

Primary Vinyl Cations in Solution: Kinetics and Products of β,β -Disubstituted Alkenyl(aryl)iodonium Triflate Fragmentations

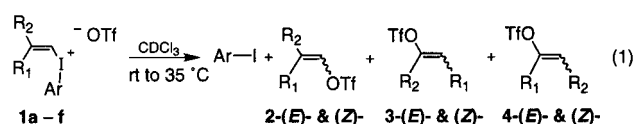
Robert J. Hinkle,* Anne J. McNeil,^{1a} Quinn A. Thomas,^{1b} and Marie N. Andrews

The College of William & Mary
Department of Chemistry, P.O. Box 8795
Williamsburg, Virginia 23187-8795

Received May 17, 1999

Hypervalent iodine intermediates have been utilized as outstanding nucleofuges in the generation of unstable carbenium ions.² More specifically, alkenyl(phenyl)iodonium salts³ have served as vinyl cation^{4–6} equivalents in a number of transformations, including: (a) cross-coupling reactions with organic stannanes⁷ as well as acrylates,⁸ (b) reactions with enolates,⁹ and (c) reactions with various nucleophiles under copper-mediated conditions.¹⁰ Further, the phenyliodonio moiety is a much better leaving group than triflate (by a factor of 10⁶) during solvolytic generation of a cyclohexenyl cation.¹¹ We have synthesized several new, highly activated β,β -disubstituted alkenyl(aryl)iodonium triflates and observed their fragmentations.¹² Members of this class of salts were chosen for two reasons: (a) a second β -substituent is calculated to stabilize the primary vinyl cation¹³ and (b) direct β -elimination is impossible. Herein, we report new kinetic data and the effects of electron-withdrawing groups on the reaction. These values, in addition to studies on stereoisomeric alkenyl(aryl)iodonium salts, now provide firm evidence of the generation of primary vinyl cations in solution.¹⁴

Salts **1a–f** were stereospecifically synthesized from alkenylstannanes using standard procedures.¹⁵ Fragmentations of these salts in CDCl₃ lead to enol triflate isomers **2–4** (eq 1). Although



Cmpd	R ₁	R ₂	Ar
1a	Et	Me	4-(CF ₃)C ₆ H ₄
1b	Et	Bu	Ph
1c	Et	Bu	4-(CF ₃)C ₆ H ₄
1d	Bu	Et	Ph
1e	Bu	Et	4-(CF ₃)C ₆ H ₄
1f	Bu	Et	3,5-(CF ₃) ₂ C ₆ H ₃

chloroform is not a typical medium for solvolyses, solvent polarity has very little effect on the reaction rate of solvolyses of cyclohexenyl(aryl)iodonium salts because there is no net change in charge as well as no significant charge-separation in the transition state.¹¹

Enol triflates from decomposition of all of the starting materials were observed by GC-MS analysis of consumed salts. At temperatures between 20 and 35 °C, a total of six enol triflate isomers were detected. Authentic stereoisomeric mixtures of enol triflates were then synthesized and co-injected with those derived from decomposition to verify their identities.¹⁶

The most important of these vinyl triflate compounds are **2-(E)-** and **2-(Z)-**. These enol triflates result from heterolytic C–I bond cleavage followed by direct ⁻OTf trapping of cation **I** (Scheme 1). The four other enol triflate isomers result from migration of R₁ and/or R₂ to form a more stable secondary vinyl cation (**II** or **III**) which is then trapped by triflate anion. A concerted alkyl (*trans*) shift of R₂ followed by triflate anion trapping would only lead to enol triflate isomers **4(E)-** and **4(Z)-** and not the corresponding regioisomers, **3(E)-** and **3(Z)-**. Alternatively, a synchronous alkyl shift (*trans*) of R₂ could be followed by a simple hydride migration between secondary cations **III** and **II**. Subsequent trapping by the triflate anion would then lead to products which appear to be derived from migration of *either* R₁ or R₂.

However, it is the presence of *both* **2(E)-** and **2(Z)-** in nonnucleophilic solvent which offers firm support for the primary vinyl cation. The presence of all six isomers is excellent support for a mechanism involving heterolytic C–I bond cleavage and migration of both the *trans* and *cis* β -alkyl groups as well as trapping of the *unrearranged* cation (Scheme 1). If a simple S_N2 mechanism were operative, only one nonrearranged isomer of **2** (via S_N2) would be present (Scheme 2).^{17–19}

Another possible mechanism involving initial coordination of the triflate to the positively charged iodine atom to form λ^3 -iodane **5** followed by S_N2 displacement would lead to the same stereoisomer (Scheme 2).^{17a} The involvement of a λ^3 -iodane in this mode of in-plane S_N2 reactivity was reported by Okuyama and co-workers for several β -monosubstituted iodonium salts. However, only inverted products were observed rather than a mixture of stereoisomers. Other mechanisms involving ligand coupling or addition/elimination are unlikely with such a poorly nucleophilic and weakly basic anion such as triflate.

(12) For a report showing decomposition of an iodonium salt via a phenonium ion, see: Hinkle, R. J.; Thomas, D. B. *J. Org. Chem.* **1997**, *62*, 7534–7535.

(13) A second β -methyl group stabilizes the primary vinyl cation by 24.0 kcal/mol (MP3/6-31G**//6-31G*). See ref 6, p 34.

(14) While the current work was in progress, Okuyama and co-workers described rearrangements of less-reactive disubstituted alkenyl(phenyl)iodonium salts. Okuyama, T.; Sato, K.; Ochiai, M. *Chem. Lett.* **1998**, 1177–1178.

(15) Hinkle, R. J.; Stang, P. J. *Synthesis* **1994**, 393–396. Zhdankin, V. V.; Scheuller, M. C.; Stang, P. J. *Tetrahedron Lett.* **1993**, *34*, 6853–6856.

(16) Enol triflates were synthesized according to standard procedures by means of the hindered base method and the appropriate ketone or aldehyde: Stang, P. J.; Treptow, W. *Synthesis* **1980**, 283–284.

* To whom correspondence should be addressed: rjhink@chem1.chem.wm.edu.

(1) (a) Arnold and Mable Beckman Foundation Scholarship Awardee. (b) Formerly Quinn D. Aubry. Current address: University of Southern Mississippi, Department of Polymer Science, Box 10076, Hattiesburg, MS 39406.

(2) For early work on the cubyl cation, see: (a) Moriarty, R. M.; Tuladhar, S. M.; Penmasta, R.; Awasthi, S. K. *J. Am. Chem. Soc.* **1990**, *112*, 3228–3230. (b) Eaton, P. E.; Yang, C.-X.; Xiong, Y. *J. Am. Chem. Soc.* **1990**, *112*, 3225–3226. (c) Eaton, P. E.; Cunkle, G. T. *Tetrahedron Lett.* **1986**, 6055–6058.

(3) Hypervalent iodine compounds in general have been the subject of several recent reviews and monographs: (a) Moriarty, R. M.; Prakash, O. In *Advances in Heterocyclic Chemistry*; Katritzky, A. R., Ed.; Academic: New York, 1998; pp 1–87. (b) Varvoglis, A. *Tetrahedron* **1997**, *53*, 1179–1255. (c) Zhdankin, V. V.; Stang, P. J. *Chem. Rev.* **1996**, *96*, 1123–1178. (d) Varvoglis, A. *Hypervalent Iodine in Organic Synthesis*; Academic: New York, 1997.

(4) Vinyl cations containing α -alkyl groups are a well-studied class of intermediates and are significantly more stable than those which do not contain the α -substituent. See, *inter alia*: (a) Kobayashi, S.; Hori, Y.; Hasako, T.; Koga, K.; Yamataka, H. *J. Org. Chem.* **1996**, *61*, 5274–5279. (b) Summerville, R. H.; Schleyer, P. v. R. *J. Am. Chem. Soc.* **1974**, *96*, 1110–1120. (d) Summerville, R. H.; Senkler, C. A.; Schleyer, P. v. R.; Dueber, T. E.; Stang, P. J. *J. Am. Chem. Soc.* **1974**, *96*, 1100–1109.

(5) For NMR studies of stabilized vinyl cations, see: Siehl, H.-U. *Pure Appl. Chem.* **1995**, *67*, 769–775. Siehl, H.-U.; Kaufmann, F.-P.; Hori, K. *J. Am. Chem. Soc.* **1992**, *114*, 9343–9349.

(6) For a recent, comprehensive treatment of vinyl cation chemistry, see: *Dicoordinated Carbocations*; Rappoport, Z., Stang, P. J., Eds.; John Wiley and Sons: New York, 1997.

(7) Kang, S.-K.; Ho, P.-S.; Yoon, S.-K.; Lee, J. -C.; Lee, K.-J. *Synthesis* **1998**, 823–825; Ryan, J. H.; Stang, P. J. *J. Org. Chem.* **1996**, *61*, 6162–6165; Hinkle, R. J.; Poulter, G. M.; Stang, P. J. *J. Am. Chem. Soc.* **1993**, *115*, 11626–11627; Moriarty, R. M.; Epa, W. R. *Tetrahedron Lett.* **1992**, 4095–4098.

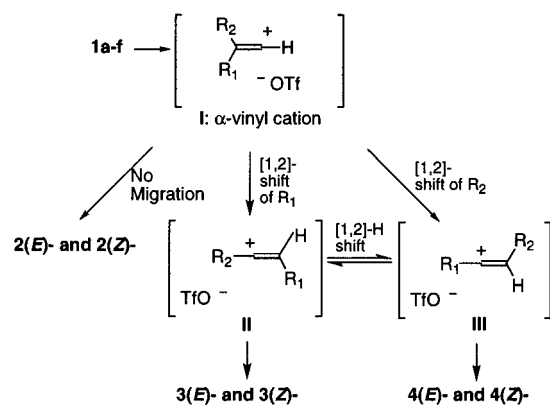
(8) Moriarty, R. M.; Epa, W. R.; Awasthi, A. K. *J. Am. Chem. Soc.* **1991**, *113*, 6315–6316.

(9) Ochiai, M.; Shu, T.; Nagaoka, T.; Kitagawa, Y. *J. Org. Chem.* **1997**, *62*, 2130–2138.

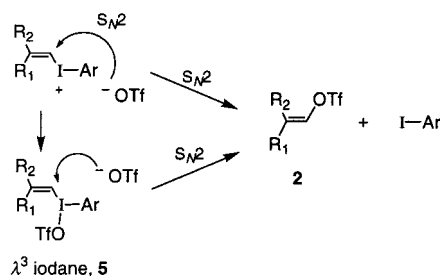
(10) Ochiai, M.; Sumi, K.; Takaoka, Y.; Kunishima, M.; Nagao, Y.; Shiro, M.; Fujita, E. *Tetrahedron* **1988**, 4095–4112.

(11) Okuyama, T.; Takino, T.; Sueda, T.; Ochiai, M. *J. Am. Chem. Soc.* **1995**, *117*, 3360–3367.

Scheme 1



Scheme 2

**Table 1.** Kinetic Data^a from Decompositions of Alkenyl(aryl)iodonium Triflate Salts

salt	R ₁	R ₂	Ar	temp (°C)	k × 10 ⁴ (mol/L·sec)
1d	Bu	Et	Ph	35	0.24
1e	Bu	Et	4-(CF ₃)C ₆ H ₄	35	2.01
1f	Bu	Et	3,5-(CF ₃) ₂ C ₆ H ₃	20	0.67
1f	Bu	Et	3,5-(CF ₃) ₂ C ₆ H ₃	25	1.75
1f	Bu	Et	3,5-(CF ₃) ₂ C ₆ H ₃	30	3.24
1f	Bu	Et	3,5-(CF ₃) ₂ C ₆ H ₃	35	6.62

^a Rate constants were determined by fragmentation of salts in CDCl₃ filtered through basic alumina immediately before use and monitored by ¹H NMR spectroscopy for disappearance of starting materials.

Table 2. Relative Percentages of Products in Decomposition Reactions of **1c**, **1d**, **1e**, and **1f** in Basic Alumina-Filtered CDCl₃

salt	R ₁	R ₂	Ar	R ₂ migration	R ₁ migration	no migration
1c	Et	Bu	4-(CF ₃)C ₆ H ₄	59	29	12
1d	Bu	Et	Ph	74	14	12
1e	Bu	Et	4-(CF ₃)C ₆ H ₄	71	16	13
1f	Bu	Et	3,5-(CF ₃) ₂ C ₆ H ₃	69	25	8

Reactions of the activated salt **1f** in the prototypical solvolysis solvent (MeOH) afford acetylenes and allenes as the predominant products. This most likely occurs because of the increase in nucleofugality of the iodoarene moiety and because increased basicity of the solvent promotes α -elimination to the corresponding alkyldiene-carbene in addition to cationic intermediates. Performing the reaction in trifluoroacetic acid produced a mixture of enol triflates, albeit with the presence of large amounts of unidentified byproducts.

We attempted to utilize spectrophotometric techniques to measure the rates of fragmentation, but the absorbances of the substituted aryl iodide product of cleavage and the iodonium salt were not clearly separable. Instead, kinetic measurements of the reactions were performed by analysis of time-arrayed ¹H NMR spectra at 20, 25, 30, and 35 °C using basic alumina filtered CDCl₃ (Table 1). The resonances of the ortho-protons in the iodonium salts as well as the iodoarene byproduct were analyzed. Plots of the decompositions were found to be first order in iodonium substrate, bolstering our belief that the reactions are occurring

via an S_N1 mechanism. Further, using the Arrhenius equation, we obtained the following kinetic parameters for salt **1f**: E_a = 26.8 kcal/mol; ΔH^\ddagger = 26.2 kcal/mol; ΔS^\ddagger = 11.9 cal/mole·K.

These values are consistent with the heterolytic cleavage of the alkene–iodine bond in the transition state in the vicinity of room temperature. Most notable is the positive entropy of activation indicating an increase in disorder as the arylidonio moiety departs.

For information on the effects of electron-withdrawing groups on the iodoarene moiety, kinetic measurements of **1d**, **1e**, and **1f** were performed at 35 °C. As we expected, increasing the electron-withdrawing nature of the aromatic ring significantly increased the rates for fragmentation and rearrangement of the salts. For comparison, complete consumption of **1d** required ca. 10 h at 35 °C whereas **1f** only took ca. 1.5 h. Further, using Hammett constants for CF₃ groups (σ para = 0.54; σ meta = 0.43), we calculated a ρ value of +1.7.²⁰ This electronic effect is consistent with data reported by Okuyama and co-workers and a heterolytic cleavage mechanism (Scheme 1) in which the increased relative charge at the iodine atom in the salts would increase the nucleofugality of the entire iodoarene moiety.¹¹ It is inconsistent, however, with a homolytic mechanism followed by SET.¹¹ In the latter case, the iodobenzene cation radical would be destabilized by the presence of electron-withdrawing substituents.

Investigation of a stereoisomeric pair of iodonium salts (**1c** and **1e**) reveals that the alkyl group *trans* to the iodonium moiety generally migrates to a greater extent than the alkyl group which is *cis* (Table 2). This evidence indicates that the cation is either: (a) free, but not linear as expected, or (b) there may be some migration which occurs simultaneously with iodoarene cleavage, or (c) the vinyl cation is a member of a tight-ion pair. This latter possibility is most likely in the relatively nonpolar solvent investigated (chloroform). However, we do not observe any “internal return” products (electrophilic aromatic substitution with the iodoarene) such as those described by Okuyama and co-workers and therefore the ion pair likely involves the triflate anion.¹¹

We have demonstrated a definitive example of the generation of a primary vinyl cation in solution. The increased nucleofugality of the arylidonio moiety of β,β -disubstituted alkenyl(aryl)iodonium salts was accomplished by incorporation of strongly electron-withdrawing trifluoromethyl groups into the aromatic ring. This in turn, allowed the determination of kinetic parameters for decompositions as well as quantitative evaluation of the effects of electron-withdrawing groups on the reaction ($\rho = +1.7$). We are in the process of further investigating the solvolyses of these compounds in a wider variety of solvents as well as with a greater variety of substituents. The results of these studies will be reported in due course.

Acknowledgment. We gratefully acknowledge support of this work by The College of William & Mary, the Research Corporation (Grant CC4659), and the Arnold and Mable Beckman Foundation for a scholarship (AJM).

Supporting Information Available: Experimental procedures, copies of GCMS traces of fragmentation products resulting from compounds **1a**, **b**, **e**, and **f**, and kinetic plots of disappearance of iodonium salts (PDF). This material is available free of charge via the Internet at <http://pubs.acs.org>.

JA9916310

(17) Formal S_N2 reactions are documented for simple alky(vinyl)(phenyl)-iodonium salts: (a) Okuyama, T.; Takino, T.; Sago, K.; Ochiai, M. *J. Am. Chem. Soc.* **1998**, *120*, 2275–2282. (b) Okuyama, T.; Takino, T.; Sato, K.; Oshima, K.; Imamura, S.; Yamataka, H.; Asano, T.; Ochiai, M. *Bull. Chem. Soc. Jpn.* **1998**, *71*, 243–257. (c) Ochiai, M.; Oshima, K.; Masaki, Y. *J. Am. Chem. Soc.* **1991**, *113*, 7059–7061.

(18) A theoretical study of vinylic S_N2 vs A_DN-E reactions was recently published: Lucchini, V.; Modena, G.; Pasquato, L. *J. Am. Chem. Soc.* **1995**, *117*, 2297–2300.

(19) An addition–elimination pathway is proposed for salts containing a β -phenylsulfonyl moiety: Ochiai, M.; Oshima, K.; Masaki, Y. *Tetrahedron Lett.* **1991**, *32*, 7711–7714.

(20) When multiple substituents are contained in the same aromatic ring, the σ -values are additive. Hammett, L. P.; *Physical Organic Chemistry*, 2nd ed.; McGraw-Hill: New York, 1970; p 367.