Hypervalent Iodine

Synthesis and Structural Verification of an ArI(OTf)$_2$, NO$_2$-Ph-I(OTf)$_2$**

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Abstract: PhI(OTf)$_2$ and related ArI(OTf)$_2$ species have been incorrectly invoked as intermediates in oxidation reactions for many years. We recently established that such compounds did not yet exist but remain an attractive target. Here we describe the synthesis, isolation, and structural characterization of NO$_2$-PhI(OTf)$_2$, which is resistant to decomposition and more reactive than PhI(OTf)(OAc), the species previously misidentified as PhI(OTf)$_2$.

PhI(OTf)$_2$ is an I^{III} species that was first proposed to be a discrete species by Zhdankin and co-workers in 1989.[1] In the 2010s, as part of the renaissance in hypervalent iodine chemistry,[2] what was purported to be PhI(OTf)$_2$ saw increased use as a versatile oxidant in organic chemistry including synthesis of hydrazones,[3] diazeniums,[4] functionalized cyclopropane rings,[5] the cyclization of hydroxy stilbenes or carboxylic acids,[6] the functionalization of acetylenes,[7] aryl C–H alkylations,[8] oxyaminations,[9] alpha arylations[10] and oxidative coupling of NHCs.[11] The most common synthetic pathway to what was thought to be PhI(OTf)$_2$ is from commercially available PhI(OAc)$_2$, followed by addition of 2 equivalents of TMS-OTf, typically as an in situ reaction (Scheme 1). Other than in Zhdankin's original paper indicating PhI(OTf)$_2$ to be a reactive oil, using PhI=O and 2 TMS-OTf, no isolation has been reported. Wirth discussed spectroscopic characterization of the reaction mixture of PhI(OAc)$_2$ and 2 TMS-OTf and concluded that ^{1}H VT NMR experiments at −40°C were consistent with PhI(OTf)$_2$, although incomplete consumption of TMS-OTf is evident.[9] In 2015 our group found that reaction of "PhI(OTf)$_2$" with 2,5-diphenyltellurophene unexpectedly gave a mixed Te^{IV}(OTf)(OAc), leading us to re-examine the reaction mixture from PhI(OAc)$_2$ and 2 TMS-

OTf and concluded that the reaction stopped at one meta-thesis, yielding in actual fact PhI(OAc)(OTf).[12] This molecule was structurally confirmed as an isolable species by Shafir and co-workers in 2016.[13] Despite these reports, descriptions of PhI(OTf)$_2$ arising from PhI(OAc)$_2$/2 TMS-OTf continued to appear in the literature, including invoking PhI(OTf)$_2$ in detailed calculated reaction mechanisms/pathways.[8,10] These calculations can require a great deal of time and effort, thus it is critical the correct actual molecules are used. In 2020 we published a more detailed analysis using computational and synthetic techniques, making the conclusion that "PhI(OTf)$_2$ does not exist (yet)",[14] including an examination of Zhdankin's original report. For Zhdankin's synthesis from PhIO and 2 TMS-OTf, we found that while the transformation was calculated to be energetically feasible with a ΔG of −41 kJ mol^{-1}, the main observed product was the diphenyl iodonium cations, apparently arising from some electrophilic aromatic substitution (EAS) process. A phenyl containing intermediate could be detected in the ^{1}H NMR prior to generation, but the signals were upfield from those in PhI(OAc)(OTf), and not consistent with PhI(OTf)$_2$. For PhI(OAc)$_2$ and 2 TMS-OTf, in addition to reconfirming the NMR data as consistent with PhI(OAc)-(OTf) we calculated a ΔG for the first metathesis reaction giving PhI(OAc)(OTf) to be favourable with a ΔG of −67 kJ mol^{-1}, but the second metathesis giving PhI(OTf)$_2$ to be unfavourable by 30 kJ mol^{-1}.

In 2020 a study on the one and two electron oxidative capacity of PhIL$_2$ species found that L=OTf gave by far the strongest oxidation potentials of the ligands considered making ArI(OTf)$_2$ a highly desirable target.[15] In this report we describe achieving a strategy to shut down this decomposition pathway, allowing for the synthesis, isolation and structural characterization of a genuine ArI(OTf)$_2$.

Our strategy to achieve an ArI(OTf)$_2$ involved a 2-pronged approach, in which we attempted to shut down decomposition by EAS (as observed via Zhdankin's pathway) and achieve a complete substitution of ligands on the iodine to triflate (which does not occur in the case of PhI(OAc)$_2$/2 TMS-OTf). For the second goal it was decided to take advantage of the high Si–F bond strength and use ArIF$_2$ precursors in conjunction with TMS-OTf. For suppressing EAS, we initially attempted blocking the reactive C–H positions with methyl groups. ArIF$_2$ precursors were known for the parent phenyl, *p*-tolyl and 2,4,6-trimethyl derivatives. Several syntheses of these have been reported, we employed Selectfluor in conjunction with corresponding iodoarenes,[16] and also used this method for the unknown pentamethyl substituted derivatives.

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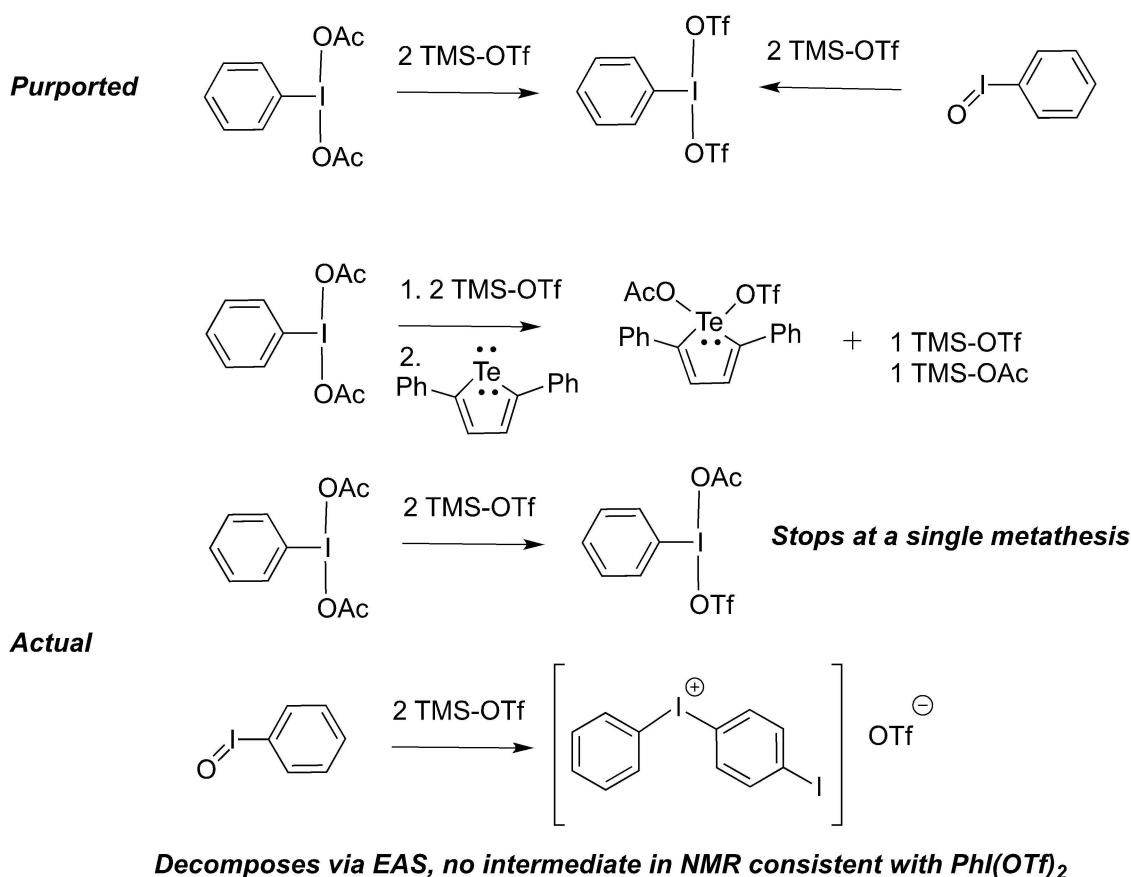
Scheme 1. Historically claimed syntheses of PhI(OTf)$_2$ and the findings from our lab on those syntheses.

When PhIF$_2$ was reacted with 2 equivalents of TMS-OTf in CD$_2$Cl$_2$, ^{19}F and ^{1}H NMR showed complete consumption of PhIF$_2$ and the generation of a mixture, from which PhI, HF, TMS-F and unconsumed TMS-OTf could be identified, as well as other phenyl containing products. Mass spectrometry revealed the presence of iodonium cation [Ph-I-Ph-I]$^+$ (Scheme 2), unsurprising given our previous results replicating Zhdankin's 1989 work.[1,14] Stang has reported that PhIF$_2$ in conjunction with TMS-OTf gives a transient PhIF(OTf) species,[17] which is an excellent source of the [PhI]$^+$ cation, consistent with our observations. Blocking the most reactive *para* position with a methyl group and repeating the procedure gave identical results, except that the EAS reaction occurred at the *ortho* position of the ring. Blocking the *ortho* and *para* positions resulted in EAS at the least activated *meta* position of the ring. Finally, when all positions were blocked, mass spectrometry indicated the primary organic fragment to be [Ar-I-Ar]$^+$, where a C–I bond has been apparently cleaved. This species was also present in the reaction with the tolyl derivative. We have not been able to determine a mechanism for the later transformation, but overall, this set of results indicated that blocking the C–H positions with methyl groups did not sufficiently suppress decomposition via EAS processes.

The next strategy to suppress EAS was to synthesize a derivative with a deactivating group, for which *p*-nitro was chosen, targeting NO$_2$-PhIF$_2$ as the starting material. This

compound was previously reported using a 4 step synthesis involving use of gaseous Cl$_2$ and aqueous HF.[18] We accessed NO$_2$-PhIF$_2$ from NO$_2$-PhI(OTFA)$_2$, which was in turn synthesized from NO$_2$-PhI, HOTFA and Oxone using a procedure adapted from Zhdankin.[19] NO$_2$-PhIF$_2$ could then be easily generated via addition of Olah's reagent, pyridinium-HF in HF,[20] to NO$_2$-PhI(OTFA)$_2$. NO$_2$-PhIF$_2$ presents greatly improved stability and handling properties compared to the other ArIF$_2$ species described above, for which the syntheses are tedious, poor yielding and in our hands, readily decompose. The structure, which was previously unreported, was confirmed via X-ray crystallography. The solid is however very hygroscopic and it proved difficult to remove all traces of water, even under vacuum at 60 °C overnight, attempting to use higher temperatures started to induce decomposition. Alternatively, NO$_2$-PhIF$_2$ can be generated in an anhydrous manner in the glovebox from NO$_2$-PhI and XeF$_2$ with the reaction in CH$_2$Cl$_2$ initiated by catalytic TMS-OTf.

The reaction of NO$_2$-PhIF$_2$ (generated via Olah's reagent) with 2 equivalents of TMS-OTf in CDCl$_3$ led to rapid dissolution of the semi-soluble NO$_2$-PhIF$_2$ to receive a clear solution with a yellow precipitate. In the ^{1}H NMR spectrum 2 sets of signals consistent with NO$_2$-Ph-X fragments were apparent. In the ^{19}F NMR spectrum complete consumption of NO$_2$-PhIF$_2$ was observed with generation of TMS-F and 2 peaks in the region around −78 ppm where
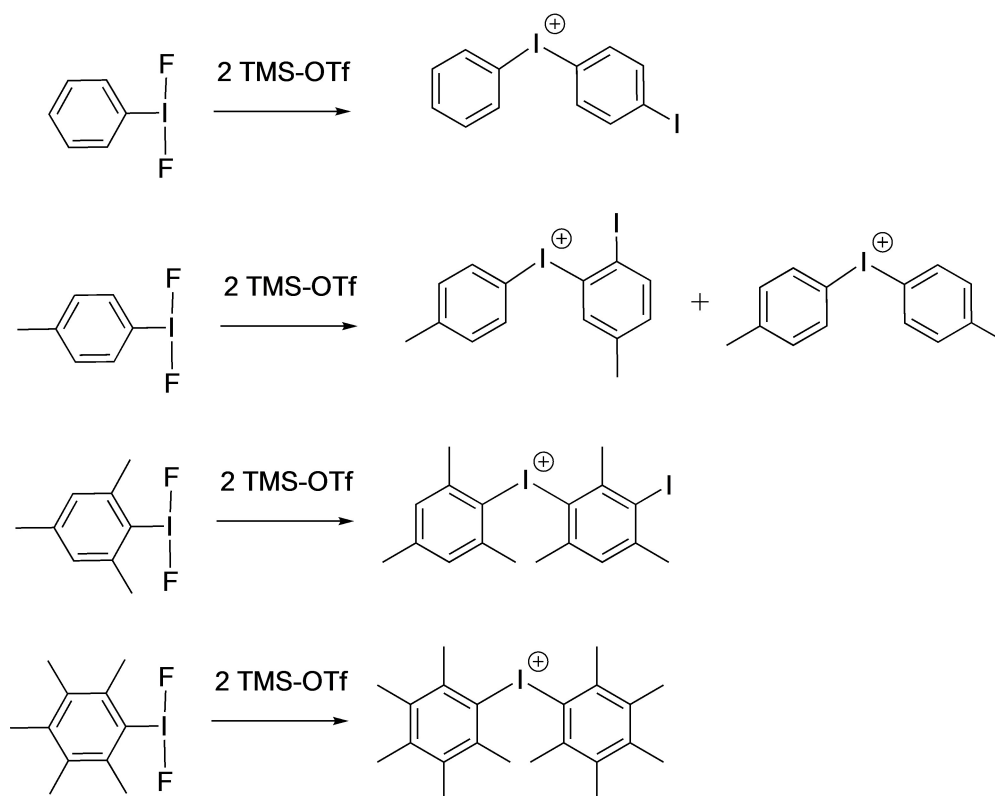
Scheme 2. Results from TMS-OTf metathesis on methyl substituted Ar-IF$_2$ species.

triflate fragments arise. Solvent removal in vacuo and reuptake of the residue in CDCl$_3$ bared a species bearing one set of NO$_2$-Ph-X signals and one ^{19}F chemical shift at −75.3 ppm, consistent with covalently bound triflate, where a more ionic triflate is found up field between −78 and −79 ppm.[21] The protons in the phenyl ring were 0.18 and 0.40 ppm downfield from the respective signals in the NO$_2$-PhIF$_2$ starting material. Single crystals were grown in the glovebox freezer via vapour diffusion at −35 °C (CH$_2$Cl$_2$: pentane) and X-ray studies confirmed the species as the targeted bistriflate complex NO$_2$-PhI(OTf)$_2$, obtainable in 92 % yield (Scheme 3). The crystals decomposed within 30 seconds of transfer from the vial into n-paratone oil at room temperature and we also experienced destroyed nylon Cryoloops during transfer from the oil onto the Goniometer

head. Decomposition ceased once inside the 150 K stream of N$_2$.

The other, CDCl$_3$ insoluble compound precipitated in crystal quality and X-ray studies showed it to be the -NO$_2$ analogue of Zefirov's reagent.[22] We believe this arises from the residual moisture in the starting NO$_2$-PhIF$_2$ starting material as addition of 2 μL of water to a solution of NO$_2$-PhI(OTf)$_2$ in CD$_2$Cl$_2$ resulted in immediate conversion to the Zefirov's analogue (Scheme 4). If the NO$_2$-PhIF$_2$ synthesized from XeF$_2$ is used no Zefirov's analogue is observed in the reaction with TMS-OTf.

The I–O bond lengths in NO$_2$-PhI(OTf)$_2$ are 2.142(4) and 2.145(4) Å (Figure 1). These can be compared to the I–O bond lengths in the mixed PhI(OAc)(OTf) species determined by Shafir and co-workers which contained an
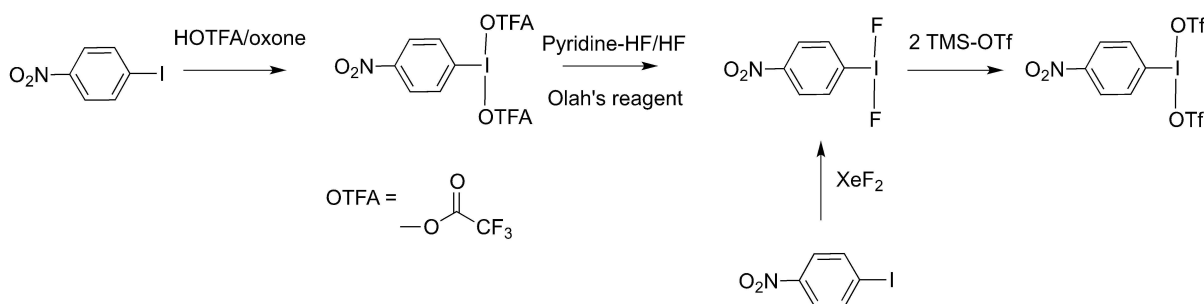
Scheme 3. Synthetic pathway to NO$_2$-PhI(OTf)$_2$.
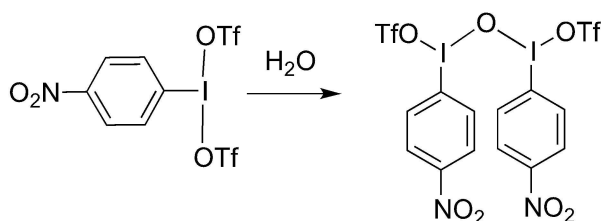
Scheme 4. Reaction of NO$_2$-PhI(OTf)$_2$ with water giving the -NO$_2$ analogue of Zefirov's reagent.

I–O bond to the triflate of 2.347 Å and to the acetate of 2.056.[13] This indicates a much tighter association for the triflate to the iodine in NO$_2$-PhI(OTf)$_2$ than PhI(OAc)-(OTf); consistent with the strongly downfield ^{19}F NMR chemical shift for NO$_2$-PhI(OTf)$_2$ of −75.3 ppm compared to PhI(OAc)(OTf) at −78.5 ppm.[11] The strong association is also reflected in the S–O bonds, with an elongation to the O that is bound to iodine and a shortening of the other S–O bonds. The I–C bond is 2.103(5) Å, slightly elongated from 2.088 reported for PhI(OAc)(OTf). There is a long contact at 2.896 Å between the iodine and an unbound oxygen of the triflate from a neighbouring molecule in the solid state.

An examination of the electronic properties of NO$_2$-PhI(OTf)$_2$ via theoretical methods was undertaken. We had previously found that the method wPBE/def2TZVP does a better job modelling the geometry of bound triflate than other common methods,[14] so this has been used here. The geometry optimization for NO$_2$-PhI(OTf)$_2$ closely matches the X-ray structure.

In terms of the thermodynamics of NO$_2$-PhI(OTf)$_2$ generation from NO$_2$-PhIF$_2$, using TMS-OTf, unlike PhI-(OTf)$_2$ for which the second metathesis from PhI(OTf)-(OAc) is unfavourable, from NO$_2$-PhI(OTf)$_2$ the first metathesis to give NO$_2$-PhIF(OTf) is favourable with a ΔG of −23 kJ mol^{-1} and the second giving NO$_2$-PhI(OTf)$_2$ is also favourable at −16 kJ mol^{-1}. It should be noted that calculations using NO$_2$-PhI(OAc)$_2$ as a starting material indicate the same situation as from PhI(OAc)$_2$, in that the first metathesis is favourable at −13 kJ mol^{-1}, while the second is not at +23 kJ mol^{-1}. From PhIF$_2$, calculations indicate both metatheses are favourable with the first giving PhIF(OTf) at −34 kJ mol^{-1} and the second to PhI(OTf)$_2$ at −16 kJ mol^{-1}. Combined, these calculations together with the experimental observation of [Ph-I–Ph-I]$^+$ with one equivalent of TMS-OTf remaining unreacted in the reaction of PhIF$_2$ and 2 TMS-OTf, suggesting that PhIF(OTf) decomposes before reacting with the second equivalent of TMS-OTf, indicates that the -NO$_2$ group does not provide any key driving force for the metathesis, but rather prevents the EAS decomposition pathway.

The LUMO is responsible for the electrophilic/oxidative behaviour of this class of compound. The nature and energy of the LUMO of NO$_2$-PhI(OTf)$_2$ was compared to known PhI(OAc)(OTf) and non-existent PhI(OTf)$_2$ (Figure 2). The general features of the LUMO are the same in all 3 molecules, with σ antibonding character between the iodine and oxygen atoms and π antibonding character in the aryl ring. The LUMO for NO$_2$-PhI(OTf)$_2$ is 1.26 eV lower in energy than PhI(OAc)(OTf) and 0.48 eV lower in energy than PhI(OTf)$_2$, suggesting incorporating the electron withdrawing -NO$_2$ makes it a better oxidizing agent than

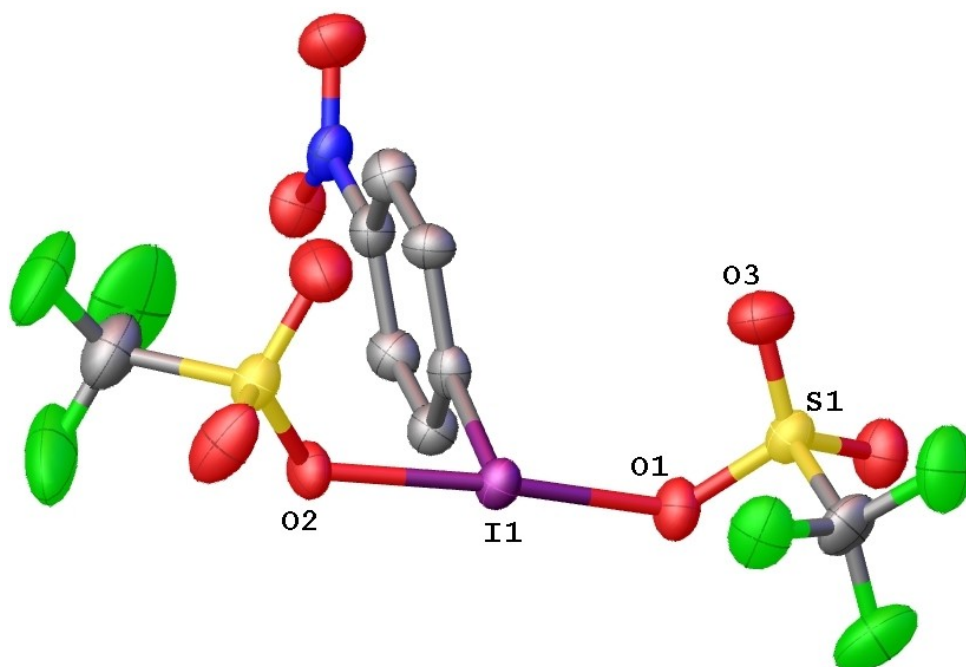**Figure 1.** Solid state structure of NO$_2$-PhI(OTf)$_2$. Ellipsoids are depicted at the 50% probability level. Selected bond lengths (Å): I(1)-O(1) 2.142(4), I(1)-O(2) 2.145(4), S(1)-O(1) 1.525(4), S(1)-O(3) 1.406(6).[25]
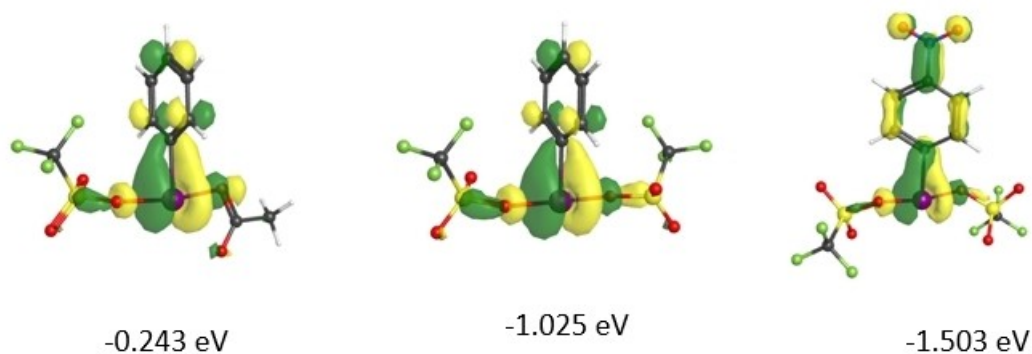
Figure 2. LUMOs for PhI(OTf)(OAc), PhI(OTf)$_2$ and NO$_2$-PhI(OTf)$_2$.

unstable PhI(OTf)$_2$ while shutting down the key decomposition pathway. The LUMO is more delocalized into the aryl ring and the nitro group than in the other 2 derivatives.

As an initial test for the potential reactivity of NO$_2$-PhI(OTf)$_2$ we sought a system that was oxidizable and known to accommodate 2 triflates. Burford reported the antimony(V) compound Ph$_3$Sb(OTf)$_2$ as an intermediate for the synthesis of pyridine stabilized Sb^V dications.[23] Burford accessed the compound via chloride abstraction from Ph$_3$SbCl$_2$, we envisioned that it could be reached via reaction of NO$_2$-PhI(OTf)$_2$ with Ph$_3$Sb. The reaction was carried out in CD$_2$Cl$_2$. ^{1}H NMR spectroscopy of the reaction mixture showed immediate reduction of NO$_2$-PhI(OTf)$_2$ into NO$_2$-PhI and conversion of Ph$_3$Sb into Ph$_3$Sb(OTf)$_2$ which was confirmed by observation of resonances identical to those

reported by Burford for Ph$_3$Sb(OTf)$_2$ in both the ^{1}H and ^{19}F NMR spectra, demonstrating oxidative behaviour and delivery of both triflates from NO$_2$-PhI(OTf)$_2$ (Scheme 5).

With this result in hand, we targeted a less trivial example, the Te^{IV}(OTf)$_2$ analogue of 2,5-diphenyltellurophene, a compound we have been previously unable to synthesize via metathesis from Te^{IV}X$_2$ species where X$=$F, Cl, OAc. It has been shown the Te^{II}/Te^{IV} redox couple can be used to access interesting properties of tellurophene containing materials/materials precursors,[24] and a bis-triflate could offer a good entry point to generating a variety of Te^{IV} analogues by virtue of triflate being an excellent leaving group. NO$_2$-PhI(OTf)$_2$ was reacted with 2,5-diphenyltellurophene in CH$_2$Cl$_2$ solvent resulting in a deep red solution. After work-up a red crystalline material was
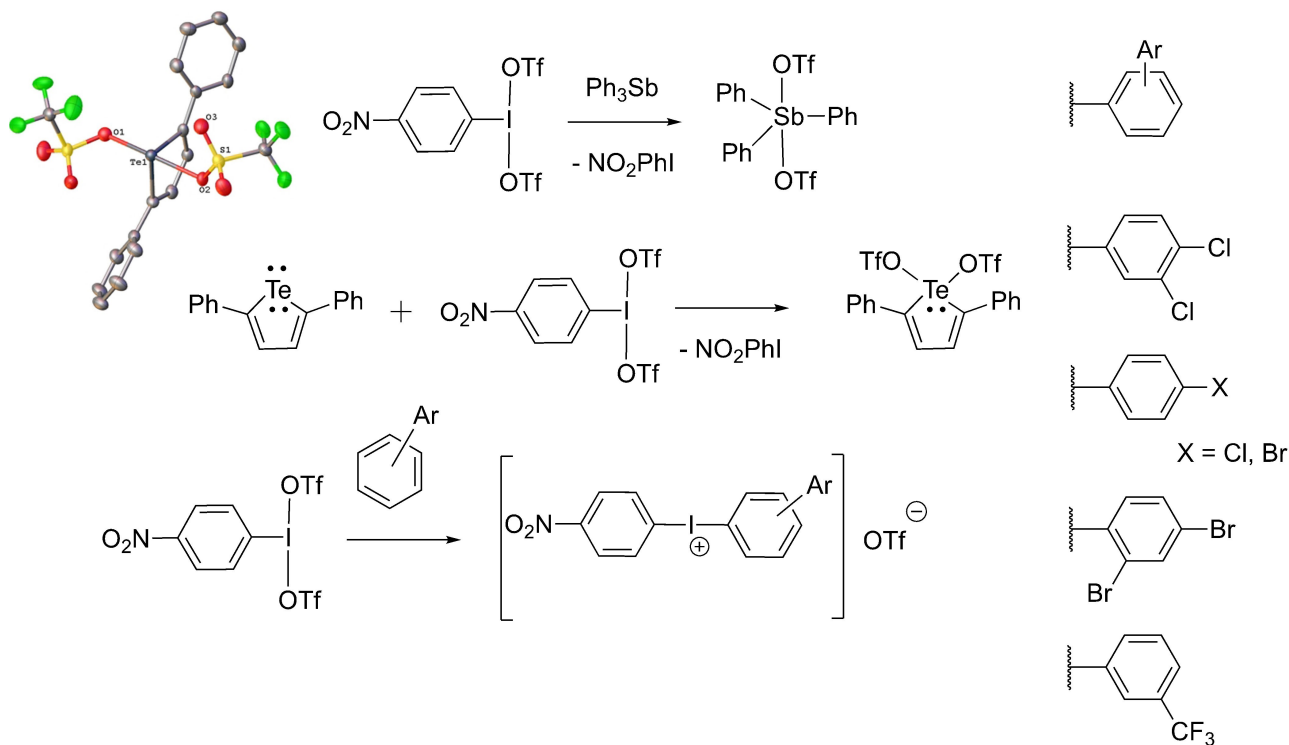
Scheme 5. Preliminary reactivity studies on NO$_2$-PhI(OTf)$_2$.

obtained, ^{1}H NMR in CDCl₃ showed a new tellurophene species where the ^{1}H signals in the backbone were shifted downfield 0.1 ppm from the starting tellurophene. [125]Te NMR returned a chemical shift of 1024 ppm, downfield of both the Te[IV] bisacetate (683 ppm) and mixed acetate/triflate species (900 ppm) we have previously reported.[12] The structure as the Te[IV]-bistriflate was confirmed by X-ray crystallography, demonstrating that NO_2-$PhI(OTf)_2$ can be used to generate previously inaccessible high oxidation state bis-triflate species.

Intermediates in attempts on the way to $PhI(OTf)_2$ are susceptible towards EAS as a mode of decomposition as discussed above and $PhI(OAc)_2$ that is activated by BF_3 can be used as a substrate in EAS with mesitylene.[13] We have found $PhI(OTf)(OAc)$ does not react with benzene, and as a test to show the increased electrophilicity of NO_2-$PhI(OTf)_2$ it was reacted with more deactivated *o*-dichlorobenzene in CH_2Cl_2 for 30 minutes. After workup, the ^{1}H NMR showed the formation of a product consistent with generation of an iodonium cation substituted at the 3-position. Mass spectrometry of the solution returned a spectrum dominated by a cation at *m/z* 393.9, consistent with (3,4-dichlorophenyl)-(4-nitrophenyl)iodonium, which was isolated in a 67% yield. This result shows a clear increase in the reactivity of NO_2-$PhI(OTf)_2$ over $PhI(OTf)(OAc)$, the regularly misidentified compound. Extending the scope, we found successful reactions occurred with bromobenzene, chlorobenzene, 1,3-dibromobenzene and benzotrifluoride, all relatively deactivated arenes. No reaction occurred with nitrobenzene or *p*-nitroiodobenzene showing there is a limit, although the no reaction with *p*-nitroiodobenzene is a positive feature, in that as decomposition slowly occurs NO_2-$PhI(OTf)_2$ is not then prone to react with resultant *p*-nitroiodobenzene.

In conclusion, a genuine $ArI(OTf)_2$ has been synthesized. Not only can it be observed, but can be isolated, stored and structurally characterized. Its electronic properties suggest it should be a significantly more powerful oxidant than the $PhI(OAc)(OTf)$ which has been used as "$PhI(OTf)_2$". Preliminary reactivity studies suggest it is indeed more reactive. We look forward to developing its chemistry and encourage others to explore its chemistry as an oxidant in inorganic and organic applications.

Our successful synthesis and isolation of a genuine $ArI(OTf)_2$, a species we once believed to not exist, leads us to propose that deactivated nitro substituted phenyl rings could be utilised to revisit other ArI(III) species that were previously only observable or implicated by means of computation, spectroscopy, or reactivity.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available in the Supporting Information of this article.

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[25] Deposition Number 2205934 contains the supplementary crystallographic data for this paper. These data are provided free of charge by the joint Cambridge Crystallographic Data Centre and Fachinformationszentrum Karlsruhe Access Structures service.