Characterization of oligomers of 3,3,3-trifluoro-1-phenylpropyne and 1-phenylpropyne by mass spectrometry

Carl L. Bumgardner*, Chien-Hua Huang and Richard B. Van Breemen
Department of Chemistry, North Carolina State University, Raleigh, NC 27695-8204 (USA)

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Abstract

Oligomers of $Ph-C\equiv C-CF_3$ and of $Ph-C\equiv C-CH_3$ have been prepared by heating the alkynes with dibenzoyl peroxide as an initiator. The degree of oligomerization, the average molecular weights and the nature of the end groups were determined using a combination of mass spectrometric techniques including desorption electron impact, fast atom bombardment, field desorption and MS/MS. The contrasting end-group patterns have been interpreted in terms of relative rates and HOMO/SOMO energy gaps.

Introduction

Replacement of a methyl substituent in an organic compound with a CF_3 group generally leads to dramatic changes in reactivity [1]. We and others have noted in previous studies the effect of CF_3 on the nucleophilic [2], electrophilic [3] and cycloaddition [4] reactions of $Ph-C\equiv C-CF_3$. The free-radical chemistry of this alkyne, however, has not been investigated [5]. As a part of a study of free-radical reactions of $Ph-C\equiv C-CF_3$ we became interested in the oligomerization of this alkyne and of its hydrocarbon counterpart, $Ph-C\equiv C-CH_3$.

Desorption ionization mass spectrometry has been shown to be effective for the characterization of low molecular weight polymers [6]. In particular, field desorption (FD) mass spectrometry can be used for the direct determination of molecular weight averages ($\bar{M}_n$ and $\bar{M}_w$), because minimal fragmentation is induced by this 'soft' ionization technique [7, 8]. Fast atom bombardment (FAB) mass spectrometry has also been used for the characterization of oligomers and polymers [8, 9]. Based on the observed molecular weights of oligomeric mixtures, FD and FAB mass spectrometry can be used to determine the degree of oligomerization and the nature of the end groups. Additional structural information of selected molecular ion precursors can be obtained by using tandem mass spectrometry (MS/MS) following collisional activation (CAD) to enhance fragmentation [10].

We report in this paper the free-radical oligomerization of $Ph-C\equiv C-CF_3$ and $Ph-C\equiv C-CH_3$, and the characterization of these low molecular weight

*Author to whom correspondence should be addressed.

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polymers using FD, FAB and desorption electron impact (DEI) ionization mass spectrometry. DEI and FAB ionization were combined with MS/MS to obtain additional structural information about oligomers purified by gel permeation chromatography (GPC). In this work MS/MS analyses were carried out using *B/E*-linked scanning and CAD.

Experimental

General

^{1}H NMR spectra were obtained on either a Varian EM390 or GE Omega 300 MHz spectrometer and ^{19}F NMR spectra were obtained on a Varian EM390 NMR spectrometer. Chemical shifts are reported in ppm relative to tetramethylsilane as an internal standard for ^{1}H NMR data and ^{19} F chemical shifts are in ppm downfield relative to $FCCl_3$ as the external reference. $CDCl_3$ was the sample solvent in both cases. In the NMR spectra, the spin multiplicity abbreviations, s, d, t and m, correspond respectively to singlet, doublet, triplet and multiplet. Infrared spectra were recorded using a Perkin-Elmer 1430 IR spectrophotometer. Sample purity was determined using a Hewlett Packard 5890 gas chromatograph equipped with a SE-30, 25-m fused silica column. The temperature was maintained at a 100 °C for 5 min then raised to 250 °C at the rate of 10 °C min^{-1}. Syntheses were carried out under a nitrogen atmosphere and oligomerizations under argon. All chemicals were reagent grade unless otherwise specified.

Chemicals

Methylene chloride (HPLC grade), tetrahydrofuran, benzene and zinc chloride were purchased from Fisher Scientific (Springfield, NJ). 3,3,3-Trifluoropropyne was obtained from PCR Incorporated (Gainesville, FL). Other reagents were purchased from Aldrich Chemical Co. (Milwaukee, WI).

3,3,3-Trifluoro-1-phenylpropyne

This monomer was prepared by a modification of the procedure of Bunch and Bumgardner [11]. A 40-ml portion of freshly dried and distilled tetrahydrofuran was placed in a 100 ml round-bottom flask equipped with a magnetic stirring bar and purged with nitrogen gas. The flask, immersed in a Dry Ice/acetone bath, was connected to a cold finger condenser via a T-shape glass tube with one end attached to a gas cylinder containing 3,3,3-trifluoropropyne. The acetylene was passed through the cold finger condenser until 80 droplets, approximately 3.7 g, were added to the flask. After the addition, the cold finger condenser and T-shape glass tube were removed, and the flask was sealed with a rubber septum. A 20 ml hexane solution containing 0.05 mol of n-butyl lithium was added by syringe to generate lithium acetylide. After stirring for 2 h, anhydrous zinc chloride (0.05 mol) was added to the reaction mixture. The reaction temperature was raised to 0 °C, and phenyl iodide (0.05 mol) was introduced followed by 1 g of

tetrakis(triphenylphosphine)palladium(0). The reaction mixture was allowed to warm to room temperature with stirring. After 4 h the reaction was quenched with 50 ml of 2 M aqueous HCl. The mixture was extracted with petroleum ether several times, and the combined ether layers were washed with saturated sodium bicarbonate and dried over magnesium sulfate. The drying agent was removed by filtration, and the filtrate was concentrated under vacuum. Distillation of the residue gave 1-phenyl-3,3,3-trifluoropropyne, b.p., 60–62 °C (40 mmHg) in 65–70% yield. ^{1}H NMR: 7.2–7.5 (m, 5H). ^{19}F NMR: −51 (s). IR (cm^{-1}): 2250.

Oligomerization

Oligomerizations were carried out in glass vials sealed under argon. The monomer (5.88 mmol) and dibenzoyl peroxide (0.59 mmol) were heated at 90 °C in bulk for 72 h. The crude viscous mixture was allowed to cool, then dissolved in CH_2Cl_2 to provide a stock solution containing approximately 1 μg oligomer per μl solution. This stock solution is designated C.

Gel permeation chromatography

Approximately 20 mg of stock solution C from the Ph−C≡C−CF_3 oligomerization described above was injected in each run. The solvent used for GPC was methylene chloride. GPC analysis was carried out on a Waters Associates (Bedford, MA) HPLC system consisting of two model 501 pumps, a model 740 integrator/recorder and a model 481 variable wavelength detector set at a wavelength of 245 nm. A Synchropak (Linden, IN) GPC 60 (25 cm×4.6 mm) column was used at a flow rate of 0.5 ml min^{-1} and 25 °C. The GPC effluent fractions were collected in glass vials. There were approximately 20 collections for each fraction. The solvent was evaporated under argon, and the residues were stored at 4 °C. Just before analysis by mass spectrometry, a CH_2Cl_2 stock solution consisting of 1 μg purified oligomers per μl solution was prepared. This stock solution is designated P.

Mass spectrometry

All mass spectrometric studies were carried out using a JEOL (Tokyo, Japan) JMS-HX110HF high-performance double-focusing mass spectrometer, equipped with a JMA-DA5000 data system and combination EI/CI/DCI/FAB or FD/FAB ion source. The accelerating voltage was 10 keV and the resolving power was 1000 for all low-resolution measurements. Exact mass measurements were carried out at 10 000 resolution. Prior to analysis, the mass spectrometer was calibrated using perfluorokerosene (PFK) for EI and DEI experiments and a mixture of CsI/KI (1:5 by weight) for FAB and FD studies.

In DEI analyses, 1–2 μg of stock solution P was loaded onto a 100 μm platinum wire from which the solvent quickly evaporated. The source temperature was 140 °C and the electron energy was maintained at 70 eV with a filament current at 50 μA. Samples were desorbed from the platinum wire by heating with a current that was raised at the rate of 1/8 A min^{-1}.

For FAB mass spectrometry, 1–2 μg of stock solution (C or P) was mixed with 1 μl of 3-nitrobenzyl alcohol as a matrix on a flat stainless-steel probe. The probe was inserted into the ion source where it was bombarded by xenon fast atoms at 6 keV.

In the FD study, 1–2 μg of stock solution C was deposited on a silicon emitter via a microsyringe under a stereomicroscope so that the emitter was uniformly coated with the sample. After solvent evaporation, the sample was inserted into the ion source and desorbed by slowly heating the emitter. The emitter temperature was programmed by passing through a current ranging from 0–40 mA at a selected rate. Under the experimental conditions used, the optimum anode current for sample desorption was 25 mA. The cathode potential was 1.2 keV. The pressure in the ion source was maintained at less than 10^{-6} Torr to prevent electrical discharges that could shatter the emitter.

Tandem mass analyses were carried out using *B/E*-linked scanning followed by CAD in the first field-free region of the double-focusing mass spectrometer. *B/E*-Linked scanning is a technique in which the magnetic field *B* and electric field *E* are scanned in a constant ratio while holding the accelerating voltage constant. The spectra obtained represent fragment ions of a precursor ion selected by the *B/E* ratio and the constant accelerating voltage. Helium was used as the collision gas in the first field-free region to promote fragmentation. The helium gas pressure in the collision cell was adjusted so that the intensity of the precursor ion was attenuated 70%.

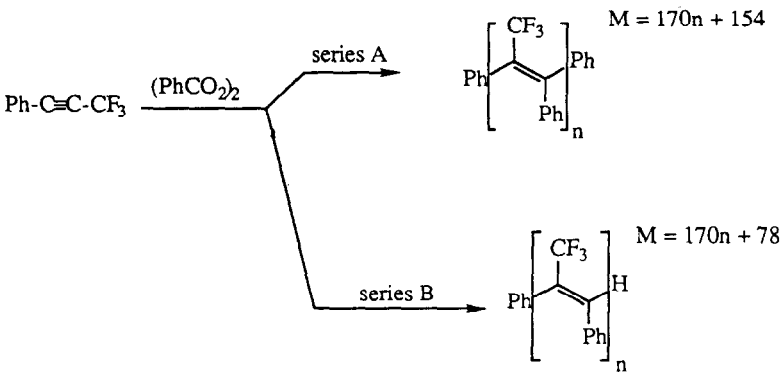
Determination of the molecular weight distribution

For number average ($\bar{M}_n$) and weight average ($\bar{M}_w$) molecular weight determinations, several FD spectra were recorded (with repetitive scanning) as the field emitter was slowly heated up to 34 mA. Data were recorded and analyzed on-line with the data system. Typically 5–10 spectra were averaged, and for calculation of the intensity distributions of the individual molecular species all isotopic signals were considered. A number-average molecular weight was calculated from $\bar{M}_n = \Sigma N_i M_i / \Sigma N_i$ and a weight-average molecular weight from $\bar{M}_w = \Sigma N_i M_i^2 / \Sigma N_i M_i$ where N_i is the intensity in the mass spectrum corresponding to the mass $M_i (= 1, 2, \ldots)$. Results are given in the text.

Results and discussion

Two series of oligomers, containing up to eight monomer units, were observed after heating neat Ph–C≡C–CF_3 with dibenzoyl peroxide at 90 °C for 3 d. Scheme 1 describes the two series, which are designated A and B.

Figure 1 shows the FD mass spectrum of the crude oligomer mixture. The B series of ions at *m/z* 588, 758, 928, 1098, 1268 and 1438 can be represented by the formula $M = 170n + 78$ where $n = 3$–8 and where the end



Scheme 1.

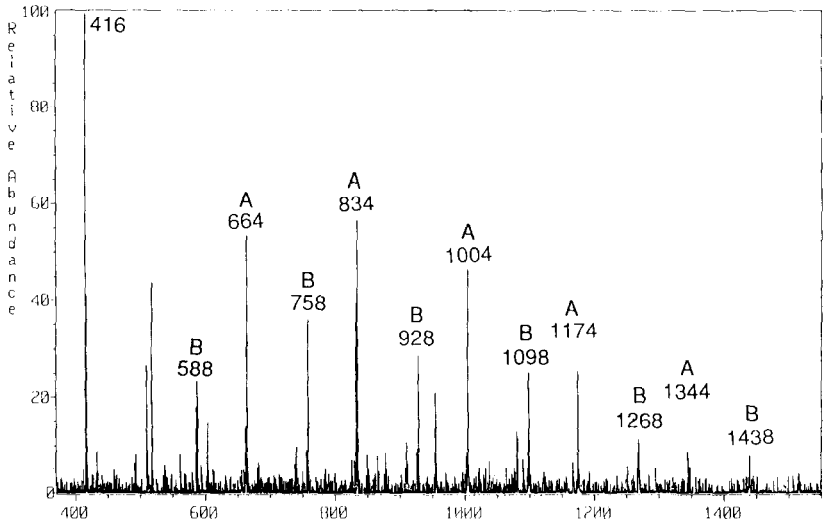


Fig. 1. Positive ion FD mass spectrum of Ph–C≡C–CF_3 oligomers.

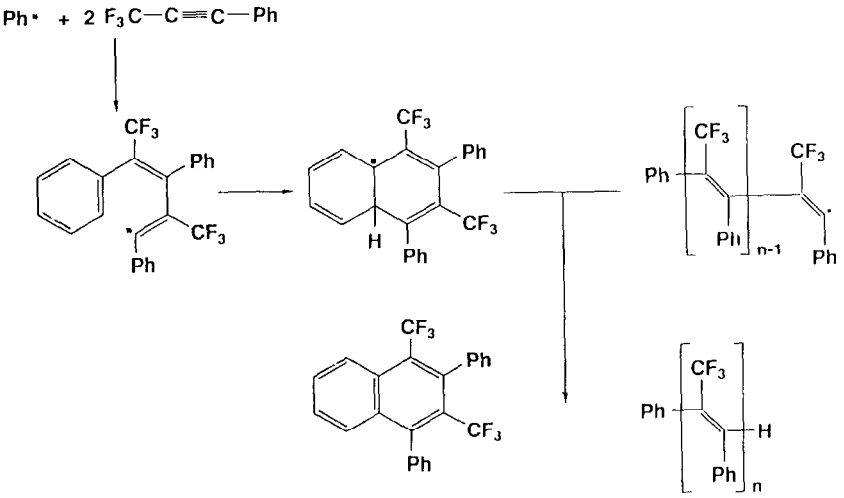
groups are phenyl and hydrogen. The A series with ions at m/z 664, 834, 1004, 1174, 1344 and 1514 corresponds to the formula $M = 170n + 154$ where $n = 3$–8 and where phenyl groups cap both ends of the oligomer. The A series terminated with phenyl groups was expected since phenyl radicals are generated through decomposition of the initiator [eqn. (1)].

$$\mathrm{Ph{-}\overset{O}{\overset{\|}{C}}{-}O{-}O{-}\overset{O}{\overset{\|}{C}}{-}Ph} \longrightarrow 2\mathrm{Ph{-}\overset{O}{\overset{\|}{C}}{-}O}\cdot \longrightarrow 2CO_2 + 2Ph\cdot \qquad (1)$$

Finding the B series, however, with phenyl and hydrogen as terminating groups presented a puzzle, for there were no apparent H-atom donors in the system. Hydrogen atoms attached to benzenoid rings have large dissociation energies and are not generally abstracted in radical reactions [12]. A clue

to the source of H atoms was provided by the appearance in the mass spectrum of a compound with m/z of 416 as shown in Fig. 1. We believe this compound has structure (**1**) and that it arises by the reactions depicted in Scheme 2.

Evidence supporting the assignments given in Schemes 1 and 2 was obtained by subjecting the reaction mixture to GPC (Fig. 2). The two partially resolved fractions were collected, concentrated and analyzed using mass spectrometry. The second fraction was enriched with respect to low molecular weight oligomers and contained primarily a molecule weighing 416 mass units as indicated by the positive ion DEI mass spectrum shown in Fig. 3. DEI was used for ionization instead of FAB because this low molecular weight oligomer at m/z 416 was volatile enough for DEI and because FAB mass spectra contain abundant ions below m/z 500. The B/E-linked scan of the molecular ion at m/z 416 following DEI and CAD is shown in Fig. 4. The fragment ions such as $[M-F]^+$ and $[M-CF_3]^+$ at m/z 397 and m/z 347 are indicated in Fig. 4 and are consistent with compound (**1**). A high-resolution exact mass measurement confirmed the composition as shown in scheme 2. Fraction 1 from the GPC separation shown in Fig. 2 contained the higher molecular weight oligomers and was analyzed by positive-ion FAB mass spectrometry. This positive-ion FAB mass spectrum is shown in Fig. 5. One of the ions from the B series, detected at m/z 758 ($n=4$), was analyzed using CAD and B/E-linked scanning (Fig. 6). In addition, the A series ion detected at m/z 834 ($n=4$) was also analyzed by CAD and B/E-linked scanning (data not shown). Both of these ions fragmented to eliminate trifluoromethyl and phenyl groups, indicative of the substituents on the polyacetylene chain. In addition, fragment ions were detected that were the



(**1**)

Calculated for $C_{24}H_{14}F_6$: 416.0100. Found: 416.0100.

Scheme 2.

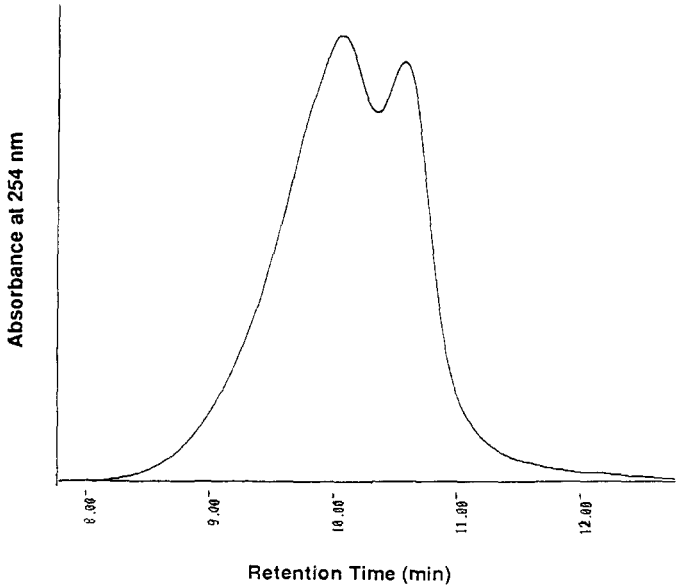


Fig. 2. GPC of Ph−C≡C−CF_3 oligomers. The two partially resolved bands (fraction 1 and 2, respectively) were collected and analyzed using mass spectrometry.

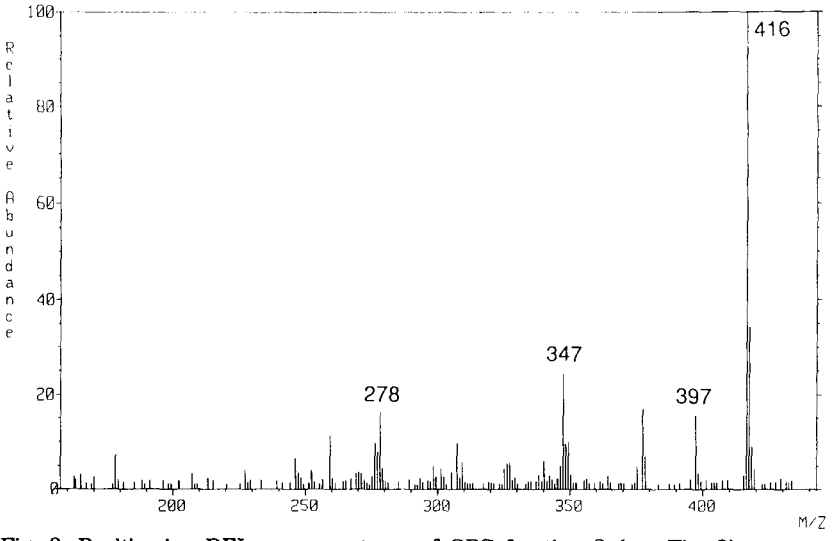


Fig. 3. Positive-ion DEI mass spectrum of GPC fraction 2 (see Fig. 2).

result of cleavage of the polymer backbone, such as m/z 417 and m/z 341 in Fig. 6. These ions were consistent with the structures shown in Schemes 1, 3 and 4.

After heating Ph−C≡C−CH_3 with initiator as described above for Ph−C≡C−CF_3, the resulting mixture of oligomers was analyzed using positive-

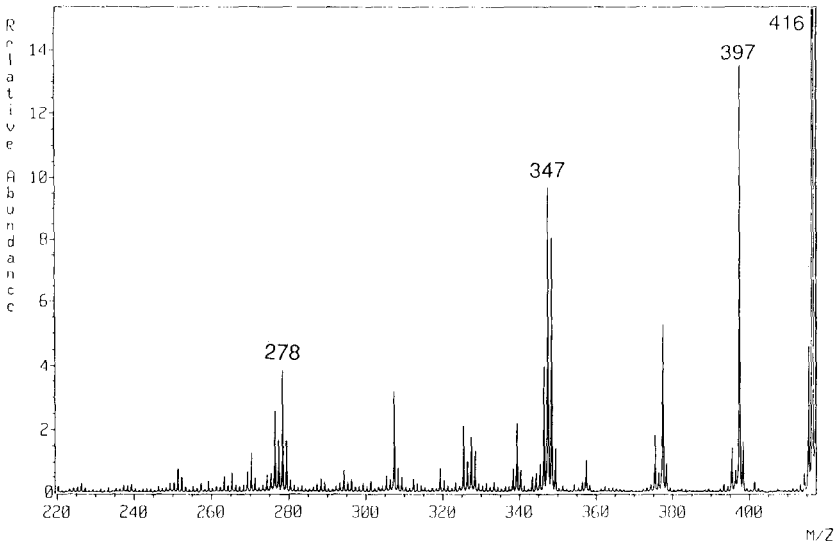


Fig. 4. *B/E*-Linked scan of *m/z* 416 following positive-ion DEI and collisional activation (CAD).

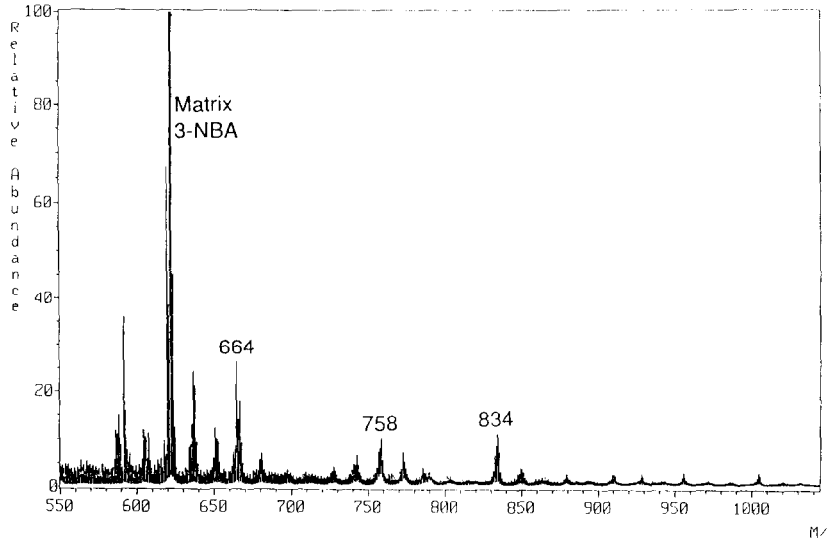


Fig. 5. Positive-ion FAB mass spectrum of GPC fraction 1 (see Fig. 2).

ion FD mass spectrometry, and the results are shown in Fig. 7. The molecular ions corresponding to the formula $M=(116)n+122$ where $n=2$–7 were detected in abundance. A less abundant second series of ions of the formula $M=(116)n+121+115$ where $n=1$–4 was also detected. Scheme 5 shows how these oligomeric products may have been formed. The striking difference between the results summarized in Scheme 1 and those in Scheme 5 is the end-group pattern. As shown in Scheme 5, Ph−C≡C−CH_3 is attacked by

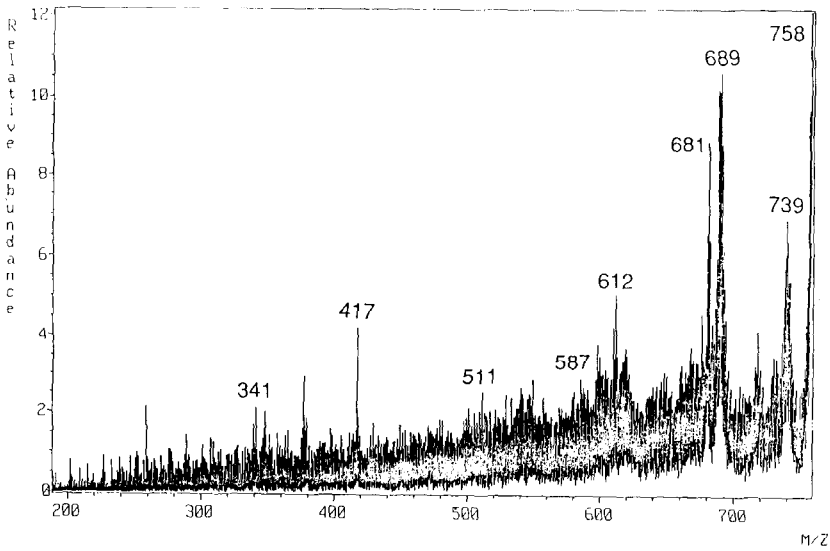
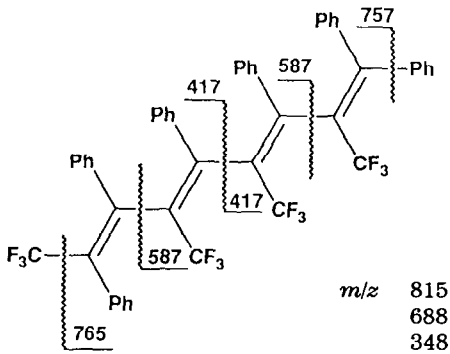


Fig. 6. *B/E*-Linked scan of *m/z* 758 following positive-ion FAB and CAD.

Fragmentation pattern *m/z* 834.



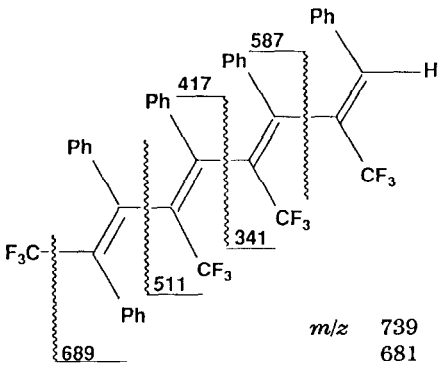
m/z		
	815	$[M-F]^+$
	688	$[765-Ph]^{\cdot+}$
	348	$[417-CF_3]^{\cdot+}$

Scheme 3.

Ph–CO–O·*, whereas reaction of Ph–C≡C–CF_3 is initiated by a phenyl radical following decarboxylation of Ph–CO–O· [eqn. (1)]. This difference suggests that Ph–C≡C–CH_3 is more reactive than Ph–C≡C–CF_3, since the former intercepts the benzoyloxy radical before it can decarboxylate. Moreover, Ph–C≡C–CH_3 is susceptible to H-abstraction to form the stabilized propargylic radical, which enters into reaction as indicated in Scheme 5. Peaks corresponding to $M = 116n + 121 + 115$ where $n = 1$–4 can be discerned in Fig. 7. The failure to observe a cyclic product comparable to (1) in the

*Induced decomposition of the initiator is also a possibility, R· + PhCOOOCOPh → ROCOPh + PhCOO·, but the conclusion that Ph–C≡C–CH_3 is more reactive than Ph–C≡C–CF_3 in these oligomerizations would be unchanged.

Fragmentation pattern *m/z* 758



m/z 739 $[M-F]^+$
681 $[M-Ph]^+$

Scheme 4.

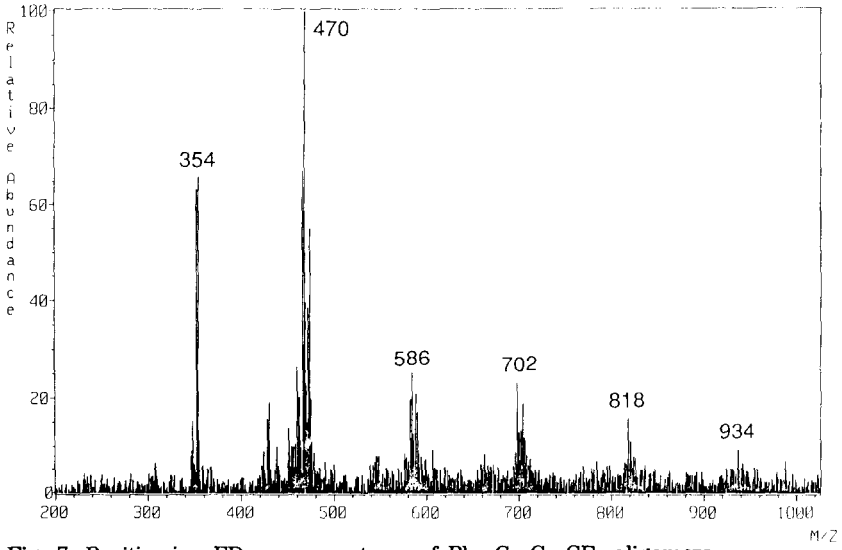
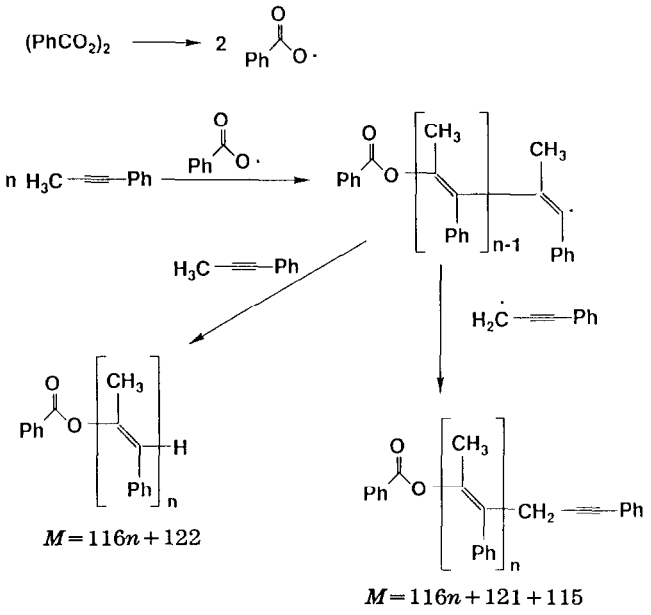


Fig. 7. Positive-ion FD mass spectrum of $Ph-C\equiv C-CF_3$ oligomers.

reaction of $Ph-C\equiv C-CH_3$ can be attributed to the greater reactivity of $Ph-C\equiv C-CH_3$ and its ability to act as a H donor.

Since $Ph-C\equiv C-CH_3$ has a higher HOMO and a higher LUMO than $Ph-C\equiv C-CF_3$ [13], the observation that $Ph-C\equiv C-CH_3$ reacts faster with $PhCO_2\cdot$ than $Ph-C\equiv C-CF_3$ suggests that the SOMO–HOMO interaction is more important than the SOMO–LUMO combination. These results, therefore, provide another example of a radical system obeying the HOMO rule [14]. The regiochemistry shown in Scheme 1 is based on model compound studies [5] and on the fragmentation patterns revealed in Fig. 6. As seen in Fig. 6, the major decomposition pathway involves loss of CF_3 from the molecular ion giving *m/z* 689. This is a facile process since CF_3 probably leaves a carbon atom to which is attached a phenyl group capable of stabilizing a



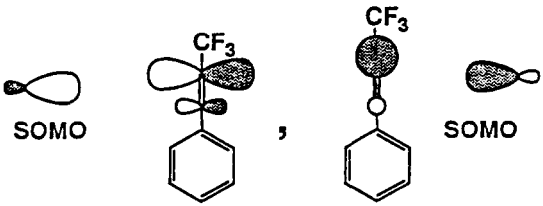
Scheme 5.

positive charge. If the regiochemistry were opposite to that given in Scheme 1 for the H-terminated series, then CF_3 loss would require cleavage from a vinylic carbon atom having no phenyl stabilization, a process expected to be high energy and therefore improbable. The regiochemistry suggested in Scheme 1 is also that expected on the basis of spin-density arguments [13] and on the relative stability of radical intermediates, with radical (**2**) being more stable than radical (**3**) [15].

$$\underset{(\mathbf{2})}{Ph-\dot{C}=} \qquad \underset{(\mathbf{3})}{=\dot{C}-CF_3}$$

Combining the relative rate data with the regiochemistry leads to the conclusion that the important frontier molecular orbital interaction is the singly occupied molecular orbital (SOMO) of the radical and the unconjugated π-bond (HOMO) of $Ph-C\equiv C-CF_3$. Although interaction of SOMO with the conjugated π^*-bond (LUMO) of $Ph-C\equiv C-CF_3$ would lead to the same regio preference†, this combination predicts that $Ph-C\equiv C-CF_3$ would be the

†The molecular orbital arguments and our data indicate preferences and do not demand regiospecificity.



more reactive acetylene in these oligomerizations, at variance with the experimental results. There is no direct evidence for the stereochemistry shown in Scheme 1. *Anti*-addition has been assumed, for this mode is often favored in radical additions [16]. However, as indicated in Scheme 2, some *syn*-addition must also occur.

The number average molecular weight, $\bar{M}_n$, and the weight average molecular weight, $\bar{M}_w$, of oligomers obtained from Ph−C≡C−CF_3 and from Ph−C≡C−CH_3 were determined utilizing the FD mass-spectrometric data [7, 8]. This analysis gave $\bar{M}_n = 669$ and $\bar{M}_w = 741$ for the oligomers derived from Ph−C≡C−CF_3 and $\bar{M}_n = 459$ and $\bar{M}_w = 577$ for the Ph−C≡C−CH_3-based polymers.

In conclusion, this work demonstrates that mass-spectrometric techniques can provide information not only on the degree of oligomerization but also through leaving group analysis, on the relative reactivities of monomers. In the oligomerizations studied, changing from CF_3 to CH_3 in the phenylacetylene system results in enhanced reactivity and a different mechanism for hydrogen-atom termination.

Acknowledgement

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References

1 C. L. Bumgardner and M.-H. Whangbo, in J. F. Liebman, A. Greenberg and W. R. Dobier Jr. (eds.), *Fluorine-Containing Molecules*, VCH, New York, 1988, p. 84; J. T. Welch and S. Eswarakrishnan, *Fluorine in Bioorganic Chemistry*, Wiley, New York, 1991, p. 7.

2 C. L. Bumgardner, J. E. Bunch and M.-H. Whangbo, *Tetrahedron Lett.*, *27* (1986) 1883; C. L. Bumgardner, J. E. Bunch and M.-H. Whangbo, *J. Org. Chem.*, *51* (1986) 4082.

3 R. A. Cox, E. Grant, T. Whitaker and T. T. Tidwell, *Can. J. Chem.*, *68* (1990) 1876; N. Yoneda, S. Matsuoka, N. Miyaura, T. Fukuhara and A. Suzuki, *Bull. Chem. Soc. Jpn.*, *63* (1990) 2124.

4 C. L. Bumgardner, S. T. Purrington, M. W. Shockley and J. C. Sloop, Paper presented at *199th ACS Nat. Meet.*, Boston, MA, April 22–27, 1990.

5 Some preliminary work involving radical addition to Ph–C≡C–CF_3 has been reported, C. L. Bumgardner and M. W. Shockley, Paper presented at *Am. Chem. Soc. 105th North Carolina Sectional Conf.*, Raleigh, NC, April 6, 1991.
6 H.-R. Schulten and R. P. Lattimer, *Mass Spectrom. Rev.*, *3* (1984) 231.
7 R. P. Lattimer and H.-R. Schulten, *Int. J. Mass Spectrom. Ion Process.*, *52* (1983) 105.
8 R. P. Lattimer and H.-R. Schulten, *Int. J. Mass Spectrom. Ion Process.*, *67* (1985) 277.
9 R. P. Lattimer, *Int. J. Mass Spectrom. Ion Process.*, *55* (1983/1984) 221.
10 F. W. McLafferty (ed.), Tandem Mass Spectrometry, Wiley, New York, 1983.
11 J. E. Bunch and C. L. Bumgardner, *J. Fluorine Chem.*, *36* (1987) 313.
12 T. H. Lowry and K. S. Richardson, *Mechanism and Theory in Organic Chemistry*, 3rd ed., Harper and Row, New York, 1987, p. 16.
13 T. A. Albright, J. K. Burdett and M.-H. Whangbo, *Orbital Interactions in Chemistry*, Wiley, New York, 1985, pp. 82 and 178.
14 S. S. Shaik and E. Canadell, *J. Am. Chem. Soc.*, *112* (1990) 1446.
15 F. G. Bordwell and M. J. Bausch, *J. Am. Chem. Soc.*, *108* (1986) 1981.
16 B. Giese, *Angew. Chem., Int. Ed. Engl.*, *24* (1985) 553.