (0.5 mol%) at 70 °C (Scheme 4).



Scheme 4: Cross-Aldol condensation reaction catalyzed by [2][OTf] in CH₂Cl₂.

While we were able to successfully trap the purported enol of type **Ma**, formed from butyraldehyde, **[2]**⁺ and water, the major product obtained from this reaction was the butyraldehyde self-condensation product (M_1 , 80% yield) with only minor formation of the desired cross-condensation product (E)-2-benzylidenebutanal (M_5 , 20% yield), even in the presence of a large excess of benzaldehyde. To confirm these results, both compounds were isolated and fully characterized by NMR spectroscopy (see ESI, Figures S₅ and S₆). Despite the poor selectivity for the formation of M_5 , we believe that future optimization may be possible. We also plan to design and study second generation catalysts derived from $[2]^+$ as the direct coupling of aldehydes to afford symmetric and asymmetric products continues to be an important synthetic approach and current topic of interest in organic chemistry.^{38b,45}

Pathway III: This pathway details the proposed catalytic cycle for the cyclotrimerization of aldehydes to afford 1,3,5-trioxanes of type N (Scheme 3). As described earlier, we could favor the formation of 1,3,5-trioxanes by eliminating the

triethyl silane and suppressing the temperatureArtiof othe reaction. By avoiding these conditions, output and the second states and the second se analyses revealed that nucleophilic attack from another aldehyde on the acyl carbon atom of Ac to give the intermediate N_a is energetically favored by 11.0 kcal/mol. The computations also revealed a buildup of positive charge on one of the former acyl carbons in compound N_a as shown in Scheme 5. For this reason, the addition of a third aldehyde molecule to N_{a} followed by intramolecular cyclization to give the 1,3,5-trioxane coordinated to the cationic antimony center (N_b) is exothermic (-19.0 kcal/mol). Finally, the dissociation of the stibonium cation back into the catalytic cycle to release the free trioxane (N) was also found to be downhill by another 14.5 kcal/mol. These calculations are not only in good agreement with our optimized reactions conditions which demonstrated that these trioxanes could be readily prepared at low temperature, but also affirm that the reversibility of each step in this process could potentially hamper product formation at elevated temperatures.³⁹

Experimental

General Considerations

NOTE: Antimony compounds are potentially toxic and should be handled accordingly. Unless otherwise noted, these procedures were all carried out using typical Schlenk techniques under an atmosphere of nitrogen or in a nitrogenfilled glove box. Solvents were dried and degassed by an Innovative Technology solvent purification system and stored over a 3 Å molecular sieves in a nitrogen-filled glove box. Dichloromethane and hexanes were dried under nitrogen over CaH and Na/K, respectively and distilled prior to use. Aldehydes with 95 to 98% purity have been purchased either from Sigma Aldrich or Alfa Aesar and were used as received. material, 1-diphenylphosphino-8-The starting iodonaphthalene, was synthetized according to a literature report.⁴⁶ Melting points were recorded on a Mel-Temp apparatus in sealed capillary tubes and are uncorrected. All reagents were used as received. NMR spectra were recorded on Bruker Avance 400 MHz/52mm spectrometer. Chemical shifts (δ) are given in ppm and are referenced to the residual solvent: ¹H: 7.26 ppm; ¹³C: CDCl₃, 77.0 ppm; ³¹P NMR: H₃PO₄ 0 ppm. All column chromatography was performed using small columns (5 x 60 mm) with silica gel (Aldrich), 700-230 mesh, 60 Å, and pore volume of 0.75 cm^3/g as the stationary phase. Electrospray Ionization mass spectra were obtained on a Waters Synapt G2 ESI-Q-TOF mass spectrometer. Elemental analyses were performed at Midwest Microlabs, LLC (Indianapolis, IN).

Crystallography

All crystallographic measurements were carried out on a Rigaku Mini CCD area detector diffractometer using graphitemonochromated Mo K α radiation (λ = 0.71073 Å) at 223 K using an Oxford Cryostream low-temperature device. A sample of suitable size and quality was selected and mounted onto a

nylon loop. Data reductions were performed using Crystal Clear Expert 2.0. The structures were solved by direct methods, which successfully located most of the non-hydrogen atoms. Subsequent refinements on F_2 using the SHELXTL/PC package (version 5.1) allowed location of the remaining non-hydrogen. Colorless, single crystals of [2][OTf] were obtained by slow vapor diffusion of diethyl ether into a dichloromethane solution saturated with the compound. This compound crystallized in the monoclinic space group $P2_{1/n}$, and key details of the crystal and structure refinement data are summarized in Table S2. Further crystallographic details may be found in the respective CIF files which were deposited at the Cambridge Crystallographic Data Centre, Cambridge, UK. The CCDC reference number for [2][OTf] was assigned as 1453179.

Computational Details

All geometries were optimized using the M06⁴⁷ density functional method with LANL2DZ basis/pseudopotential for antimony and 6-31G(d,p) basis set for other atoms. Stationary points were characterized as minima by vibrational frequency analysis from the Hessian matrix. Solvent effect was included using the SMD implicit solvent model for dichloromethane. This method was chosen for geometry optimization since, the computed bond parameters of the catalyst [Sb]⁺ are in good agreement with the experimental values (Figure S 70). The further refined energies were using M06/6-31+G(2d,2p)[LANL2DZdp] electronic energies. All calculations were performed using Gaussian 09.48 In the catalytic Pathway II dimeric H₂O species was included, in order to correctly model the hydrogen bonding interactions and solvation effects of the hydronium ion and water molecules in the solution. Propanal was used as the model aldehyde in the computational study. The enthalpy energies in the main articles were reported in kcal/mol.

Synthetic Details

Synthesis of dibromo triphenylstiborane (Ph₃SbBr₂). A 250 mL Schlenk flask was charged with triphenylstibine (5 g, 14.16 mmol), 20 mL of diethyl ether, and a magnetic stirbar. Under and atmosphere of nitrogen, bromine (2.48 g, 0.80 mL, 15.57 mmol) diluted in 2 mL of ether was added drop wise. Immediately, the precipitation of a white solid was observed. After all of the bromine had been added, the reaction mixture was stirred for 30 minutes at room temperature, after which time mother liquor was decanted away from the resulting solid. The solid product was then washed with diethyl ether (5 x 50 mL), until the washings were colorless. No further purification was needed in subsequent reactions, and Ph₃SbBr₂ was isolated in 90% yield as a white solid. Spectroscopic data was in agreement with known values.⁴⁹

Synthesis of [2][Br]. A 100 mL Schlenk flask was charged with 1-diphenylphosphino-8-iodonaphthalene (1 g, 2.28 mmol) a magnetic stirring bar and 40 mL of tetrahydrofuran. The solution was degassed and cooled to -78 $^\circ$ C followed by the drop wise addition of nBuLi (2.2 M in hexanes, 1.55 mL, 3.42

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mmol). After the addition was completed, the solution was stirred for an additional 2 hours at -78 Ciduring Whith the the color became dark red. The reaction mixture was then cooled to -110 ° (LN₂/acetone slurry) and a solution of Ph₃SbBr₂ (1.28 g, 2.51 mmol) in THF (5 mL) was added drop wise. The resulting solution was stirred at -110 °C for two hours and was then allowed to warm to room temperature overnight. After that time the color of the solution turned to pale orange. The solvent was then removed in vacuo to yield a brown solid which was washed with a 1:3 DCM:hexanes solvent mixture (3 + 15 mL) to remove traces of any unreacted starting materials and salt byproducts. The residue then was dissolved in DCM and filtered over Celite. The filtrate was then concentrated to afford [2][Br] as a yellow solid in 70% yield which was used in the next step without further purification. Note: [2][Br] very air and moisture sensitive, and should be stored under an atmosphere of nitrogen at all times. m.p. 120-122°C. ¹H NMR (400 MHz) (CDCl₃): δ 6.56-6.61, 7.08-7.13, 7.3 (m, 10H, PPh), 7.44-7.88(m, 19H, SbPh + H₃ + H₄), 8.33-8.34(d, 1H, H₂, J = 8.4 Hz), 8.41-8.44(d, 1H, H₁, J = 8.4 Hz). ¹³C NMR (100.61 MHz): δ 128.85, 128.94, 129.81, 130.68, 131.95, 132.40, 132.53, 134.14. ³¹P NMR (161.9755 MHz) (CDCl₃): δ -38.50. Elemental analysis calculated (%) for C₄₂H₃₅BrCl₄PSb ([2][Br] + 2 (CH₂Cl₂)): C: 51.31, H: 3.38. Found: C: 51.42, H: 3.65. $C_{40}H_{31}PSb^{+}$ HRMS(ESI⁺) m/z: (M-Br) calculated: 663.1202. Found: 663.1201.

Synthesis of [2][OTf]. A 100 mL Schlenk flask was charged with [2][Br] (1 g, 1.34 mmol), silver(I) triflate (370 mg, 1.47 mmol), a magnetic stirring bar, and 50 mL of DCM. The flask was covered with aluminum foil and the reaction was stirred for 5 hours in the dark. The resulting suspension was then filtered over Celite to remove AgBr, and the filtrate was concentrated in vacuo to give a brown oily material that solidified after drying under high vacuum overnight (~80% yield). The resultant brown solid was further purified by dissolving in an excess of diethyl ether (5 mL) followed by the addition of hexanes (50 mL) to precipitate [2][OTf] as a white solid that is stable to air and moisture (700 mg, 65% yield). m.p. 94-96 °C ¹H NMR (400 MHz) (CDCl₃): δ 6.46-6.51, 7.06-7.10, 7.26-7.29(m, 10H, PPh), 7.43-7.84(m, 19H, SbPh + H₃ + H₄), 8.34(d, 1H, H₂, J = 8.4 Hz), 8.42, 8.44(d, 1H, H₁, J = 8.4 Hz). ^{13}C NMR (100.61 MHz): δ 128.93, 129.01, 130.94, 132.22, 132.29, 132.30, 132,56, 133.97, 133.98. ³¹P NMR (161.9755 MHz) (CDCl_3): δ -36.10. ^{19}F NMR (376.49 MHz): δ -78.50(triflate). Elemental analysis calculated (%) for C_{42.2}H_{33.4}F₃O₃PCl_{2.4}SSb ([**2**][OTf] + 1.2 CH₂Cl₂): C: 55.37, H: 3.68. Found: C: 55.29, H: 3.61. C₄₀H₃₁PSb⁺ HRMS(ESI⁺) m/z: (M-OTf) calculated: 663.1202. Found: 663.1201.

Synthesis of [4][OTf]. A 100 mL Schlenk flask was charged with 1-bromonaphthalene (500 mg, 2.4 mmol) a magnetic stirring bar and 40 mL of tetrahydrofuran. The solution was degassed and cooled to -78 $^{\circ}$ C followed by the drop wise addition of nBuLi (2.2 M in hexanes, 2.41 mL, 5.31 mmol). The resulting solution became dark and was stirred for 2 hours at -78 $^{\circ}$ C after which time Ph₃SbBr₂ (1.36 g, 2.65 mmol) in THF (5 mL) was added drop wise. The solution was allowed to warm to room temperature overnight and the color changed from

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pale yellow to colorless. The reaction mixture was concentrated in vacuo to afford an oily material that was washed with a 1:3 DCM:hexanes solvent mixture (3 x 15 mL). The residue was then dissolved in DCM (50 mL) and then filtered over Celite. The filtrate was then concentrated to dryness to give a white semi-solid material which was used without further purification. The solid was then dissolved in DCM (40 mL) and the solution was transferred to a 100 mL Schlenk flask that was wrapped in aluminum foil. To this solution was added AgOTf (510 mg, 1.96 mmol) and the resulting suspension was allowed to stir at room temperature for 12 hours. The suspension was then filtered over Celite and the filtrate was concentrated to dryness in vacuo to give a brown oily material which was washed with cold hexanes to give a white solid. After drying under high vacuum overnight, [4][OTf] was obtained as a white solid that is stable to air and moisture (1.06 g, 70% yield). m.p.90-92°C. ¹H NMR (400 MHz) (CDCl₃): δ 7.53-7.57, 8.10-8.14, 8.30-8.35(m, 3H, H₁, H₂, H₅), 7.63-7.84(m, 19H, ShPh + H_3+H_4). ¹³C NMR (100.61 MHz): 127.66, 129.23, 130.95, 131.35, 131.73, 133.43, 133.86, 135.52, 135.57. ¹⁹F NMR(376.4983 MHz) : δ -78.30(triflate). Elemental analysis calculated (%) for: C₃₁H₂₆F₃O₃SCl₄Sb ([4][OTf + 2(CH₂Cl₂)): C: 46.59, H: 3.28. Found: C: 46.07, H: 2.80. $C_{28}H_{22}Sb^{\dagger}$ HRMS(ESI^{\dagger}) m/z: (M-OTf) calculated: 479.0760. Found: 479.0760.

Conclusions

We have synthesized two unknown stibonium triflate salts, [2][OTf] and [4][OTf], and have demonstrated for the first time that these cations can serve to catalyze: 1) the reductive coupling of aldehydes to give symmetric ethers (L), 2) the Aldol condensation of aldehydes to give α - β unsaturated compounds (M), and 3) the cyclotrimerization of aldehydes to the corresponding 1,3,5-trioxanes (N). Spectroscopic and computational data have revealed that the highly Lewis acidic cationic antimony(V) center engages the Lewis basic oxygen atom of these aldehydes in a strong interaction which ultimately polarizes the C=O bond.

We have evidence which suggested that a transient hydrosylilated product L_b is involved in the formation of ethers L. These results may provide synthetic chemists with new opportunities for the preparation of asymmetric ethers. Likewise we have also determined that water plays an important role in the Aldol condensation reation catalyzed by $[2]^+$ or $[4]^+$. We have also explored the potential for $[2]^+$ to catalyze cross-Aldol condensation reactions, however at this time the selectivity for the crossed product needs improvement. Despite this limitation, we have also found that 1,3,5-trioxanes can be readily produced at low temperature free from solvent, or in the presence of inert solvents such as $(Me_3Si)_2O$, but lower temperatures are required to tune the selectivity and increase the reactivity of the process.

For the latter two reactions, there was no apparent difference in catalytic activity or selectivity between cations $[2]^+$ and $[4]^+$. However, it was found that cation $[2]^+$ was a far superior catalyst in terms of both activity and selectivity for

the preparation of ethers L when compared Ate $\mathbf{A}_{\text{A}}^{\dagger}$ Unfortunately, the computational analyses $\mathbf{A}_{\text{A}}^{\dagger}$ to $\mathbf{A}_{\text{A}}^{\dagger}$ Unfortunately, the computational analyses $\mathbf{A}_{\text{A}}^{\dagger}$ to $\mathbf{A}_{\text{A}}^{\dagger}$ as a catalyst did not reveal any informative data regarding the presence of the diphenylphosphino moiety. While it may be possible that sterics lie at the heart of the selectivity difference observed between $[\mathbf{2}]^{\dagger}$ and $[\mathbf{4}]^{\dagger}$, we can't rule out the possibility that the phosphine substituent may impart ulterior electronic effects which ultimately govern the formation of the product. Current investigations are guided toward a more detailed mechanistic understanding how of these stibonium cations interact with carbonyl-containing substrates.

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