preciably affected by complicating competitive pathways, are supposed to be representative of the intrinsic course of the pinacol rearrangement. The kinetic data did not allow separation of the dehydration step from the migration of the methyl group since the protonated *trans*-1,2-dimethyl-1,2-cyclopentanediol is the only intermediate surviving long enough to be trapped by a base.

The observation of a rate enhancement in the rearrangement of the cis isomer and the failure to observe any product traceable to the intermediacy of a carbenium ion strongly support a rearrangement mechanism involving participation of the methyl group to the leaving of the water molecule. This behavior appears in contrast with evidence from solution-chemistry studies of the same substrates, indicating possible stabilization of the tertiary carbenium ion by the solvent in the condensed medium.

Additional evidence for this effect is provided by the observed nucleophilic assistance of water molecules in the epimerization of the trans diol in acidic solution,[8] which is not operative in the gas phase, under the conditions of the present study.

It can also be noted that, in the absence of significant interactions with the solvent, conformational effects may play a role in the gas phase. In fact, in substituted cyclopentane, the cis epimer might exhibit higher strain than the trans one. This effect, whose magnitude is unknown in the protonated substrates but apt to be small, could contribute to accelerate the rearrangement of the cis with respect to the trans diol.[32] Further work on suitable model compounds is in progress to evaluate the point. On the other hand, a conformational effect can help explain the apparently inefficient participation of the hydroxyl group in *trans*-**1**.

In fact, a proton bridge may stabilize the ring conformation bearing the OH groups in a quasi-equatorial position at the expense of the only one suited for OH participation, namely, that having the migrating group in an antiperiplanar position with respect to the leaving water molecule.

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Registry No. *cis*-**1**, 33046-19-4; *trans*-**1**, 33046-20-7; **2**, 4541-32-6; D_3^+, 12595-96-9; CH_5^+, 15135-49-6; $C_2H_5^+$, 14936-94-8; *t*-$C_4H_9^+$, 14804-25-2; *t*-$C_4H_9CH_3$, 463-82-1; CH_4, 74-82-8; *i*-C_4H_{10}, 75-28-5; $N(CH_3)_3$, 75-50-3; D, 7782-39-0; $HOC(CH_3)_2C(CH_3)_2OH$, 76-09-5; 1,2-dimethylcyclopentene, 765-47-9.

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[32] This possibility was considered by one of the referees whose suggestion is gratefully acknowledged.

Gas-Phase Cationic Methylation of Biphenyl and Methylbiphenyls. A Mass Spectrometric and Radiolytic Study

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Abstract: Alkylation of biphenyl and methylbiphenyls by Me_2F^+ and Me_2Cl^+ ions has been studied in the gas phase by a combination of radiolytic and mass spectrometric techniques, including chemical ionization and collisionally induced dissociation spectrometry. The results, in particular, the disproportionately high extent of ortho substitution, conform to a mechanistic model envisaging, in addition to direct substitution, the preliminary formation of an electrostatically bound adduct between the symmetric, bidentate electrophile and *both* rings of the substrate. Formation of the adduct increases the local concentration of the electrophile, hence the rate of alkylation at the ortho positions of biphenyl.

As an extension of previous studies on aromatic substitution by gaseous cations,[1] we have investigated the reactivity of biphenyl and methylbiphenyls toward two typical methylating agents, Me_2F^+ and Me_2Cl^+, in the dilute gas state. It had been noted that substituents containing localized n-electron pairs on halogen, oxygen, and nitrogen atoms promote a disproportionately high extent of ortho substitution by gaseous cations. This has led to the suggestion that, in addition to direct attack, ring substitution can involve the formation of a preliminary adduct, characterized by the electrostatic interaction of the cation with the n electrons of the substituent, which increases the local concentration of the electrophile at the ortho positions, accounting for the observed regioselectivity.[2-5]

Biphenyl, a substrate containing two adjacent aromatic rings, provides a suitable model to ascertain whether an analogous preliminary interaction, involving a delocalized π system rather than a localized n-electron pair, enhances the regioselectivity of the substitution by gaseous, unsolvated cations. In this connection, it is of interest that some kind of participation of the ring not being attached has been invoked to account for the ortho orientation prevailing in certain reactions of biphenyl in solution.[6,7] Furthermore, the reactivity of biphenyl is well characterized by theoretical and semiempirical treatments,[8,9] as well as by free-energy correlations,[10] which provide useful comparison terms to

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(1) For recent reviews, see: (a) F. Cacace, *Rad. Phys. Chem.* **1982**, *80*, 99. (b) Speranza, M., *Gazz. Chim. Ital.* **1983**, *113*, 37, and references therein.

(2) Attinà, M.; Giacomello, P. *J. Am. Chem. Soc.* **1979**, *101*, 6040.

(3) Attinà, M.; Cacace, F.; Ciranni, G.; Giacomello, P. *J. Chem. Soc., Perkin Trans 2* **1979**, 891.

(4) Angelini, G.; Lilla, G.; Speranza, M. *J. Am. Chem. Soc.* **1982**, *104*, 7091.

(5) (a) Attinà, M.; Cacace, F. *J. Am. Chem. Soc.* **1983**, *105*, 1122. (b) Attinà, M.; Cacace, F.; de Petris, G. *Ibid.* **1985**, *107*, 1556.

(6) Coombes, R. G.; Golding, J. G. *Tetrahedron Lett.* **1976**, 774.

(7) (a) Taylor, R. *J. Chem. Soc. B* **1966**, 727. See, however: (b) Schofield, K. *Aromatic Nitration*; Cambridge University Press: Cambridge, 1980; p 261 and references therein.

(8) Streitwieser, A., Jr. *Molecular Orbital Theory for Organic Chemists*; Wiley: New York, 1961.

(9) For a calculation of delocalization energy, indices of aromatic stabilization, and resonance energy of biphenyl, see: Milun, M.; Sabotka, Ž.; Trinajstic, N. *J. Org. Chem.* **1972**, *37*, 139, and references therein.

(10) (a) Humffray, A. A.; Bruce, R. L. *J. Org. Chem.* **1979**, *44*, 724, and references therein. (b) Stock, L. M.; Brown, H. C. *Adv. Phys. Org. Chem.* **1963**, *1*, 35.

Table I. CID Mass Spectra of $C_{13}H_{13}^+$ Ions

	relative intensities[a]			
	protonation of methylbiphenyls by t-Bu^+			methylation of biphenyl by Me_2Cl^+
m/z	*2*	*3*	*4*	
39	2.4	2.1	2.4	1.8
51	4.5	4.3	4.8	3.2
63	4.1	3.6	4.7	2.8
65	4.1	4.1	3.8	3.6
77	6.8	6.1	6.6	6.3
91	11.7	12.1	10.7	12.7
102	3.2	3.3	3.6	3.4
115	9.6	8.6	10.0	9.5
128	9.3	9.2	7.9	9.4
139	3.6	4.6	3.6	3.6
141	6.6	7.1	7.0	8.4
152	34.1	34.7	34.8	35.2

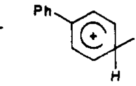
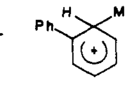
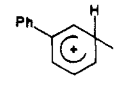
[a] The intensities are normalized with respect to the sum of the intensities of a spectrum which represents the average of 30 scans. The peak at m/z 154 contains a contribution from unimolecular fragmentation and therefore has been omitted, as well as ions at m/z 164, 167, and 168 which originate from low-energy fragmentation processes. Position of the methyl group is italicized.

Table II. Similarity Indexes of the CID Mass Spectra of $C_{13}H_{13}^+$ Ions

	protonated 2-methylbiphenyl[a]	protonated 3-methylbiphenyl[a]	protonated 4-methylbiphenyl[a]	methylated biphenyl[b]
protonated 2-methylbiphenyl	3.3[c]	10.6	9.4	21.7
protonated 3-methylbiphenyl		11.8[c]	15.6	16.9
protonated 4-methylbiphenyl			4.6[c]	27.8
methylated biphenyl				10.5[c]

[a] Proton transfer from t-Bu^+. [b] Methyl transfer from Me_2Cl^+. [c] These values provide an indication of the inherent reproducibility of the CID spectra measurements.

Table III. Estimated Thermochemical Data[a]

substrate	ionic reactant	ionic product	$\Delta H°$, kcal mol^{-1}
biphenyl	Me_2F^+ Me_2Cl^+ Me_3O^+		−58 −38 −7
biphenyl	Me_2F^+ Me_2Cl^+ Me_3O^+		−50 −30 +1
biphenyl	Me_2F^+ Me_2Cl^+ Me_3O^+		−43 −23 +8
2-methylbiphenyl	t-Bu^+	(2-methylbiphenyl)H^+	−1
3-methylbiphenyl	t-Bu^+	(3-methylbiphenyl)H^+	−1
4-methylbiphenyl	t-Bu^+	(4-methylbiphenyl)H^+	−2

[a] See ref 17.

gas-phase results. Finally, the dihedral angle of the biphenyl rings can be modified by suitable ortho substituents, thus affecting their degree of conjugation and their mutual electronic effects, which may represent a mechanistically valuable tool.[11]

This study has been carried out with the coordinate application of mass spectrometric techniques, e.g., chemical ionization (CI) and collisionally induced dissociation (CID) spectrometry, with radiolytic experiments performed in carefully selected gaseous systems at nearly atmospheric pressure, a combination which has proved particularly powerful in previous investigations.[12]

Experimental Section

Materials. The gases, having a stated purity in excess of 99.9 mol %, were obtained from Matheson Gas Products Inc. MeF (Matheson), whose stated purity was 99 mol %, contained trace impurities, including Me_2O and Me_2CO, whose total amount, determined by GLC, corresponded to ca. 0.4 mol %. The chemicals used as reactants or reference standards in the analyses were obtained from commercial sources or prepared according to unexceptional procedures,[13] their identity and purity being established by GLC, MS, and NMR spectrometry. The samples used as substrates in the radiolytic experiments, as well as in CI and CID spectrometry, were assayed by GLC on the same columns subsequently used for the analysis of the products, and, when required, purified by preparative GLC.

Radiolytic Experiments. The gaseous samples were prepared using a greaseless vacuum line, as described in earlier reports, and enclosed in sealed 250-mL Pyrex ampoules. The irradiations were carried out at a dose rate of 1×10^4 Gy h^{-1} to a total dose of ca. 3×10^4 Gy in a 220 Gammacell (Nuclear Canada Ltd.) fitted with a thermostatic device which maintained the samples at 100 °C during the irradiation.

The radiolytic products were analyzed by GLC, using Sigma 1 or Sigma 3 chromatographs from Perkin-Elmer Co., equipped with flame ionization or photoionization detectors, and by GLC/MS, using a Hewlett-Packard 5982 A quadrupole mass spectrometer. The identity of the products was established by comparison of their capacity factors with those of authentic samples, as well as from their mass spectra. The yields of the products were deduced from the areas of the corresponding elution peaks, using the internal standard calibration method.

The following columns were used: (i) a 50-m long, 0.25-mm. i.d. fused silica capillary column, coated with methyl silicone SP 2100 fluid, deactivated with Carbowax 20M [The column provides a clean separation of 11 out of the 12 isomeric dimethylbiphenyls, in a much shorter time and with a much better resolution than previously used columns.[14]]; (ii) a 2-m long, 2-mm i.d. stainless steel column, packed with SP 2100 (10% w/w) + Bentone 38 (6%) on 80/100 mesh AW, silanized Chromosorb W; (iii) a 3.5-m long, 2-mm i.d. stainless steel column, packed with SP 2100 (20%) + Carbowax 1500 (0.1%) on 100/120 mesh Supelcoport.

Mass Spectrometric Measurements. The protonation and the methylation of biphenyl, methylbiphenyls, and dimethylbiphenyls were carried out in the ion source of a ZAB-2F mass spectrometer (VG Micromass Ltd.) operated in the CI mode and fitted with a MKS Baratron Model 221A capacitance manometer. The protonation experiments were carried out under the following typical conditions: isobutane pressure, ca. 0.5 torr, source temperature 180 °C, emission current 0.5 mA, electron energy 100 eV. Similar conditions prevailed in the methylation experiments, except for the lower pressure of MeF and MeCl, 0.25–0.30 torr. The mass resolving power was 2000 and the energy resolution, 4000. The CID spectra were recorded by admitting He into the collision cell and increasing its pressure until a main beam reduction of 30% was achieved.

Results

CID Spectra of $C_{13}H_{13}^+$ Ions. The CID spectra of the $C_{13}H_{13}^+$ adducts from the alkylation of biphenyl with Me_2Cl^+ ions in MeCl are compared in Table I with those of model ions from the protonation of the isomeric methylbiphenyls with t-Bu^+ ions in isobutane, both sets of reactions occurring under typical CI conditions. Even a cursory examination reveals the close similarity of the CID spectra reported, which contain nearly equal abundances of the same fragment ions. Table II provides a more quantitative comparison, giving the similarity indexes (SI)[15,16] of

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(11) (a) Zaraiskii, A. P., *Usp. Khim.* **1978**, *47*, 847. (b) Schmid, E. D.; Brosa, B., *J. Chem. Phys.* **1972**, *56*, 6267, and references therein.

(12) (a)Attinà, M.; Cacace, F.; de Petris, G., Fornarini, S.; Giacomello, P. *J. Am. Chem. Soc.* **1985**, *107*, 2297. (b) Attinà, M.; Cacace, F. *Ibid.* **1986**, *108*, 318.

(13) The preparation of the commercially unavailable dimethylbiphenyl isomers was carried out according to: (a) Bamfield, P.; Quan, P. M. *Synthesis* **1978**, 537, for 2,6-, 3,5-, and 2,4′-dimethylbiphenyl. (b) Taylor, E. C.; Kiensle, F.; Mc Killop, A. *J. Am. Chem. Soc.* **1970**, *92*, 6088, for 2,4- and 2,5-dimethylbiphenyl. (c) Laseter, J. L.; Mende, U.; Griffin, G. W. *Org. Mass Spectrom.* **1970**, *4*, 599, for 2,3-, 3,4-, and 2,3′-dimethylbiphenyl.

(14) As an example, the resolution of six isomeric dimethylbiphenyls required longer than 1 h when a capillary Apiezon L column was used (cf. ref 13c) as compared with the complete resolution of 11 isomers in less than 25 min, achieved in this work.

(15) Lay, J. O.; Gross, M. L.; Zwinselman, J. J.; Nibbering, N. M. M. *Org. Mass Spectrom.* **1983**, *18*, 16.

Table IV. Representative CID Mass Spectra of $C_{14}H_{15}^+$ Ions

	relative intensity[a]														
	protonation of dimethylbiphenyls[b]									methylation of methylbiphenyls[b,c]					
	2,2'	*3,3'*		*4,4'*		*2,3*		*2,4*	*3,4*	*2*		*3*		*4*	
m/z	II	I	II	I	II	I	II	II	II	III	IV	III	IV	III	IV
39	3.2	3.1	2.1	2.9	1.9	3.1	1.4	1.5	1.7	1.2	3.9	2.2	2.2	2.8	1.8
51	3.1	4.4	2.9	3.9	2.2	5.1	2.3	2.5	2.6	5.7	3.8	5.4	3.0	4.6	4.7
65	6.6	6.4	6.5	6.8	6.2	4.1	2.9	2.7	2.8	5.8	4.0	4.9	3.4	5.7	4.9
77	4.6	4.7	3.7	5.6	4.2	8.8	9.6	9.0	9.0	8.4	7.4	9.7	9.6	7.6	7.8
91	16.5	17.5	17.5	18.9	17.4	12.4	10.2	9.0	10.0	13.3	11.2	11.6	12.0	14.3	14.2
102	3.1	2.8	3.2	2.7	2.5	4.4	3.9	4.8	5.0	5.1	5.4	4.2	4.8	3.4	4.5
105	2.0	2.4	2.7	1.6	2.3	5.3	5.6	7.5	7.0	8.2	6.7	8.6	7.9	8.0	5.9
115	14.0	14.9	12.4	15.1	13.0	13.4	10.4	11.4	11.3	12.1	12.0	13.1	13.0	13.9	13.1
128	12.3	11.4	11.4	13.4	11.5	12.4	12.4	12.1	11.8	10.9	14.7	11.6	13.1	10.7	11.8
141	9.0	*a*	9.2	*a*	9.0	*a*	9.4	9.5	8.9	*a*	*a*	*a*	*a*	*a*	*a*
151	25.6	32.4	28.5	29.3	29.7	30.9	31.9	29.9	29.8	26.4	30.8	28.8	30.9	29.0	31.4

[a] Some peaks at m/z 141, 154, 164, 167, and 168 contain contributions from unimolecular fragmentation processes and therefore have been omitted, as well as those at m/z 181 and 182, originating from low-energy fragmentation processes. [b] Positions of Me groups italicized. Columns I and II refer respectively to protonation by $C_nH_5^+$ ions (n = 1, 2) in CH_4 CI, and by *t*-Bu^+ ions in isobutane CI. [c] Columns III and IV refer respectively to alkylation by Me_2F^+ and by Me_2Cl^+.

Table V. Similarity Indexes of Representative CID Mass Spectra of $C_{14}H_{15}^+$ Ions from the Protonation of Dimethylbiphenyls and the Methylation of Methylbiphenyls

	protonated adducts[a]								methylated adducts					
substrates	*2,2'*	*3,3'*		*4,4'*	*2,3*		*2,4*	*3,4*	*2*		*3*		*4*	
2,2'	17.5	21.8	17.6[b]	26.8	88.5	82.3[b]	109.8	101.4	65.7[c]	80.7[d]	83.7[c]	87.8[d]	58.2[c]	70.9[d]
3,3'		28.4		13.8	74.7	55.0[b]	88.6	80.8	70.7[c]	83.5[d]	86.4[c]	83.1[d]	56.9[c]	72.2[d]
4,4'				22.7	74.5		95.8	85.4	63.4[c]	74.9[d]	76.1[c]	78.1[d]	48.7[c]	63.3[d]
2,3					30.1		14.2	8.7	49.7[c]	67.1[d]	18.5[c]	41.6[d]	30.7[c]	43.8[d]
2,4							8.1	7.3	43.0[c]	63.3[d]	11.7[c]	38.5[d]	37.6[c]	49.2[d]
3,4								18.1	35.4[c]	57.8[d]	9.7[c]	38.4[d]	32.1[c]	42.5[d]

[a] All values refer to protonation by *t*-Bu^+ ions under isobutane CI conditions, except where otherwise noted. Positions of Me groups italicized. [b] Protonation by $C_nH_5^+$ ions (n = 1, 2) under methane CI conditions. [c] Alkylation by Me_2Cl^+ ions under MeCl CI conditions. [d] Alkylation by Me_2F^+ ions under MeF CI conditions.

all pairs of CID spectra. One should bear in mind that, by definition, the larger the diffferences between two spectra, the higher their SI values. Owing to unavoidable fluctuations of the instrumental parameters, the CID spectra of the same ion, obtained with the same reaction, are not identical, and their SI are included in Table II to provide an indication of the inherent reproducibility of the measurements. While the definition of the minimum SI value indicative of actual structural differences is somewhat arbitrary, a conservative estimate[16] sets the threshold above 40.

Given the above the results outlined in Tables I and II show that model ions from the protonation of isomeric methylbiphenyls can hardly be discriminated on the grounds of their CID spectra. In principle, this could be traced to the isomerization of initially different isomers, excited by the exothermicity of their formation process, to a common, most stable structure, e.g., that of 2-methyl-4-phenylbenzenium ion. However, the exothermicity of the proton transfer from *t*-Bu^+ to methylbiphenyls is remarkably low, as shown in Table III, which favors an explanation based on the failure of CID spectrometry to provide a positive discrimination among isomeric methylbiphenyl arenium ions containing the Me group in different positions of the same ring (vide infra).

The CID spectra of the $C_{13}H_{13}^+$ adduct from the reaction of Me_2Cl^+ ions with biphenyl are indistinguishable from those of the model ions, which suggests a protonated methylbiphenyl structure for the alkylated product.

CID Spectra of $C_{14}H_{15}^+$ Ions. Ten model $C_{14}H_{15}^+$ ions have been obtained by protonating with *t*-Bu^+ and $C_nH_5^+$ ions (n = 1, 2) under CI conditions 2,2'-, 2,3'-, 2,4'-, 2,3-, 2,4-, 2,5-, 3,3'-, 3,4-, 3,5-, and 4,4'-dimethylbiphenyl. The CID spectra of several model ions, fully representative of those of all isomers investigated, are compared in Table IV with the CID spectra of $C_{14}H_{15}^+$ adducts from the reactions of Me_2F^+ and Me_2Cl^+ with isomeric methylbiphenyls. The SI calculated for representative pairs of spectra are reported in Table V. On inspection it may be seen that the model $C_{14}H_{15}^+$ ions can be divided into two classes, which include respectively the isomers whose methyl groups are bound to different rings (class A), and those whose methyl groups are bound to the same ring (class B).[18] Further discrimination among individual isomers belonging to the same class is apparently beyond the structural resolution of CID spectrometry, consistent with the considerations concerning $C_{13}H_{13}^+$ ions.

The CID spectra of $C_{14}H_{15}^+$ ions from the methylation of methylbiphenyls with Me_2F^+ and Me_2Cl^+ ions can be regarded as linear combinations of class A and class B spectra. The trend of the SI suggests a definite preference for the alkylation of the methyl-substituted ring (class B spectra),[19] which depends on the nature of the substrate, increasing in the order 4-methylbiphenyl < 2-methylbiphenyl < 3-methylbiphenyl.

Radiolytic Methylation. The products from the gas-phase methylation of biphenyl with radiolytically formed Me_2Cl^+ and

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(16) Harrison, A. G.; Gäumann, T.; Stahl, D., *Org. Mass Spectrom.* **1983**, *18*, 517.

(17) Thermochemical data for neutral species: (a) Cox, J. D.; Pilcher, G. *Thermochemistry of Organic and Organometallic Compounds*; Academic Press: London, 1970. Heats of vaporization estimated according to: (b) Wadso, I. *Acta Chem. Scand.* **1966**, *20*, 544. The PA values are taken from: (c) Lias, S. G.; Liebman, J. F.; Levin, R. D. *J. Phys. Chem. Ref. Data* **1984**, *13*, 695. PA of the methylated ring positions of 2- and 4-methylbiphenyl taken equal to that of unsubstituted biphenyl; cf.: (d) Devlin, J. L., III; Wolf, J. F.; Taft, R. W.; Hehre, W. J. *J. Am. Chem. Soc.* **1976**, *98*, 1990. The PA of position 3 of 3-methylbiphenyl taken equal to that of the meta position of PhMe; see ref d. PA values of methylbiphenyls deduced from the corresponding gas-phase basicity values: i.e., 2-methylbiphenyl 188.9; 3-methylbiphenyl, 191.8; 4-methylbiphenyl, 189.4 kcal mol^{-1}, according to equilibrium constants measurements by FT ICR spectrometry: private communication of M. Speranza. As to $H_f°$ values of Me_2X^+, see ref 21.

(18) The very possibility of discriminating among the two structural classes suggests that interannular methyl shifts are not fast, or at least not complete, under CI conditions, even in protonated ions appreciably excited, as in the methane CI.

(19) Attempts to obtain a quantitative estimate of the proportions of class A and class B isomers in the ionic population seem at present unwarranted, owing to large uncertainties, which affect experimental and computational procedures. At the risk of overinterpreting CID data, see: Holmes, J. L. *Org. Mass Spectrom.* **1985**, *20*, 169.

Table VI. Gas-Phase Radiolytic Methylation of Biphenyl by Me_2F^+ and Me_2Cl^+ Ions

MeF	system composition[a] (Torr) substrate(s)	additive	methylated products[b]				apparent k ratio
600	Ph_2: 1.0		methylbiphenyls	74% o			
				14% m			
				12% p			
200	Ph_2: 0.8		methylbiphenyls	56% o			
				23% m			
				21% p			
600	Ph_2: 0.9		methylbiphenyls	72% o	xylenes	52% o	
	PhMe: 0.8			16% m		25% m	0.8[c]
				12% p		23% p	
570	Ph_2: 0.9	MeCl: 30	methylbiphenyls	67% o	xylenes	53% o	
	PhMe: 0.8			18% m		25% m	0.9[c]
				15% p		21% p	
570	Ph_2: 0.9	MeCl: 30[d]	methylbiphenyls	65% o	xylenes	50% o	
	PhMe: 0.7			20% m		28% m	1.2[c]
				15% p		22% p	
600	Ph_2: 0.9	NMe_3: 4.0	methylbiphenyls	60% o	xylenes	49% o	
	PhMe: 7.0			23% m		27% m	0.8[c]
				17% p		23% p	
570	Ph_2: 0.9	Me_2O: 30	methylbiphenyls	56% o	xylenes	42% o	
	PhMe: 0.7			24% m		35% m	0.6[c]
				20% p		23% p	
570	Ph_2: 0.9	Me_2O: 30	methylbiphenyls	53% o	isodurene		0.6[e]
	mesitylene: 0.9			29% m			
				18% p			
720	Ph_2CH_2: 0.8		$PhCH_2C_6H_4Me$	43% o	xylenes	51% o	
	PhMe: 1.0			27% m		25% m	0.3[f]
				27% p		24% p	
720	Ph_2CH_2: 0.8		$PhCH_2C_6H_4Me$	45% o	isodurene		0.3[g]
	mesitylene: 0.8			28% m			
				23% p			

[a] All systems contained O_2 (5 Torr) as a radical scavenger. [b] Standard deviation of isomer percentages ca. 5%. [c] $k_{biphenyl}:k_{toluene}$. [d] Irradiation temperature, 120 °C instead of 100 °C as in all other systems. [e] $k_{biphenyl}:k_{mesitylene}$. [f] $k_{diphenylmethane}:k_{toluene}$. [g] $k_{diphenylmethane}:k_{mesitylene}$.

Me_2F^+ ions are reported in Table VI, together with results of competition experiments aimed at evaluating the reactivity of biphenyl relative to activated aromatic substrates such as toluene and mesitylene. Data concerning the gas-phase methylation of diphenylmethane are included in the table for comparison purposes.

The absolute yields are measured in the radiolytic experiments by the G_{+M} values of the products, i.e., the number of molecules formed per 100 eV absorbed by the gas. In neat MeF combined G_{+M} values of methylbiphenyls are typically ca. 0.6, corresponding to an overall absolute yield of ca. 20%. It should be noted, in this connection, that biphenyl competes with other nucleophiles, either initially contained as impurities in MeF, e.g., Me_2O, or formed from the radiolysis.

The presence of additives, such as Me_2O and NMe_3, that intercept gaseous cations causes a sharp decrease of the absolute yields which drop to 0.15 in MeF containing 4 torr of NMe_3 and to 0.04 in MeF containing 30 torr of Me_2O. These effects are consistent with the postulated ionic character of the alkylation process, independently supported by direct observation of the ionic methylated adducts in mass spectrometric experiments, and ensured by the presence of O_2, used at concentrations even *higher* than that of the substrate, as an effective scavenger of methyl radicals.

The reactivity of biphenyl toward Me_2X^+ ions, measured by the k ratio reported in Table VI, is comparable to that of toluene and appreciably lower than that of mesitylene. While the available data allow only indirect comparison of biphenyl with diphenylmethane, they nevertheless show the appreciably lower reactivity of the latter.

The positional selectivity of the Me_2X^+ attack is characterized by a predominant ortho–para orientation, consistent with the electrophilic nature of the reagents, whose paramount feature is the sharp bias in favor of ortho substitution. In fact, the o/2p ratios measured in MeF at 570–600 torr range from 3.1 (Me_2F^+) to 2.2 (Me_2Cl^+). Lowering the pressure to 200 torr causes a noticeable decrease of the positional selectivity, in particular of the o/2p ratio, which drops to 1.3 (Me_2F^+). The predominant ortho orientation is peculiar to biphenyl, while toluene and diphenylmethane are characterized by a comparable reactivity of the ortho and para positions.

In order to evaluate the dependence, if any, of the orientation on the nature of the electrophile, radiolytic ethylation experiments have been carried out by irradiating gaseous systems containing methane as the bulk constituent (720 torr), O_2 (5 torr), and biphenyl (ca. 1 torr). The highly reactive Et^+ cations alkylate efficiently biphenyl, yielding ethylbiphenyls whose isomeric composition corresponds to 48% ortho, 32% meta, and 19% para. Competition experiments have shown that biphenyl and mesitylene react at comparable rates with gaseous Et^+ ions.

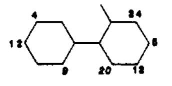
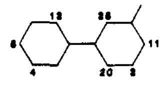
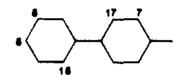
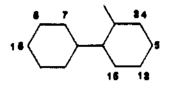
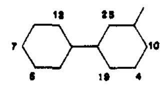
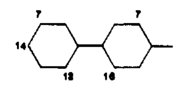
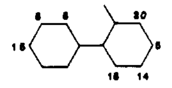
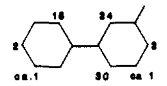
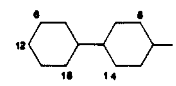
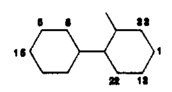
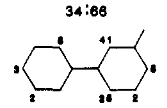
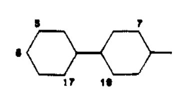
The isomeric composition of the methylated products from the attack of Me_2F^+ and Me_2Cl^+ ions on methylbiphenyls, illustrated in Table VII, allows one to evaluate the reactivity of the methyl-substituted ring of these substrates relative to the unsubstituted one. The reactivity of the two rings toward Me_2F^+ and Me_2Cl^+ is nearly equal in 4-methylbiphenyl, while the methylated ring is favored by a factor ranging from 1.3 to 1.6 in the alkylation of 2-methylbiphenyl. The bias is even more pronounced in the case of 3-methylbiphenyl, whose methylated ring is alkylated 1.6 times (Me_2F^+) and 3.3 times (Me_2Cl^+) faster than the unsubstituted one.

Without attempting a detailed analysis of the complex product pattern outlined in Table VII, a few major features deserve brief mention.

2-Methylbiphenyl is characterized by a relatively high rate of substitution at position 3, which contrasts with the low relative rates at position 6, and especially 2′ and 6′. The alkylation of 3-methylbiphenyl occurs at a surprisingly high extent at position 2, whose reactivity significantly exceeds that of position 6. Lowering the pressure causes, in general, a decrease of the positional selectivity, while the presence of a gaseous base (NMe_3) has limited effects on the isomeric composition of the products, except in the case of 3-methylbiphenyl, where the extent of substitution at positions 2 and 6 is appreciably enhanced.

Finally, as long as the unsubstituted ring of the substrate is concerned, the orientation observed in the methylation of 2-methylbiphenyl is significantly different from that measured in

Table VII. Positional Selectivity of the Gas-Phase Alkylation of Methylbiphenyls by Me_2X^+ Ions

reagent	gaseous system (torr)	2-methylbiphenyl	3-methylbiphenyl	4-methylbiphenyl
Me_2F^+	MeF (760)	 38:62	 39:61	 51:49
Me_2F^+	MeF (200)	 42:58	 43:57	 54:46
Me_2F^+	MeF (760) Me_3N (4)	 43:57	 34:66	 56:44
Me_2Cl^+	MeF (670) MeCl (30)	 41:59	 23:77	 48:52

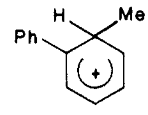
the case of 3- and 4-methylbiphenyl. The latter substrates are characterized by o/2p ratios generally well above unity, while alkylation of 2-methylbiphenyl by both Me_2F^+ and Me_2Cl^+ displays o/2p ratios *below* unity, i.e., in the range from 0.5 to 0.75.

Discussion

Alkylating Reagent. Ionization of gaseous MeF and MeCl at pressures above a few tenths of a torr yields Me_2F^+ and Me_2Cl^+ as the major ionic species via reaction sequences well established by mass spectrometric[20-22] and radiolytic[23] studies. Me_2Cl^+ ions can be obtained as well by ionization of MeF containing small amounts of MeCl, exploiting the fast[21] methylation of MeCl by Me_2F^+. A number of mass spectrometric and radiolytic investigations have elucidated the role of dimethylhalonium ions as gaseous methylating agents, particularly toward aromatic[23-27] and heteroaromatic[28,29] substrates, showing that Me_2Cl^+ is a considerably milder and more selective electrophile than Me_2F^+. This different reactivity is reflected by the higher methyl cation affinity of MeCl, 64 kcal mol^{-1}, than that of MeF, 44 kcal mol^{-1},[21] and by the higher exothermicity of aromatic methylation by Me_2F^+ than by Me_2Cl^+, as shown in Table III. Concerning the kinetic aspects of the alkylation, Me_2Cl^+ is remarkably unreactive toward benzene,[24-26] while its reactivity toward activated aromatics, measured at 78 °C by high-pressure mass spectrometry,[26] increases in passing from toluene, 1.0, to ethylbenzene, 1.9, to *o*-xylene, 3.2, to *m*-xylene, 4.1, and to mesytylene, 8.4. The lower selectivity of Me_2F^+ is reflected by the reactivity ratios measured in MeF at 760 torr and 37.5 °C with a radiolytic technique: i.e., benzene, 1.0; toluene, 0.7; *m*-xylene, 1.5; mesitylene, 1.2. However, in comparing the data concerning Me_2F^+ and Me_2Cl^+ one should bear in mind that the latter refer to a higher temperature, 78 vs. 37.5 °C. There are reasons to believe that changing the temperature could affect to a different extent the selectivity of the two electrophiles.[25] In order to rationalize the different reactivity of the two dimethylhalonium ions, it has been suggested that the higher degree of charge delocalization confers a more planar geometry to the Me groups of Me_2F^+, which favors the nucleophilic attack of aromatics, while the C atoms of Me_2Cl^+ possess a more pronounced sp^3 character, hence a higher barrier to nucleophilic displacement.[23]

Alkylation Process. The primary step of the reaction can be regarded as the nucleophilic displacement of the methyl halide from the dimethylhalonium ion by the aromatic substrate, e.g., eq 1. The exothermicity of the process, given in Table III, confers

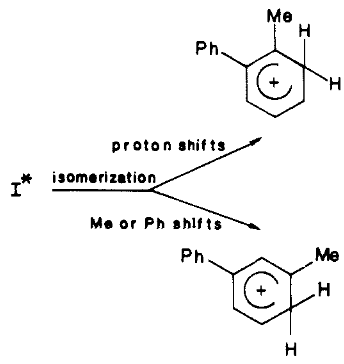
$$Ph_2 + Me_2\overset{+}{X} \longrightarrow MeX + \qquad (1)$$



I

excess internal energy to the primary adduct, which, unless collisionally deactivated, can undergo intramolecular isomerization via 1,2 proton shifts, possibly accompanied by slower[30] Me or Ph shifts, e.g., eq 2a–c.

$$I^* + M \xrightarrow{\text{deactivation}} I + M^* \qquad (2a)$$



(2b)

(2c)

The mass spectrometric experiments, carried out at pressures of ca. 0.5 torr and relatively high source temperatures (180 °C) are characterized by a comparatively low efficiency of collisional deactivation and by a relatively long time, ca. 10^{-5} s, before detection and structural assay. Consequently, extensive isomerization of the primary arenium ions via process 2b can be expected,

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(20) Herod, A. A.; Harrison, A. G.; McAskill, N. A. *Can. J. Chem.* **1971**, *49*, 2217.

(21) (a) Beauchamp, J. L.; Holz, D.; Woodgate, S. D.; Patt, S. L. *J. Am. Chem. Soc.* **1972**, *94*, 2898. The methyl cation affinity of MeF given by these authors, and used to calculate the $\Delta H°$ values of Table III corresponds to 44 kcal mol^{-1}. Very recent measurements by P. Kebarle, [reported as a private communication in (b) Hovey, J. K.; Mc Mahon, T. B. *J. Am. Chem. Soc.* **1986**, *108*, 528] give a value higher by ca. 15 kcal mol^{-1}. If one accepts the new value, the exothermicity of the Me_2F^+ alkylation processes should correspondingly be reduced.

(22) Sieck, L. W.; Gorden, R., Jr. *Int. J. Chem. Kinet.* **1973**, *5*, 445.

(23) Speranza, M.; Pepe, N.; Cipollini, R. *J. Chem. Soc., Perkin Trans. 2* **1979**, 1179.

(24) Stone, J. A.; Lin, M. S.; Varah, J. *Can. J. Chem.* **1981**, *59*, 2412.

(25) The Me_2Cl^+ attack on arenes has a *negative* temperature dependence. See: Sen Sharma, D. K.; Kebarle, P. *J. Am. Chem. Soc.* **1982**, *104*, 19.

(26) Stone, J. A.; Splinter, W. M.; Splinter, D. E. *Can. J. Chem.* **1984**, *62*, 1373.

(27) Aliprandi, B.; Cacace, F.; Cipollini, R. *Radiochim. Acta* **1983**, *34*, 103.

(28) Pepe, N.; Speranza, M. *J. Chem. Soc., Perkin Trans. 2* **1981**, 1430.

(29) Angelini, G.; Speranza, M.; Lilla, G. *J. Am. Chem. Soc.* **1982**, *104*, 7091.

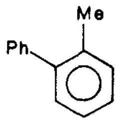
(30) 1,2-H shifts in arenium ions are characterized in solution by activation energies considerably lower than those typical of 1,2-methyl and 1,2-phenyl shifts in the same systems; cf.: (a) Koptyug, V. A. In *Contemporary Problems in Carbonium Ions Chemistry III* Boschke, F. L., Ed.; Springer-Verlag: Berlin, 1984, p 146. The solution-chemistry trends are consistent with the available gas-phase evidence; cf.: (b) Cacace, F.; Ciranni, G.; Sparapani, C.; Speranza, M. *J. Am. Chem. Soc.* **1984**, *106*, 8048, and references therein.

while occurrence of process 2c cannot be ruled out. However, the available mass spectrometric results provide no compelling evidence for fast interannular Me shifts.

Subject to such limitations, the CID spectrometric results provide ample evidence for the intervention of Wheland-type arenium ions as charged intermediates of the alkylation process.

Formation of neutral methylated products in the radiolytic reactions requires deprotonation of the arenium ions by a gaseous base,[31] e.g., eq 3. Despite the need of such an additional step

$$I + B \longrightarrow BH^+ +$$



(3)

for the formation of the neutral radiolytic products, their composition is believed to provide a more faithful picture of the intrinsic selectivity of process 1 than available from the mass spectrometric approach, owing to the lower temperature, and especially the much higher pressure prevailing in the radiolytic systems. In fact, the high frequency of thermalizing ion–molecule collisions at nearly atmospheric pressure, of the order of 10^{10} s^{-1}, is expected to substantially reduce the extent of isomerization processes affecting the primary ions, except perhaps fast 1,2 proton shifts.

Consistent with this view, radiolytic methylation of methylbiphenyls, involving the intermediacy of excited, protonated dimethylbiphenyls, provides no indication whatsoever of a migration of the methyl group initially present in the substrate.

Given the above, a discussion of the intrinsic selectivity of the gas-phase methylation can reasonably be based on the radiolytic results, especially since the latter are entirely consistent with the evidence from CID spectrometry.

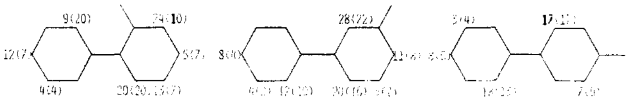
Substrate and Positional Selectivity of the Methylation of Biphenyl. The substrate selectivity has been investigated by the competitive method, using as the reference substrate toluene, rather than benzene, whose reactivity toward Me_2Cl^+ is very low. The results characterize biphenyl as slightly less reactive than toluene, typical k ratios being 0.8–0.9 in systems at 600 torr. These values are consistent with the relative reactivity of the two substrates in solution, characterized by $k_{\text{biphenyl}}:k_{\text{toluene}}$ ratios of 0.7–0.9 in mixed-acids nitration,[7b] 0.9 in molecular-chlorine halogenation,[32] etc.

The results concerning positional selectivity are of more direct interest to the specific purposes of this work and deserve a brief discussion. One can take either of two points of view, not necessarily mutually exclusive, to account for the predominant ortho orientation that represents the paramount feature of the Me_2X^+ attack. It could reflect the intrinsically higher activation of the ortho positions of biphenyl, arising from the conjugative effect of the Ph group, and unopposed in the gas phase by steric factors associated with solvation, ion pairing, etc. The alternative explanation envisages interaction of the symmetric, bidentate Me_2X^+ ions with the π systems of both rings, including the one not being alkylated, hereafter referred to as the "spectator" ring. Clearly, formation of such a complex would favor ortho positions, increasing the local concentration of the cation.

Unfortunately, the situation is less than clearcut, since the positional selectivity of biphenyl is affected by a variety of factors that include conjugative, inductive, and polarization effects of the substituent group(s), compounded by its steric effect that often modifies the twist angle of the two rings.[33]

It follows from the foregoing that a choice between the two alternatives can, at present, only tentatively be made on the grounds of indirect or circumstantial evidence.

Chart I. Experimental and Calculated (Figures in Parentheses) Isomeric Composition of Methylated Products from Methylbiphenyls



In solution, electrophilic substitution of biphenyl is generally characterized by predominant para orientation; e.g., the o/2p ratio is as low as 0.41 in Friedel–Crafts ethylation.[32] A conspicuous exception is represented by nitration in certain solvents, whose high o/2p ratios, however, have always been regarded as presenting a problem,[7b] since the negative inductive effect of the phenyl group should selectively affect ortho positions. Indeed, such "abnormal" orientation has been traced to the interaction of the electrophile with the spectator ring.[34] It should be said, however, that application of the frontier orbital theory to aromatic substitution favors ortho orientation of "hard" electrophiles such as NO_2^+.[35]

In passing from solution to the gas phase, two factors need to be considered. First, in a reaction involving a free, unsolvated cation the structure of the transition state is closer to that of the reactants, and the negative inductive effect of the Ph group should influence ortho positions more than in solution. Indeed, evidence for the inductively deactivating effect of the Ph group in the gas-phase alkylation by Me_2X^+ ions can be found in this very study by comparing the substrate and positional selectivity of toluene and of diphenylmethane. Furthermore, the tendency to charge delocalization, typical of gas-phase ion–molecule reactions,[36] favors close interaction of *both* methyl groups of Me_2X^+, which carry a large fraction of the positive charge, with *both* rings of biphenyl.

Circumstantial evidence on this point can be found in the results of this study. As an example, the extent of ortho substitution by Me_2F^+ is *higher* than by Me_2Cl^+, reaching the remarkable rate of 74%. Such a trend, plainly inconsistent, in the absence of coordination effects, with the intrinsic selectivity of the two cations, finds a reasonable explanation in the higher degree of charge delocalization in Me_2F^+, that enhances the positive charge of the methyl groups, hence their ability to interact with both rings of biphenyl.

Furthermore, under conditions that would favor dissociation, or dealkylation of the postulated Me_2X^+–biphenyl complex, e.g., at lower pressures or in the presence of nucleophiles such as Me_2O or NMe_3, ortho orientation undergoes a sharp decline. Thus, in passing from 600 to 200 torr, the o/2p ratio decreases from 3.1 to 1.3, while, significantly, the m/2p ratio is all but unaffected.

As a whole, methylation of biphenyl provides a supportive, albeit not conclusive, evidence for a preliminary coordination of the Me_2X^+ cation with the π system of the spectator ring, according to a mechanism analogous to those suggested to account for the predominant ortho orientation in the gas-phase alkylation of benzenes containing substituents with localized n-electron pairs.[2-5] Additional evidence for the coordination effect will be discussed in the next paragraph. The kinetic role of the postulated coordination mechanism, as compared to direct substitution, appears to depend on several factors, including the specific Me_2X^+ ion considered, the dihedral angle of the substrate rings (vide infra), and the composition and pressure of the gaseous system.

Methylation of Methylbiphenyls. The considerations concerning biphenyl apply to methylbiphenyls as well. In this connection, it is instructive to compare the actual isomeric composition of the products from the attack of Me_2F^+ on methylbiphenyls in MeF gas at 600 torr with that calculated, assuming the additivity of the substituent effects, from the partial rate factors deduced from the methylation of biphenyl and of toluene (Chart I). On inspection, it may be seen that the agreement is reasonable for 3-

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[31] Even in the absence of deliberately added bases, such as NMe_3, gaseous bases of adequate strength are invariably present in the radiolytic systems, either as trace impurities of the starting methyl halides (e.g., Me_2O in MeF), or formed during the radiolysis.

[32] Norman, R. O. C.; Taylor, R. *Electrophilic Substitution in Benzenoid Compounds*; Elsevier: Amsterdam, 1965; p 149.

[33] Spectroscopic measurements show that the twist angle of 2-methylbiphenyl exceeds that of biphenyl by more than 30°; see ref 11b, and Suzuki, H. *Bull. Chem. Soc. Jpn.* **1960**, *33*, 109.

[34] Taylor, R. *J. Chem. Soc. B* **1966**, 727. See also the comments in ref 7b.

[35] Fleming, I. *Frontiers Orbitals and Organic Chemical Reactions*; Wiley: New York, 1976; p 63.

[36] Operation of such factors is especially evident in glycols, diamines, etc. See: Aue, D. H.; Bowers, M. T. *Gas Phase Ion Chemistry*; Bowers, M. T., Ed.; Academic Press: New York, 1979; Vol. 2, p 17.

and 4-methylbiphenyl, while large discrepancies are noticeable in the case of 2-methylbiphenyl, whose dihedral angle is considerable increased,[33] and the ring conjugation accordingly decreased, by the steric repulsion of the Me group in the ortho position. The order of the gas-phase basicities, measured by a FT–ICR equilibrium technique,[17] i.e., biphenyl < 2-methylbiphenyl < 4-methylbiphenyl < 3-methylbiphenyl, bears witness to the effect of reduced coplanarity.

The o/2p ratio of the unmethylated ring of 2-methylbiphenyl is *lower* than unity, in contrast with the 3.1 ratio typical of biphenyl. This can hardly be explained by the decreased ring conjugation that should affect para as well as ortho positions. The trend conforms to the coordination hypothesis, as the large dihedral angle of the rings can be expected to substantially decrease the ability of Me_2F^+ to interact with both π systems, thus selectively reducing the local concentration of the electrophile at the ortho positions.

As to 3-methylbiphenyl, the unmethylated ring is characterized by a o/2p ratio, ca. 1.5, remarkably low when compared to the 3.1 ratio measured in biphenyl, and particularly difficult to justify with the conjugative, inductive, or polarizability effects of the methyl group in position 3 of the spectator ring. Such observation can easily be explained in the framework of the coordination hypothesis, since, assuming a symmetrical interaction of Me_2F^+ with both rings, their competition would be biased in favor of the one whose ortho positions are more activated, i.e., of the ring carrying a Me group at position 3. Such a state of affairs would necessarily entail a decrease of the substitution rate at the ortho positions of the unmethylated ring, consistent with the experimental result.

Turning now to more general aspects, in the absence of coordination effects the intrinsic activating power of the Ph and the Me groups is comparable, the positive inductive effect of the latter being plainly evident in the case of 3-methylbiphenyl, whose position 2 is significantly more reactive than position 6. It should be noted that, in this case, the comparison is unaffected by coordinative effects, both positions 2 and 6 being ortho to the spectator ring.

The situation is entirely different in 4-methylbiphenyl, whose positions 3 and 5, ortho to the Me group, are less reactive than positions 2 and 6. Clearly, any negative inductive effect of the spectator ring is more than offset by its ability to coordinate the Me_2F^+ cation, consistent with the considerations developed in the previous paragraph.

Without unduly dwelling on a detailed analysis of the positional selectivity of methylbiphenyls alkylation, the high percentage of 2,3-dimethylbiphenyl from 2-methylbiphenyl deserves a brief comment. Such singularity would not be easy to justify invoking electronic or coordinative activation, especially in view of the much lower reactivity of position 5. However, it could be suggestive of an additional effect that may further complicate the reactivity pattern of biphenyls. In fact, a tentative explanation can proceed from the large dihedral angle of 2-methylbiphenyl, caused by the large steric repulsion experienced by the ortho methyl group. Attack on position 2 could be accelerated by considerable decrease of steric repulsion in the ipso-substituted arenium ion, allowing a higher degree of conjugative stabilization by the Ph group. The ipso-substituted ion could subsequently undergo intramolecular isomerization via 1,2 methyl shifts, accounting for the high proportions of 2,3-dimethylbiphenyl eventually formed.

The extensive mass spectrometric studies on the alkylation of methylbiphenyls, in particular those concerning the model ions prepared by protonation of 10 isomeric dimethylbiphenyls, are of interest from a different point of view. In fact, their results allow a critical appraisal of the structural resolution of CID spectrometry in the analysis of an unusually large group of closely related isomeric ions, differing by minor structural features. Furthermore, the preparation of the ions has been accomplished by a low-exothermicity process, which should reduce the extent of skeletal isomerization before structural assay. The results illustrate the possibilities, and the limitations, of conventional CID spectrometry in the resolution of a complex structural problem. In fact, the protonated adducts from the dimethylbiphenyls could be positively assigned to two major types, differing for the presence of one, and respectively of both methyl groups in the same ring. However, in our hands, further discrimination of individual isomeric structures could not be achieved at any satisfactory confidence level, owing especially to the insufficient reproducibility in the measurement of spectra that differ exclusively for small variations in the relative abundances *of the same ions*.[37]

Acknowledgment. This work has been financially supported by the Italian National Research Council (CNR) and the Ministry of Pubblica Istruzione. The authors are grateful to M. Speranza and to R. Gabrielli of the FT-MS Service of Area della Ricerca di Roma (CNR) for measurement of the proton affinity of methylbiphenyls, and to E. Crestoni for experimental help.

Registry No. t-Bu^+, 14804-25-2; Me_2Cl^+, 24400-15-5; Me_2F^+, 64710-12-9; Me_3O^+, 43625-65-6; biphenyl, 92-52-4; 2-methylbiphenyl, 643-58-3; 2-methylbiphenyl carbocation, 104035-27-0; 2-methylbiphenyl conjugate acid, 104051-51-6; 3-methylbiphenyl, 643-93-6; 3-methylbiphenyl carbocation, 104035-28-1; 3-methylbiphenyl conjugate acid, 104051-52-7; 4-methylbiphenyl, 644-08-6; 4-methylbiphenyl carbocation, 104035-29-2; 4-methylbiphenyl conjugate acid, 104051-50-5.

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(37) Full fruition of promising approaches based on charge stripping CID, UV, and IR laser spectroscopy, etc., may hopefully allow satisfactory discrimination of isomeric gaseous ions by purely mass spectrometric techniques.