

On the Route to the Photogeneration of Heteroaryl Cations. The Case of Halothiophenes

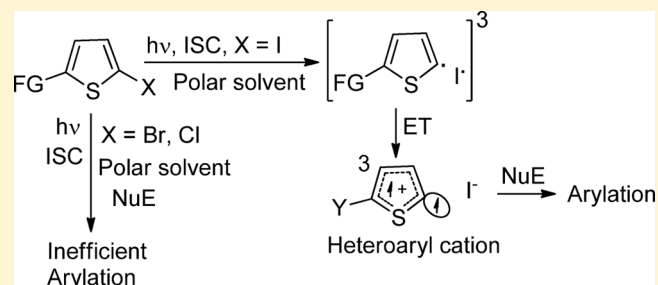
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S Supporting Information

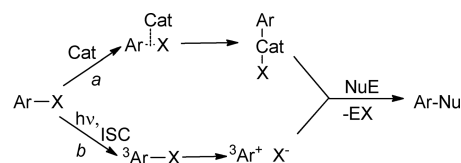
ABSTRACT: 2-Chloro-, 2-bromo-, and 2-iodothiophenes undergo photochemical dehalogenation via the triplet state. In the presence of suitable π -bond nucleophiles, thienylation occurs with modest yield from chloro and bromo derivatives (via photogenerated triplet 2-thienyl cation). Specific trapping by using oxygen along with computational analysis carried out by means of a density functional method support that, in the case of iodo derivatives, homolytic thienyl–I bond fragmentation occurs first and heteroaryl cations are formed by electron transfer within the triplet radical pair, thus opening an indirect access to such cations.



INTRODUCTION

The mild conditions of transition metal-catalyzed cross-coupling arylations have been the basis of the enormous success of this class of reactions.¹ Transition metal catalytic reactions are generally depicted as involving oxidative addition of the starting compound to the metal that imparts an electrophilic character to the reactive complex, thus enabling the reaction with both n - and π -nucleophiles (NuE in Scheme 1, path a). Metal-free alternatives conserving mild conditions

Scheme 1. Ar–X Activation via Metal Catalysis (path a) and by Photochemical Means (path b)



Cat = Transition metal catalyst
ISC = Inter System Crossing
NuE = n or π -bond nucleophiles.

are still a challenge,² but photochemical reactions have proved to give a significant contribution to this field.³ Indeed, the high energy of excited states makes possible to confront the barrier of the Ar–X bond cleavage process and to generate convenient intermediates (e.g., aryl radicals or aryl cations) for organic synthesis.⁴ For example, our research group has developed photo-S_N1 arylations⁵ through triplet phenyl cations (³Ar⁺) by photoheterolysis of the triplet state of phenyl halides (³Ar–X),⁵ sulfonates,⁶ phosphates,^{6a} and sulfates.⁷ Contrary to their singlet counterpart, which behaves as unselective electrophiles,⁵ triplet cations attack selectively π -nucleophiles (NuE), thus

leading to the arylation of alkenes, alkynes, and (hetero)-aromatics (Scheme 1, path b).

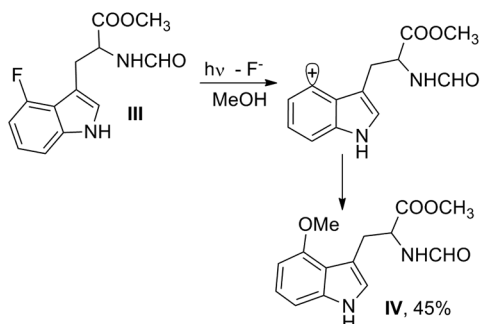
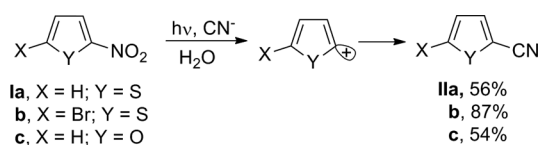
These photochemical reactions are efficient when irradiating, in polar protic solvents, aryl chlorides substituted with strong (NH₂, NMe₂, OH, OMe, CH₂SiMe₃)^{5,8} or mild (alkyl, SiMe₃) electron-donating groups.⁹ In highly ion-stabilizing 2,2,2-trifluoroethanol (TFE), heterolysis of the Ar–Cl bond can likewise take place in parent chlorobenzene¹⁰ or in 4-chlorobenzaldehydes and acetophenones when protected as 1,3-dioxolanes.¹¹ Recently, we demonstrated that the likelihood of the photoheterolysis step was established through DFT calculations evaluating the geometry, the spin, and charge distribution on the benzene ring of the aromatic in its triplet state (³ArX).¹² Indeed, the process is efficient where the triplet state showed an out-of-plane deformation of the C atom bringing the nucleofugal group, and, after stretching the Ar–X bond up to 4 Å, a negative charge must develop on the leaving atom with only a small fraction of the spin density. Another key parameter for the feasibility of the heterolytic step is the energy required for elongating the ³Ar–X bond (<27 kcal mol^{–1}).¹²

We then deemed to extend this approach to the photogeneration of heteroaryl cations due to the pivotal role that substituted heterocycles have in bioactive compounds and drugs.¹³ This is a difficult task, and only a couple of photoheterolytic cleavages were claimed to generate heteroaryl cations as shown in Scheme 2.^{14,15} An intriguing case was the photocyanation of substituted nitrothiophenes **Ia,b** and nitro-furan **Ic** (Scheme 2a).¹⁴ Another unusual leaving group was the fluoride anion in the methoxylation of (\pm)-*N*-formyl-4-

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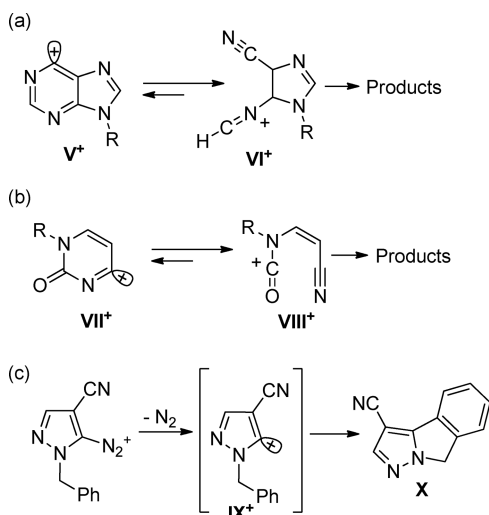
Scheme 2. Rare Examples of Photogenerated Heteroaryl Cations



fluorotryptophan methyl ester (**III**) to give (\pm)-*N*-formyl-4-methoxytryptophan methyl ester (**IV**, 45% yield, [Scheme 2b](#)).¹⁵

One of the main drawbacks in dealing with heteroaryl cations is that in most cases these underwent ring opening to more stable open-chain cations. In fact, calculations showed that the heteroaryl cations derived from the dediazonation of adeninediazonium ion (**V**⁺, [Scheme 3a](#))^{16a} or cytosinediazonium

Scheme 3

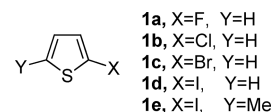


ium ion (**VII**⁺, [Scheme 3b](#))^{16b} were in equilibrium with the more thermodynamically favored **VI**⁺ and **VIII**⁺, respectively. Nonetheless, dediazonation of some electron-rich five-membered heterocycles (see the case of pyrazolyl cation intermediate **IX**⁺, [Scheme 3c](#)) has been postulated as a possible pathway for the thermal formation of **X** via intramolecular arylation.¹⁷

The obvious choice for photogenerating a heteroaryl cation was photolysis of electron-rich five-membered heterocycles, in particular of highly aromatic thiophenes. Shelf-stable halothiophenes were selected in place of more delicate thienyl diazonium salts¹⁸ as the cation precursors. The photo-substitution of thiophenes has been previously investigated mainly on derivatives bearing conjugating and electron-

withdrawing substituents, such as nitro, carbonyl, or carboxyl groups, and a thienyl radical was invoked as the intermediate.¹⁹ Thus, as a first attempt to generate a triplet thienyl cation, we decided to explore the photochemical behavior of 2-halothiophenes (Th-X, **1a–e**, [Chart 1](#)). A combined computa-

Chart 1. Substrates Examined in the Present Work



tional and experimental investigation was carried out, and the results were compared with those of an extended range of halobenzenes previously studied by our research group.

RESULTS

Computational Investigation. To clarify the course of the photoreaction, a preliminary computational study on thiophenes **1a–d** was carried out. A detailed description of the theoretical approach is available in the [Supporting Information](#). Briefly, density functional theory (DFT) at the (U)B3LYP/6-311+G(2d,p) level was adopted to optimize the absolute minimum of **1a–c** as in our previous studies on phenyl halides.¹² In the case of **1d**, because the above basis set is not defined for the iodine atom, a mixed set was employed, viz. 6-311+G(2d,p) for C, H, S atoms and LANL2DZ for the iodine atom.¹² Solvent effects (MeOH and C₆H₁₂ bulk) were included at the same level of theory by single-point calculations using the CPCM method (conductor-like polarizable continuum model).²⁰

The energy (in the 50–60 kcal mol⁻¹ range, see [Table S2](#) in [Supporting Information](#)) of the triplet halothiophenes ³**1a–d** in methanol and in cyclohexane bulk was calculated. As apparent from [Figure 1](#), all triplet states were nonplanar and exhibited a

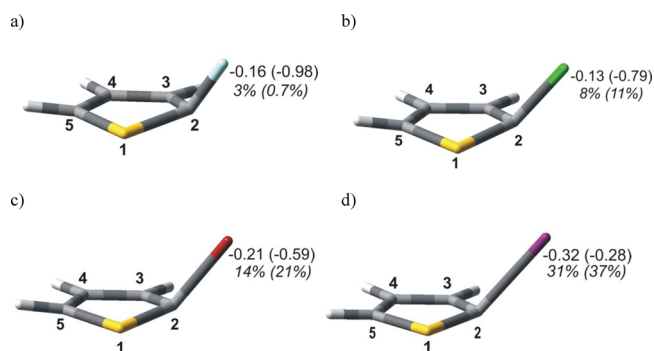


Figure 1. Geometries, ESP atomic charges, and spin densities (in italics) (in parentheses after elongation of C₂–X bond up to 4.00 Å) calculated in MeOH at the CPCM-UB3LYP/gen//UB3LYP/gen level of theory for (a) ³**1a**, (b) ³**1b**, (c) ³**1c**, and (d) ³**1d**.

deviation from the molecular plane by the halogen atom (X) and (to a lower degree) by the carbon atom (C₂) bearing X (see also [Figures S1–S5](#) in [Supporting Information](#)). The homolytic vs heterolytic character of the C₂–X bond cleavage in ³**1a–d** was evaluated by stretching the bond in the optimized configuration of these triplets¹² up to 4 Å (MeOH and C₆H₁₂ bulk), a distance where the bond can be considered broken.¹²

The key parameters (ΔE , that is the energy required to stretch the C₂–X bond up to 4.00 Å, charge, and spin density at

the X atom after C–X bond elongation) are summarily indicated in Figure 2a,b and reported in tabular format (see

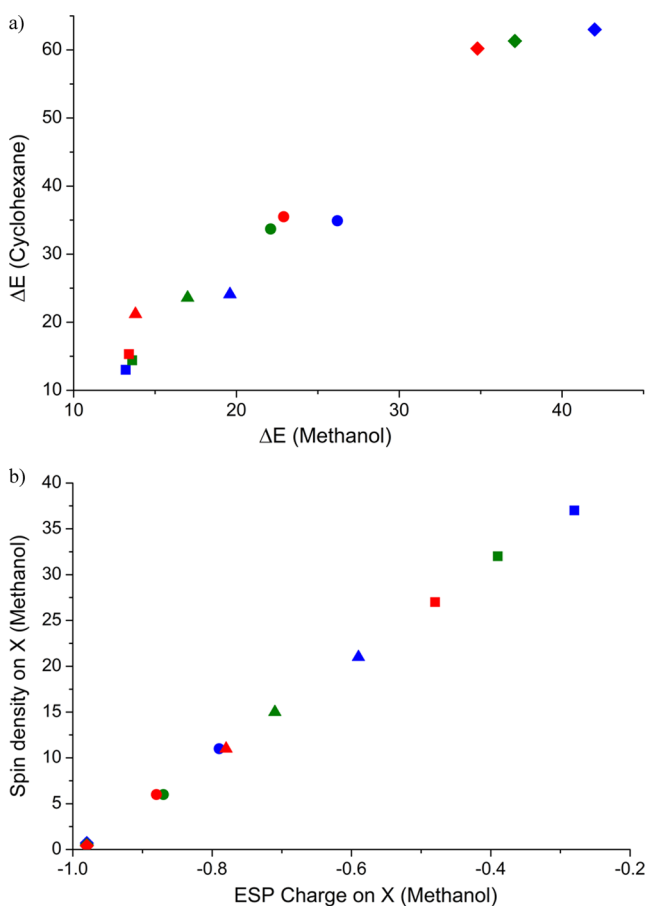


Figure 2. (a) Calculated ΔE in MeOH and in C_6H_{12} bulk: \blacklozenge fluoro derivatives, \bullet chloro derivatives, \blacktriangle bromo derivatives, \blacksquare iodo derivatives (halothiophene, blue; 2-halo-5-methylthiophene, green; 2-halo-5-methoxythiophene, red). (b) ESP charge distribution and spin density on the halogen (X), calculated in MeOH or C_6H_{12} bulk: \blacklozenge fluoro derivatives, \bullet chloro derivatives, \blacktriangle bromo derivatives, \blacksquare iodo derivatives (halothiophene, blue; 2-halo-5-methylthiophene, green; 2-halo-5-methoxythiophene, red).

Table S5 in Supporting Information). The values calculated for 5-methyl-2-halothiophenes and 5-methoxy-2-halothiophenes were likewise reported for the sake of comparison. The barrier confronted decreased from 42 (for $^3\mathbf{1a}$) to 13 kcal mol $^{-1}$ (for $^3\mathbf{1d}$) in methanol bulk, with a much larger value in cyclohexane in the case of $^3\mathbf{1a}$, while the energy involved in the Th–X bond stretching was independent of solvent polarity for the case of $^3\mathbf{1b-d}$ [$\Delta E(C_6H_{12}) \approx \Delta E(\text{MeOH})$ in Figure 2a]. Because the presence of an electron-donating group (Me, OMe) was found to favor Ar–X heterolytic cleavage in aryl halides,¹² the effect of EDG substituents (in the 5-position) was also investigated in that case. Notably, a decrement of the ΔE required for the cleavage was observed in methanol when moving from unsubstituted to 5-methoxy-2-halothiophene, except for the case of iodo derivatives where such groups had no effect (Figure 2a).

In protic solvent, bulk elongation of the C_2 –X bond involved the localization of a full negative charge and a minor spin localization at the fluoro atom in $^3\mathbf{1a}$ (see Figures 2b and Figure S1b) fully supporting heterolysis. With the other halides,

however, charge localization was much lower and spin density increased, suggesting a shift from heterolysis to the homolysis of Th–X bond (see Figure 2b and Figures S2–S5). The effect on charge separation and spin localization of a methyl or a methoxy group was negligible in fluoro- and chlorothiophenes and small in bromo and iodo analogues. In contrast, homolysis was exclusive for all of the examined halothiophenes in cyclohexane (see Table S5).

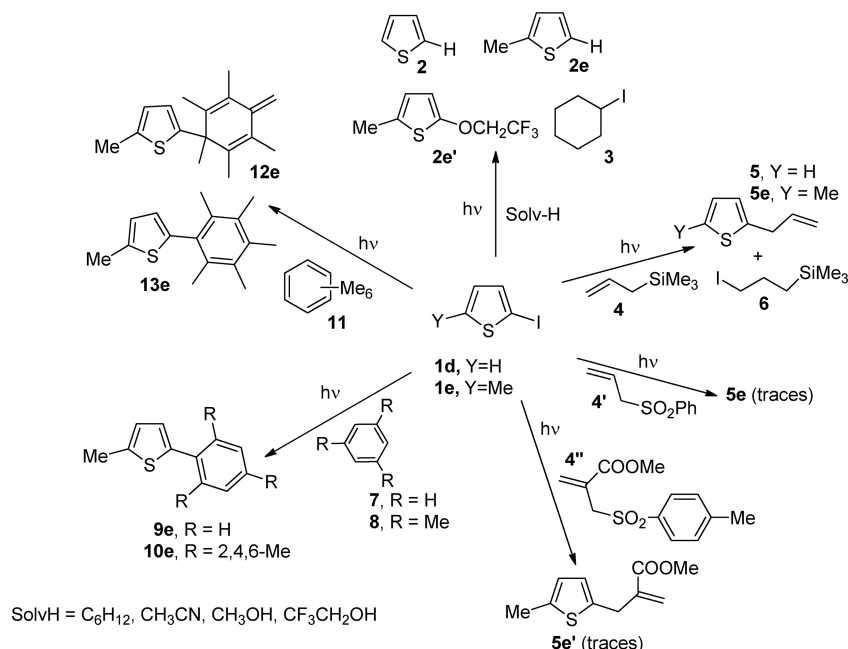
For the sake of completeness, calculations on $^3\mathbf{1a-d}$ were also carried out by adopting the functional M06-2X (with def2TZVP as the basis set) which has been reported to be accurate in describing noncovalent interactions and bond dissociation processes.²¹ Solvation was carried out by using SMD model.²² In this case, geometries of $^3\mathbf{1a-d}$ at both the equilibrium and after stretching of the Th–X bond up to 4 Å have been optimized in solvent (MeOH bulk). The results observed with this method supported what was already predicted by the former approach. Indeed, the ΔE values obtained are quite similar, while both spin and charge distribution (see Table S6 in Supporting Information for further details) confirmed the heterolytic nature of the Th–Cl(Br) bond cleavage in $^3\mathbf{1b-c}$ and the homolysis of the Th–I bond in $^3\mathbf{1d}$. In the last case, however, the Th–I bond in the equilibrium geometry was already homolytically cleaved.

Photochemical Results. 2-Fluorothiophene ($\mathbf{1a}$) was not experimentally studied because the calculated barrier to cleave the Th–F bond was too high (42 kcal mol $^{-1}$). 2-Bromo- and 2-iodothiophene ($\mathbf{1c,d}$) are known to undergo reductive dehalogenation upon irradiation^{23,24} whereas the photochemistry of 2-chlorothiophene ($\mathbf{1b}$) is so far unexplored. Whether a diagnostic heteroaryl cation intermediate was formed was investigated by irradiation in the presence of allyltrimethylsilane (ATMS, $\mathbf{4}$).²⁵ Some significant data, concerning the irradiation of $\mathbf{1b-d}$ at a fixed time (6 h, 254 or 310 nm (for $\mathbf{1d}$) centered lamps) are reported in Table 1. A base (cesium carbonate) was required in the experiments carried out in MeOH or TFE to avoid the formation of some

Table 1. Products from the Irradiation of 0.05 M 2-Halothiophenes ($\mathbf{1b-d}$) in the Presence of Allyltrimethylsilane (1 M)

2-halothiophene	solvent	conversion (%)	products (% yield) ^a
$\mathbf{1b}$, X = Cl	MeCN	68	2, traces
			5, 10
$\mathbf{1b}$	MeOH ^b	78	2, 12
			5, 10
$\mathbf{1b}$	TFE ^b	68	2, >5
			5, 10
$\mathbf{1c}$, X = Br	MeCN	100	5, 12
			2, 27
$\mathbf{1c}$	MeOH ^b	95	5, 9
			2, 9
$\mathbf{1c}$	TFE ^b	77	2, 9
			5, 16
$\mathbf{1d}$, X = I	MeCN	67	5, 49 ^c
			2, 41
$\mathbf{1d}$	MeOH ^b	100	5, 10
			2, 20
$\mathbf{1d}$	TFE ^b	100	5, 35

^aYield based on the consumption of the 2-halothiophenes and determined by GC or GC/MS analysis. ^b Cs_2CO_3 (0.05 M) added. ^cIsolated yield.

Scheme 4. Photolysis of 2-Iodothiophenes (1d,e) in Solvents and in the Presence of π -Nucleophiles

filming on the walls and to buffer the acidity released. Reduction to thiophene **2** and arylation to allylthiophene **5** are the only observed pathways. **5** was formed in up to ca. 50% yield in the case of 2-iodothiophene **1d** in MeCN (Scheme 4), for which the measured quantum yield of photodecomposition (Φ_{-1}) is 0.12 (0.34 in MeOH).

As concerning substituted iodothiophenes, reactions in solvents and in the presence of π -nucleophiles were more extensively investigated for the case of 5-methyl-2-iodothiophene (**1e**, Table 2).

In solvent, reduction was also the main process with iodide **1e**, with best yields in cyclohexane (with cyclohexyl iodide **3** as byproduct) and in methanol (with cesium carbonate). In TFE, however, 5-methyl-2-trifluoroethoxythiophene **2e'** was formed in up to 10% yield. The allylation in the presence of **4** occurred in modest yield, with the best in MeCN (62% yield). In contrast, the use of allylsulfones **4'** and **4''** afforded the corresponding allylthiophenes only in traces. Phenylation was obtained both in benzene and in benzene/CF₃CH₂OH (1/3) mixture. A 40% arylation, likewise, occurred with mesitylene. In contrast, hexamethylbenzene had a limited effect on the product mixture, with a small amount of triene **12e** and pentamethylbenzene **13e** observed on the basis of GC/MS analysis. To obtain mechanistic evidence, the effect of oxygen (saturated solution) was tested, resulting in the quenching of both reductive alkylation and iodine substitution.

DISCUSSION

To obtain a more complete picture, the same calculations carried out for 2-halothiophenes were performed for 4-halotoluenes, 4-haloanisoles, and 4-haloanilines and are likewise reported in Figure 3. It appears that 2-halothiophenes encounter the highest barrier to heterolytic fragmentation in the series (independent of the medium, Figure 2a), even higher than 4-halotoluenes. On the contrary, the barrier strongly decreases while the ESP charge at the halogen atom strongly increases in the case of methoxy- and aminobenzenes. When a heterolytic fragmentation is involved, the charge on the halogen

Table 2. Product Distribution by Irradiation (310 nm, 6 h) of 5-Methyl-2-iodothiophene (**1e**) (0.05 M) in Solvents and in the Presence of π -Bond Nucleophiles

conditions	conversion (%)	2e (% yield) ^a	further products (% yield) ^a
C ₆ H ₁₂	100	79	3 , 15
CH ₃ COOMe	27	100	-
MeCN	27	95	-
MeOH	54	86	-
MeOH, 0.05 M Cs ₂ CO ₃	100	98	-
TFE	73	62	2e' , 12^b
TFE, 0.05 M Cs ₂ CO ₃	76	72	2e' , 12^b
TFE, 0.05 M Cs ₂ CO ₃ , O ₂	88	19	2e' , < 5^b 3 , 43
C ₆ H ₁₂ , 4 (1 M)	88	56	5e , < 5^b 6 , < 5^b
MeCN, 4 (1 M)	63	18	5e , 62
TFE, 0.05 M Cs ₂ CO ₃ , 4 (1 M)	100	18	5e , 37 ^c
MeCN, 4' (0.2 M)	65	13	5e , < 5
MeCN, 4'' (0.2 M)	62	-	5e' , < 5^b
7 (neat)	62	35	9e , 65
7 /TFE (1/3), 0.05 M Cs ₂ CO ₃	64	25	9e , 48 ^c 2e' , < 5^b
TFE, 0.05 M Cs ₂ CO ₃ , 8 (1 M)	90	16	10e , 44 ^c
TFE, 0.05 M Cs ₂ CO ₃ , 11 (0.2 M)	79	43	2e' , 8^b 12e , < 5^b 13e , < 5^b

^aYield based on the consumption of **1e** and determined by means of GC analyses. ^bDetected by GC-MS analysis. ^cIsolated yield.

atom is close to -1 (see Figure 1a). Only fluorinated or chlorinated thiophenes reach this region, along with all of the haloanilines and anisoles examined (see the lower charge with the iodoanisole, though). Moreover, with thiophenes, introducing substituents had only a minor effect on barrier and charge

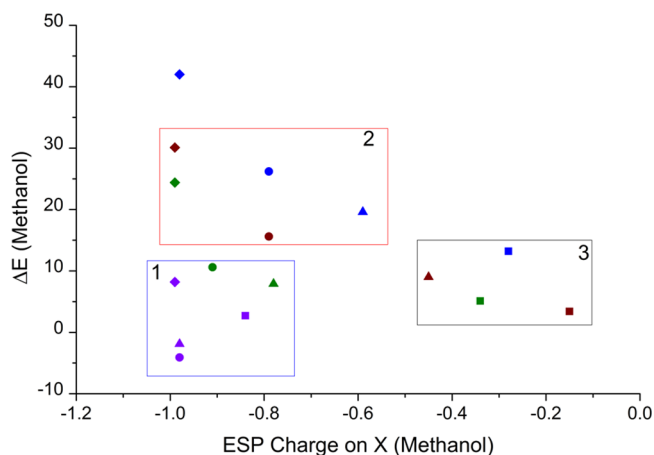


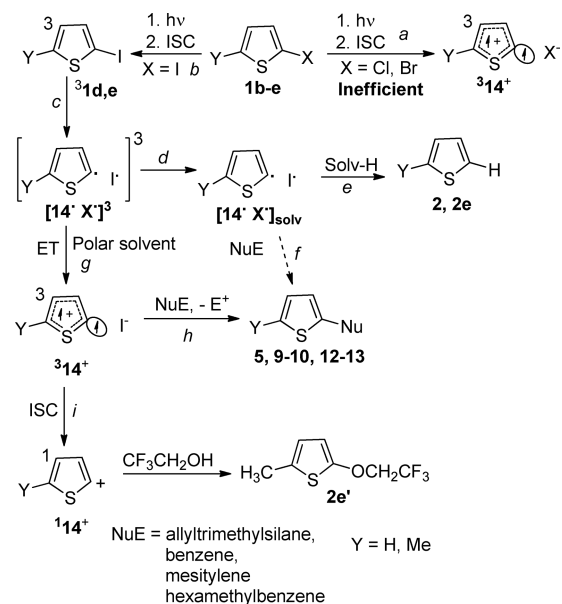
Figure 3. Energy required to stretch C–X bond up to 4.00 Å in the triplet state of some (hetero)aromatic halides vs ESP charge distribution on X atom (calculated in MeOH bulk). ◆ fluoro derivatives, ● chloro derivatives, ▲ bromo derivatives, ■ iodo derivatives (halothiophene, blue; 4-halo-*N,N*-dimethylanilines, violet; 4-halotoluenes, magenta; 4-haloanisoles, green).

localization (see also Figure 2a and 2b) On the other hand, the presence of electron-donating groups on benzene derivatives reduced the barrier in methanol. Indeed, heterolysis was an exothermic process for chloro- and bromoanilines and encountered a low barrier with the other 4-haloanilines and 4-haloanisoles. It appears that with thiophene derivatives the aryl cation was not sufficiently stabilized to make this path dominant (high energy barrier for Th–X cleavage when X = F, Cl and low ESP charge in the case of bromides and iodides, Figure 1), while this was the case for phenyl derivatives. Triplet cations, which have a $\pi^5\sigma^1$ radical cation structure, are more stabilized by electron-donating substituents for six-membered aromatics with respect to the corresponding five-membered heterocycles such as thiophenes (and expectedly with other electron rich heterocycles).

As shown in Figure 3, three groups of aromatic and heteroaromatic halides have been recognized on the basis of the nature of the (Het)Ar–X bond cleavage. In group 1, a negative ESP charge (> -0.75) developed at the halogen atom, while only a small fraction of the spin density ($< 10\%$, see Table S5) became localized there, and heterolysis takes place with a small energy barrier (≤ 10 kcal mol $^{-1}$). These are necessary but not sufficient conditions for the generation of an aryl cation. In fact, with iodo derivatives, heavy atom effects (e.g., in iodoanilines) may promote ISC to the ground state and reduce the lifetime of the triplet excited state. Thus, a fast cleavage is mandatory to avoid disexcitation.^{8a} With less electron-donating substituents (group 2), the barrier was higher (15–30 kcal mol $^{-1}$) with less charge (> -0.6) and more spin (10–20%) at the halogen. In this class, the experimentally observed outcome still involved phenylation reactions via photogenerated aryl cations derived from them but only when irradiated in a protic, ion-solvating solvent. Finally, in group 3, the required energy was relatively low, but the charge at the halogen was negligible and the spin larger ($> 30\%$), and homolysis took place as a primary process.

Both experimental and computational data above support the mechanistic scheme depicted in Scheme 5, where halothiophene triplets $^3\mathbf{1b-e}$ are the reacting states.^{19b,c,26} In fluorothiophenes, however, that are expected to be cleaved heterolytically, the high barrier makes the process too slow to

Scheme 5. Pathways and Intermediates Involved in the Photochemistry of Halothiophenes 1b–e



compete with physical decay even if the ions would be stabilized in a polar medium (see Figures 2 and 3).

The process occurring in chloro- and bromothiophenes **1b,c** is an inefficient heterolytic cleavage of the Ar–X bond (Scheme 5, path a) to form the corresponding triplet thienyl cation ($^3\mathbf{14}^+$, see structure in Figure S6 in Supporting Information). On the contrary, iodothiophenes **1d,e** underwent a photohomolytic C–X bond cleavage (paths b, c), a thermodynamically viable process (Figure 2). Thus, a triplet radical pair $[\mathbf{14}^* \mathbf{X}^*]^3$ was generated^{27,28} rather than cation $^3\mathbf{14}^+$. Diffusional separation of the radical center formed a solvated radical pair $[\mathbf{14}^* \mathbf{X}^*]_{\text{solv}}$ (path d).²⁹ The 2-thienyl radical ($\mathbf{14}^*$) is the intermediate involved both in the reduction to thiophenes **2** and **2e** (path e) and addition to π -nucleophiles in non-hydrogen-donating solvents (path f, see also the experiment in benzene, Table 2).

The homolytic cleavage of the Th–X bond in $^3\mathbf{1d,e}$ was supported by experimental evidence as the specific quenching of the radical by oxygen, the formation of iodopropylsilane **6** from alkene **4**, and the formation of iodocyclohexane **3**. In contrast, the role of aryl radicals in arylations in polar solvents is excluded, because the presence of typical radical traps, namely allyl phenyl sulfone **4'** or sulfone **4''**, did not lead to appreciable amounts of allylated derivatives (Table 2).³⁰ Furthermore, the products of the reaction with allyltrimethylsilane and those with hexamethylbenzene are typical markers of a triplet aryl cation and are best rationalized as resulting from electron transfer (ET) within the thienyl and halogen radical pair $[\mathbf{14}^* \mathbf{X}^*]^3$. This leads indirectly to ion $^3\mathbf{14}^+$ (Scheme 5, path g)^{10,31} which is trapped by π -bond nucleophiles³² to give the arylated products (path h). The formation of aryl cations from an ET mechanism within a radical pair has been sparsely documented, providing that it takes place in a high polar medium (e.g., water).^{28,31b,33} Notice further that 5-uracyl and 5-citosyl cations have been invoked when investigating the reactivity of 5-fluorouracil³⁴ and 5-bromocytosine,³⁵ respectively, where the heteroaryl radical intermediate was oxidized by the radical cation of *N*^α-acetyl-L-tryptophan *N*-ethylamide.^{34,35} More relevant to the present case, the formation of the parent triplet phenyl cation from the

corresponding aryl radical has been previously postulated in the photodechlorination of chlorobenzene.¹⁰ The formation of a small amount of trifluoroethoxythiophene (**2e'**) in TFE is best justified via ISC from triplet to singlet thienyl cation (¹14⁺, Scheme 5, path i).³⁶ Despite calculations supporting that triplet thienyl cations are slightly more stable than the corresponding singlets (by 8–10 kcal mol⁻¹, Figures S6–S10 in Supporting Information), such a small energy difference may be overestimated, as previously observed.³⁴ Indeed, solvolysis to **2e'** took place as a minor process and is fully suppressed when a reactive π -bond trap is used, supporting that the singlet cation arises from the formerly generated ³14⁺.

In conclusion, the generation of triplet phenyl cations from halobenzenes is a highly efficient process, which is hardly extended to thiophenes. However, we demonstrated that heteroaryl cations are formed from thienyl iodides in polar and protic solvents via a homolytic cleavage of the Th–I bond followed by intramolecular electron transfer within the photogenerated triplet radical pair. The cleavage occurs with reasonable efficiency (see Tables 1 and 2), though solvation of the radical pair before ET competes significantly, making reactions less clean. This work suggests that access to aryl cations is viable also via paths different than cleavage of the Ph–X bond encountered in electron-donating phenyl halides and further shows that a simply implemented functional method allows to predict the viability of either type of cleavage (homolytic or heterolytic) for a specific case.

EXPERIMENTAL SECTION

Materials and Methods. ¹H NMR spectra were recorded with a 300 MHz spectrometer, while ¹³C NMR spectra were recorded with a 75 MHz spectrometer. The attributions were made on the basis of ¹H and ¹³C NMR, as well as DEPT-135 experiments; chemical shifts are reported in ppm downfield from TMS. GC-MS analyses were carried out using a GC-DSQ single quadrupole GC/MS system. A Rtx-5MS (30 m × 0.25 mm × 0.25 μ m) capillary column was used for analyte separation with helium as carrier gas at 36 mL min⁻¹. The injection into the GC system was performed in split mode, and the injector temperature was 250 °C. The GC oven temperature was held at 40 °C for 6 min, increased to 250 °C by a temperature ramp of 10 °C min⁻¹ and held for 5 min. The transfer line temperature was 280 °C and the ion source temperature 250 °C. For **2**, mass spectral analyses were carried out in SIM mode, monitoring *m/z* 84, 58, 45 at the same time. To improve the quality of the integration of the peaks of interest the base peak function was applied to the chromatogram. This action afforded a new chromatogram that showed only the signals with *m/z* 84 as base peak. In contrast, for **2e'**, **5e'**, **6**, **12e**, and **13e**, mass spectral analyses were carried out in full scan mode.

2-Halothiophenes **1a–d**, thiophene (**2**), 2-methylthiophene (**2e**), and all of the employed π -bond nucleophiles were commercially available and used as received. 5-Methyl-2-iodothiophene (**1e**) was obtained by iodination of **2e**.³⁷ 2-(Tosylmethyl)acrylate (**4''**) was synthesized according to a literature procedure.³⁸

Photochemical Experiments. The photochemical reactions were performed by using nitrogen-purged solutions in quartz tubes in a multilamp reactor fitted with ten 15 W Hg phosphor-coated lamps (emission maximum 310 nm) or four 15 W Hg lamps (emission centered at 254 nm). The reaction course was followed by GC analyses, and the products formed were identified and quantified by comparison with authentic samples. Workup of the photolyses involved concentration in vacuo (80–100 Torr) and chromatographic separation. Solvents of HPLC purity were employed in the photochemical reactions. Quantum yields were measured at 254 nm (1 Hg lamp, 15 W). The amount of 2-methylthiophene (**1e**) and iodocyclohexane (**3**) was determined by GC analysis on the basis of calibration curves by comparison with commercial standard. Products

2 (*m/z*: 84 (M⁺, 100), 58 (38), 45 (32)), **2e'** (*m/z*: 196 (M⁺, 72), 113 (96), 85 (68)), **5e'** (*m/z*: 196 (M⁺, 100), 136 (94), 111 (34)) **6** (*m/z*: 185 (34), 115 (16), 72 (100)), **12e** (258 (M⁺, 30), 161 (100)), and **13e** (245 (M⁺, 100), 229 (98)) were determined by means of GC-MS analyses. In a typical experiment, a solution of **1b,e** (1.5 mmol, 0.05M), a π -bond nucleophile (1.0 M except where otherwise indicated), and Cs₂CO₃ (0.05 M, 1.5 mmol except where indicated) in the chosen solvent (30 mL) was nitrogen-purged in quartz tubes and irradiated.

2-(2-Propenyl)thiophene (5). To 166 μ L (0.05 M, 1.5 mmol) of **1d** was added 4.77 mL (1 M, 30 mmol) of allyltrimethylsilane (ATMS) in 30 mL of MeCN, and the mixture was irradiated at 310 nm for 6 h (67% consumption of **1d**). Purification by column chromatography (aluminum oxide neutral; eluant: pentane) afforded 61 mg of **5** (oil, 49% yield based on the consumption of **1d**). Spectroscopic data of **5** were in accordance with the literature.³⁹ Anal. Calcd for C₇H₈S: C, 67.69; H, 6.49. Found: C, 67.7; H, 6.5.

2-Methyl-5-(2-propenyl)thiophene (5e). To 181 μ L (0.05 M, 1.5 mmol) of **1e** were added 489 mg (0.05 M, 1.5 mmol) of Cs₂CO₃ and 4.77 mL (1 M, 30 mmol) of allyltrimethylsilane in 30 mL of TFE, and the mixture was irradiated for 6 h at 310 nm (100% consumption of **1e**). Purification by column chromatography (aluminum oxide neutral; eluant: pentane) gave 77 mg of **5e** (oil, 37% yield). 2-Methylthiophene (**2e**) was likewise formed in 18% yield (determined on the basis of calibration curve). **5e**: ¹H NMR (CDCl₃) δ 2.45 (s, 3H), 3.50–3.55 (d, 2H, *J* = 6.6 Hz), 5.10–5.20 (m, 2H), 5.95–6.10 (m, 1H), 6.55–6.60 (m, 2H); ¹³C NMR (CDCl₃) δ 15.1 (CH₃), 34.6 (CH₂), 115.8 (CH), 124.1 (CH), 124.7 (CH), 136.8 (CH₂), 137.9, 140.3; IR (KBr) ν_{\max} 2921, 1638, 1420, 909, 790 cm⁻¹. Anal. Calcd for C₈H₁₀S: C, 69.51; H, 7.29. Found: C, 69.5; H, 7.3.

2-Methyl-5-phenylthiophene (9e). To 181 μ L (0.05 M, 1.5 mmol) of **1e** were added 489 mg (0.05 M, 1.5 mmol) of Cs₂CO₃ and 7.5 mL (2.8 M, 0.1 mmol) of benzene in 30 mL of TFE, and the mixture was irradiated for 6 h at 310 nm (64% consumption of **1e**). Purification by column chromatography (silica; eluant: hexane) gave 80 mg of **9e** (white solid, 48% yield based on the consumption of **1e**), mp = 42–43 °C, lit.⁴⁰ = 39–41 °C. Compound **2e** was likewise formed in the reaction (25% yield based on the consumption of **1e** and determined on the basis of calibration curve). GC-MS analyses also revealed the presence of 2-(3,3,3-trifluoroethoxy)-5-methylthiophene (<5%). Spectroscopic data of **9e** were in accordance with the literature.⁴¹ Anal. Calcd for C₁₁H₁₀S: C, 75.82; H, 5.78. Found: C, 75.8; H, 5.8.

2-(2,4,5-Trimethylphenyl)-5-methylthiophene (10e). To 181 μ L (0.05 M, 1.5 mmol) of **1e** were added 489 mg (0.05 M, 1.5 mmol) of Cs₂CO₃ and 4.17 mL (1 M, 30 mmol) of mesitylene in 30 mL of TFE, and the mixture was irradiated for 6 h at 310 nm (90% consumption of **1e**). Purification by column chromatography (silica; eluant: hexane) gave 129 mg of **10e** (colorless oil, 44% yield based on the consumption of **1e**). Compound **2e** was also formed in the reaction (16% yield based on the consumption of **1e** and determined on the basis of calibration curve). **10e**: ¹H NMR (CDCl₃) δ 2.20 (s, 6H), 2.40 (s, 3H), 2.55–2.60 (d, 3H, *J* = 0.9 Hz), 6.60–6.65 (d, 1H, *J* = 3.5 Hz), 6.75–6.80 (m, 1H), 6.97 (s, 2H). ¹³C NMR (CDCl₃) δ 15.2 (CH₃), 20.6 (CH₃), 21.0 (CH₃), 124.9 (CH), 126.1 (CH), 127.9 (CH), 131.4, 137.5, 138.2, 139, 139.4. IR (KBr) ν_{\max} 2911, 1454, 845, 791 cm⁻¹. Anal. Calcd for C₁₄H₁₆S: C, 77.72; H, 7.45. Found: C, 77.7; H, 7.4.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.6b00978.

Absorption parameters measured for compounds **1b–e**; ¹H and ¹³C NMR spectra of compounds **1e**, **5**, **5e**, **9e**, and **10e**; details of the calculations on intermediates (PDF)

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Notes

The authors declare no competing financial interest.

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