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Synthesis, Structure and Properties of Amino-Substituted Benzhydrylium Ions – a Link Between Ordinary Carbocations and Neutral Electrophiles

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Abstract: Optimized synthetic procedures for the straightforward access eleven amino-substituted diarylmethylium to tetrafluoroborates are described. These benzhydrylium ions cover a range of seven orders of magnitude in electrophilicity and provide a link between ordinary carbocations and neutral electrophiles. Five of these highly stabilized benzhydrylium tetrafluoroborates were characterized by single crystal X-ray crystallography. While the experimentally determined bond lengths and angles in the solid state perfectly agree with those calculated by DFT methods for the gas phase and aqueous solution, crystal packing accounts for large differences in the twist angles of the aryl groups found in the solid state as compared to calculated structures.

Introduction

Benzhydrylium ions (Ar₂CH⁺) have played an important role for the development of the mechanistic model of Organic Chemistry. After differentiating S_N1 and S_N2 mechanisms, Ingold and Hughes studied the influence of salt additives on the rates of benzhydryl halide solvolyses and discovered the so-called mass-law (common-ion) effects.^[1] Solvolysis studies of substituted benzhydryl chlorides by Kohnstam revealed the relationship between the "mass-law constants" α and the stabilization of the carbocations.^[2] Winstein's investigations of the solvolyses of optically enriched p-chlorobenzhydryl chloride in various solvents provided essential insights on the role of ion pairs in solvolysis reactions.^[3] Benzhydryl halides were furthermore used by Winstein and Grunwald as model compounds to elucidate the origin of dispersion in the correlations of solvolysis rates with solvent ionizing power Y.^[4] Isomerizations of various benzhydryl thiocyanates contributed significantly to the interpretation of the ambident reactivities of thiocyanate anions.^[5,6] Eventually, rate constants of the reactions of benzhydrylium ions with alkenes, allylsilanes, and arenes gave rise to the first reactivity scales of $\pi_{\rm CC}$ -systems.^[7]

However, all these reactions have been performed with destabilized, unsubstituted, or only weakly stabilized

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benzhydrylium contrast, ions. In amino-substituted benzhydrylium ions were rarely used in these mechanistic investigations. UV-Vis spectra of a series of amino-substituted benzhydrylium ions, generated by dissolving the corresponding benzhydrols in acidic solution, have been reported,^[8] and stable salts have been isolated of the bis(p-(dimethylamino)phenyl)methylium ion,^[9] the bis(p-(diethylamino)phenyl)methylium ion,^[9c] and the bis(julolidin-9-yl)methylium ion.[10] While detailed structural information about the nature of ion paring in 4,4'bis(dimethylamino)benzhydrylium tetrafluoroborate was derived from heteronuclear Overhauser effect spectroscopy (HOESY) in CD₂Cl₂ solution,^[91] to our knowledge, X-ray analyses have not been reported for amino-substituted benzhydrylium salts.

In our efforts to quantify polar organic reactivity,[11] benzhydrylium ions have been used as reference electrophiles for the characterization of the reactivities of π -, n-, and σ nucleophiles.^[12,13] By variation of the substituents at 4- and 3position of the benzhydrylium ions, their electrophilic reactivities have been varied by 18 orders of magnitude,^[14,15] while the steric surroundings of the reaction center are kept almost constant. Using benzhydrylium ions and structurally related quinone methides as reference electrophiles, the reactivities of more than 1100 nucleophiles have been characterized^[16] using the linear free-energy relationship (1), where electrophiles are characterized by one (electrophilicity E) and nucleophiles are characterized by two solvent-dependent parameters (nucleophilicity N and susceptibility s_N).

$$\lg k = s_{\rm N}(N + E) \qquad (1)$$

Later on, differently substituted benzhydrylium ions have also been used as reference electrofuges (with electrofugality $E_{\rm f}$ in equation 2) for the quantification of leaving group abilities (nucleofugalities $N_{\rm f}$ and susceptibilities $s_{\rm f}$) in heterolytic cleavages, e. g. $S_{\rm N}1$ reactions,^[17] and as reference Lewis acids (with Lewis acidity *LA* in eq 3) for establishing a Lewis basicity (*LB*) scale with respect to C-centered Lewis acids.^[18]

$\lg k = s_{\rm f}(N_{\rm f} + E_{\rm f})$	(2)
lg <i>K</i> = <i>L</i> A + <i>LB</i>	(3)

In all these correlations amino-substituted benzhydrylium ions (Table 1), which cover a reactivity range of seven orders of magnitude in E (four orders of magnitude in E_f) and eight orders of magnitude in Lewis acidity LA, adopt an essential role,

bridging the gap between ordinary carbenium ions and neutral electrophiles, electrofuges, or Lewis acids.

Table 1. Electrophilicity (*E*), electrofugality (*E*_t), Lewis acidity (*LA*), and gasphase methyl anion affinities ΔG_{MA} (in kJ mol⁻¹) for benzhydrylium ions **1**⁺–**11**⁺.



Ar_2CH^+	E ^[a]	$E_{\rm f}^{\rm [b]}$	LA _{CH2CI2} ^[c]	LA _{MeCN} ^[c]	$\Delta G_{\rm MA}{}^{\rm [d]}$
1⁺	-10.04	5.05	-12.76	-12.76	-639.8
2 ⁺	-9.45	5.61	-12.62	-12.61	-642.2
3⁺	-8.76	4.83	-11.16	-11.46	-654.5
4 ⁺	-8.22	5.22	-10.92	-11.27	-654.0
5⁺	-7.69	5.35	-10.46	-10.83	-658.3
6⁺	-7.02	4.84	-9.30	-9.82	-670.7
7 ⁺	-5.89	3.46	-7.72	-7.89	-667.1
8⁺	-5.53	3.03	-6.82	-7.52	-688.2
9⁺	-4.72	1.78	-5.72	[e]	-689.9
10 ⁺	-3.85	3.13	-5.39	(-6.33) ^[f]	-711.9
11⁺	-3.14	1.79	-4.47	[e]	-708.5

^[a] Electrophilicity *E* from ref [12]; ^[b] Electrofugality *E*_f from ref [17a]; ^[c] Lewis acidities *LA* in dichloromethane and MeCN from ref [18]; ^[d] Methyl anion affinities (ΔG_{MA}) from ref [18]; ^[e] Not measured; ^[f] Extrapolated from the relationship *LA*_{MeCN} = 0.878*LA*_{CH2GI2} – 1.60, from ref [18].

When we introduced benzhydrylium ions as reference electrophiles in 2001, we described the principle of the synthesis of the amino-substituted benzhydrylium ions $1^{+}-11^{+}$ (Table 1) and included the promise "*Since the synthetic procedures still require optimization, we will describe details of these syntheses later*".^[12] We will now honor this pledge and furthermore report about their spectroscopic properties as well as their structural aspects by means of quantum chemical calculations and the first X-ray structures of benzhydrylium salts.

Results and Discussion

Syntheses of diarylmethylium tetrafluoroborates

The procedure initially described by Jutz for the generation of the perchlorate of Michler's Hydrol Blue, 6^+ -ClO₄^{-,[9a]} was modified for the synthesis of the benzhydrylium tetra-fluoroborates (1^+-5^+) -BF₄⁻, which are less electrophilic than 6^+ .

Starting materials for the synthesis of the benzhydrylium tetrafluoroborates $(1^+-5^+)BF_4^-$ were the aminobenzenes 12a-e (Scheme 1). Julolidine (12b) and N-phenylpyrrolidine (12e) are commercially available. Lilolidine (12a) was prepared by the method of Hallas and Taylor:^[19] Acylation of indoline with 3chloropropionyl chloride followed by intramolecular Friedel-Crafts alkylation and reduction with lithium aluminium hydride yielded 12a in 44% yield over three steps. For the synthesis of 1-methylindoline (12c), we followed the route described by Gawinecki and co-workers:^[20] 1-Formylindoline^[21] was prepared in 82% yield from indoline and formic acid following the procedure used for the formylation of N-methylaniline.^[22] Reduction of 1-formylindoline with LiAlH₄ delivered 1methylindoline (86%). Reductive formylation of auinoline with formic acid^[23] furnished 1-formyl-1,2,3,4-tetrahydroquinoline in 60% yield, which was subsequently reduced by lithium aluminium hydride to deliver **12d** (92% yield).^[20]



Scheme 1. Aminobenzenes 12a-e.

By following published procedures for Vilsmeier–Haack formylations the aminobenzenes **12a**–**d** were further converted to the corresponding aldehydes **13a**–**d** (**13e** is commercially available). Then, phosphorus oxychloride-promoted condensation of **12a**–**e** with the corresponding carbaldehydes **13a**–**e**^[24] and subsequent treatment with an aqueous solution of sodium tetrafluoroborate gave rise to the formation of (**1**⁺–**5**⁺)-BF₄⁻ (Scheme 2). The syntheses of 4,4'-bis(dimethylamino)-benzhydrylium (**6**⁺) salts with different counterions (TfO⁻, BF₄⁻, PF₆⁻, CIO₄⁻) starting from the 4,4'-bis(dimethylamino)benzhydrol have been described before.^[9]

For synthesizing benzophenones with weaker electrondonating amino substituents, we used an S_NAr reaction elaborated by Hepworth and coworkers.^[8g] As described in the literature,^[8g] **15a** was obtained in 81% yield by heating a solution of 4,4'-difluorobenzophenone (**14**) with an excess of morpholine in sulfolane (Scheme 3). Reduction of **15a** with sodium borohydride gave the benzhydrol **16a**,^[8g] which was converted into the benzhydrylium tetrafluoroborate **8**⁺-BF₄⁻ by treatment with ethereal tetrafluoroboric acid. The deep blue color of the reaction mixture indicated the formation of **8**⁺-BF₄⁻, which precipitated upon addition of diethyl ether, in analogy to the synthesis of **6**⁺-BF₄⁻.^[9]



Scheme 2. Synthesis of benzhydrylium tetrafluoroborates (1^+-5^+) -BF₄⁻ by phosphorus oxychloride-promoted condensation.



Scheme 3. Synthesis of the tetrafluoroborate 8^+ -BF₄⁻.

Nucleophilic aromatic substitutions of 4,4'-difluorobenzophenone (14) were also used to introduce anilino substituents. The reactions of 14 with mixtures of *N*-methylaniline or diphenylamine and potassium *tert*-butoxide furnished 15b and 15c, respectively, in moderate yields (Scheme 4). The benzophenones 15b and 15c were subsequently reduced to the benzhydrols 16b and 16c, which were treated with ethereal tetrafluoroboric acid to give the benzhydrylium salts 7⁺-BF₄⁻ and 9⁺-BF₄⁻, which precipitated from the reaction mixture.



Scheme 4. Synthesis of benzhydrylium tetrafluoroborates $(7^{+},9^{+})$ -BF₄⁻.

Because of their tendency to condense,^[25] attempts to crystallize benzhydrols **16b** or **16c** from boiling petroleum ether delivered ethers **17b** and **17c** (Scheme 5), as indicated in the ¹H NMR spectra by the disappearance of the OH resonances ($\delta_{\rm H} = 2.1$ – 2.7 ppm, in CDCl₃) and the replacement of the Ar₂CH–OH doublet at $\delta_{\rm H} = 5.7$ –5.8 ppm (³J_{1H-OH} = ca. 3.5 Hz) of the benzhydrol by a singlet at $\delta_{\rm H} = 5.3$ –5.4 ppm for the corresponding ether (Ar₂CH)₂O. Given that they cleanly react with tetrafluoroboric acid, also ethers **17b** and **17c** (which sometimes form during evaporation of the solvent from **16b** or **16c**) can be employed as starting materials for the synthesis of the benzhydrylium tetrafluoroborates $7^+BF_4^-$ and $9^+BF_4^-$ (final step in Scheme 4).



Scheme 5. Condensation of benzhydrols 16b or 16c to give the ethers 17b and 17c.

For the synthesis of the benzhydrylium salts 10^+ -BF₄⁻ and 11^+ -BF₄⁻ we started from the diarylmethanes 18a,b (Scheme 6).^[26,27] Trifluoroacetylation of the amino groups of 18a,b, as described by Armstrong and Jones for analogous compounds,^[28] and subsequent reduction of the resulting amides 19a,b yielded the diarylmethanes 20a,b. Oxidation of the central CH₂ unit by DDQ in methanol and subsequent reduction of the resulting benzophenones 21a,b with sodium borohydride furnished the benzhydrols 22a,b. The reactions of 22a,b with tetrafluoroboric acid in diethyl ether yielded the corresponding benzhydrylium tetrafluoroborates 10^+ -BF₄⁻ and 11^+ -BF₄⁻.



Scheme 6. Synthesis of benzhydrylium tetrafluoroborates $(10^{+}-11^{+})$ -BF₄⁻.

Spectroscopic Characterization of Benzhydrylium lons 1⁺– 11⁺. In contrast to the yellow or red alkyl- and alkoxy-substituted benzhydryl cations, which have absorption maxima between 443 and 535 nm,^[29] the *p*-amino-substituted benzhydrylium ions are blue with absorption maxima between 586 and 674 nm (Figure 1, Table 2).

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Figure 1. Absorption spectra of selected benzhydrylium tetrafluoroborates in CH_2CI_2 .

Table 2. UV-Vis absorption maxima λ_{max} (in nm) of solutions of benzhydrylium
tetrafluoroborates $(1^{+}-11^{+})$ -BF ₄ ⁻ in different solvents (with their lg ε values in
parentheses)

Ar_2CH^+			λ_{\max} (nm)				
	CH_2CI_2	MeCN	DMSO ^[a]	H₂O	other solvents		
1⁺	640 (5.21)	632 (5.16)	640 (5.10)	630 (4.98)	638 (5.14) ^[b]		
2 ⁺	643 (5.31)	635 (5.26)	644 (5.21)	634 (5.17)	638 (5.23) ^[c] 637 (5.27) ^[d]		
3⁺	626 (5.21)	616 (5.14)	625 (5.11)	614 (5.01)	619 (5.14) ^[b]		
4 ⁺	628 (5.26)	620 (5.21)	629 (5.17)	618 (5.13)	623 (5.23) ^[c]		
5⁺	620 (5.34)	612 (5.28)	622 (5.21)	610 (5.15)	613 (5.20) ^[e]		
6⁺	613 (5.28)	605 (5.22)	616 (5.14)	604 (5.15)	608 (5.17) ^[c]		
7 ⁺	623 (5.21)	613 (5.20)	[f]	[f]			
8⁺	621 (5.29)	612 (5.17)	[1]	[f]	613 (4.49) ^[e]		
9 ⁺	674 (5.04)	645 (5.06)	(f)	[f]	657 (5.01) ^[9]		
10 ⁺	593 (5.29)	586 (5.21)	(1)	(f)			
11⁺	601 (5.19)	592 (5.10)	(f)	[1]			

^[a] Cations **2⁺-6⁺** react slowly with DMSO, which results in a lower precision of lg ε in this solvent. For the nucleophilic reactivity of DMSO (oxygen attack), see ref [30]; ^[b] In 98% acetic acid, from ref [8d]; ^[c] In 98% acetic acid, from ref [8b]; ^[d] As perchlorate salt in nitromethane, from ref [10]; ^[e] Benzhydrol dissolved in 98% acetic acid, from ref [8g]; ^[f] Reliable measurements are not possible because the benzhydrylium ion reacts with the nucleophilic solvent. ^[g] Benzhydrol dissolved in an acetic acid/trifluoroacetic acid-mixture (90/10), from ref [8f].

The absorption maxima of $1^{+}-11^{+}$ are almost identical in dichloromethane and DMSO, at approximately 10 nm longer wavelengths than in acetonitrile and water. The λ_{max} values in dichloromethane correlate moderately with the electrophilicity parameters *E* of $1^{+}-11^{+}$. Figure 2 shows that the more reactive (less stabilized) carbenium ions generally absorb at shorter wavelengths. This trend does not hold for the structurally similar electrophiles $1^{+}/2^{+}$ and $3^{+}/4^{+}$, however, which may somehow be related to the observation that carbenium ions 1^{+} and 3^{+} react over higher intrinsic barriers than their higher homologs 2^{+} and 4^{+} . Due to extended conjugation, the broad, red-shifted absorption band of the diphenylamino-substituted benzhydrylium ion 9^{+} differs significantly from those of the other benzhydrylium ions.



Figure 2. Plot of the absorption maxima λ_{max} of benzhydrylium ions in different solvents (from Table 2) against the electrophilicity *E*. The correlation line depicted is for CH₂Cl₂ ($\lambda_{max} = -6.02E + 578.9$, R² = 0.815; the data for **9**⁺ was omitted for the correlation).

The ¹³C NMR chemical shifts of the central carbon atoms of substituted benzhydrylium ions (Table 3) correlate well with the empirical electrophilicity parameters *E* (Figure 3). For the whole range of electrophiles, the best correlation of electrophilicity with δ (¹³C) is obtained by a second-order polynomial (see legend of Figure 3), while for the smaller subset of amino-substituted benzhydrylium ions also a linear regression can be performed. In the case of the amino-substituted benzhydrylium ions **1⁺-11⁺** also the proton resonances at the carbocationic center (in CD₃CN) correlate linearly with the electrophilicity *E* ($\delta_{H} = 0.131E + 8.72$, R² = 0.97, see Figure S1 in the Supporting Information).

The cationic centers of tritylium ions (Figure 3, grey rhombic entries) are shifted downfield by 20–30 ppm compared to those of benzhydrylium ions of equal electrophilicity *E*. However, the correlation of electrophilicity parameters with δ_c holds only within the different families, and in the series of the (dimethylamino)-substituted tritylium ions, increasing electrophilicity is even associated with a higher shielding of the carbenium center (Figure 3, grey rhombs).

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Table 3. Reactivity parameters *E* and ¹³C and ¹H NMR spectroscopic data for benzhydrylium ions Ar₂CH⁺. ¹³C and ¹H NMR spectra for **1**⁺–**11**⁺ (as tetrafluoroborates) were recorded in CD₃CN.^[a]

	Ar_2CH^+	E	$\delta_{\! m C}$ [ppm]	$\delta_{\!H}[ppm]$
1⁺	(lil)₂CH ⁺	-10.04	157.0	7.43
2 ⁺	(jul)₂CH⁺	-9.45	157.6	7.41
3⁺	$(ind)_2 CH^+$	-8.76	158.2	7.56
4 ⁺	(thq)₂CH⁺	-8.22	159.8	7.63
5⁺	(pyr)₂CH⁺	-7.69	161.5	7.82
6⁺	(dma) ₂ CH ⁺	-7.02	161.9	7.85
7 ⁺	(mpa)₂CH⁺	-5.89	164.0	8.00
8⁺	(mor)₂CH⁺	-5.53	162.3	7.93
9⁺	(dpa)₂CH⁺	-4.72	165.3	8.12
10⁺	(mfa)₂CH⁺	-3.85	167.2	8.19
11 ⁺	(pfa)₂CH⁺	-3.14	169.0	8.31
	(OCH ₂ CH ₂) ₂ -D ^[b]	-1.36	176.8 ^[c]	
	(MeO) ₂ -D ^[b]	0.00	179.5 ^[c] 178.6 ^[d]	
	(MeO),(Me)-D ^[b]	1.48	183.3 ^[c]	
	(MeO),(H)-D ^[b]	2.11	183.5 ^[e]	
	(Me) ₂ -D ^[b]	3.63	191.7 ^[d] 192.3 ^[f]	
	(Me),(H)-D ^[b]	4.43	195.3 ^[f] 196.1 ^[g]	
	(F),(H)-D ^[b]	5.20	197.1 ^[9]	
	(H) ₂ -D ^[b]	5.47	199.8 ^[g] 200 ^[f]	

^[a] This work; ^[b] For structures of benzhydrylium ions (X),(Y)-D see Figure 3; ^[c] At -70 °C in FSO₃H/SbF₅/SO₂CIF or FSO₃H/SO₂CIF, from ref [31a]; ^[d] At -20 °C in CF₃SO₃H, from ref [31b]; ^[e] At -70 °C in FSO₃H/SbF₅/SO₂CIF, from ref [31c]; ^[f] At -78°C in SbF₅/SO₂CIF, from ref [31d]; ^[g] At -70 °C in SbF₅/SO₂CIF, from ref [31c].

We have previously reported a linear correlation of the electrophilicity parameters of benzhydrylium ions with their experimentally determined one-electron reduction potentials (Figure 4a).^[32,33] Additionally, a moderate correlation of quantum-chemically calculated LUMO energies (Supporting Information, Figure S2) and a significantly better one of gas-phase methyl anion affinities ΔG_{MA} (Figure 4b) with one-electron reduction potentials can be observed.





Figure 3. Correlation of the ¹³C NMR chemical shifts for the central carbon in Ar₂CH⁺ (from Table 3, red squares and black circles) with the electrophilicity parameters *E* of benzhydrylium ions. The ¹³C NMR chemical shifts of benzhydrylium ions can be described by the second-order polynomial $\delta_{\rm C} = 0.105 E^2 + 3.18 E + 179 (r^2 = 0.995)$. The ¹³C NMR chemical shifts of the carbocationic centers in tritylium tetrafluoroborates are marked by grey rhombic symbols (data were taken from refs [31e,f]).



Figure 4. a) Correlation of the electrophilicity parameters *E* of benzhydrylium ions with their one-electron reduction potentials $\mathcal{E}^{\circ}_{red}$. b) Correlation of gasphase methyl anion affinities ΔG_{MA} (from Table 1 and ref [18]) of benzhydrylium ions with their one-electron reduction potentials $\mathcal{E}^{\circ}_{red}$ ($\mathcal{E}^{\circ}_{red}$ vs SCE, 25 °C, in MeCN were taken from ref [32], structures of benzhydrylium ions (X),(Y)-D are shown in Figure 3).

Structural aspects of benzhydrylium tetrafluoroborates

Crystallization by the vapour diffusion method with different solvent systems delivered crystals of the benzhydrylium tetrafluoroborates 1^{+} -BF₄⁻, 2^{+} -BF₄⁻, 3^{+} -BF₄⁻, 5^{+} -BF₄⁻, and 6^{+} -BF₄⁻ that were suitable for single-crystal diffraction (Figure 5, for detailed procedures see the Supporting Information).^[34]



Figure 5. Structure of the benzhydrylium unit in the solid state of **1**^{*}-BF₄⁻, **2**^{*}-BF₄⁻, **3**^{*}-BF₄⁻, **5**^{*}-BF₄⁻, **and 6**^{*}-BF₄⁻. The counterion BF₄⁻ and in the case of **6**^{*} one molecule of CH₃CN were omitted for clarity. Thermal ellipsoids are drawn at a 50% probability level. [a] The structure of the cation shows dislocation. Only the component with the highest occupation is depicted.

In order to compare the experimental crystal structures (Table 4, left part) with the structures of the free carbenium ions, we optimized the geometries of the benzhydrylium ions after an initial conformer search in the gas phase by the B3LYP^[36]-D3^[36]/6-311+G(d,p) method (Table 4, right part) employing the Gaussian software package.^[37] Additionally, we probed the influence of solvation by optimizing the structures with the IEF version of the PCM model.^[38,39]

In the crystals of 1^{*}, 2^{*}, 3^{*}, 5^{*}, and 6^{*}, the central carbon C₁ and the attached carbon atoms of the aryl rings (C₂ and C₅) are in an averaged distance of 1.407 (± 0.002) Å, in excellent agreement with C₁–C₂/C₅ distances in calculated structures of 1⁺–11^{*} in gas-phase and aqueous solution. As already shown by earlier quantum chemical calculations,^[40] the C₁–C₂/C₅ bond lengths are almost independent of the substituents in symmetrical systems and significantly shorter than comparable C⁺–C_{ar} bonds in tritylium ions (averaged value in methoxy- and amino-substituted tritylium ions: 1.449 Å).^[41]

Crystal structures and quantum chemical calculations in gas phase and solution furthermore indicate that the C_2 - C_1 - C_5 angle is almost unaffected by the substituents of the aryl rings (132.6–135.0° by X-ray structure determination and 131.6–132.6° by calculations).

In contrast, the twisting of the aryl groups (defined as the angle between the two planes, which pass through the aryl rings, Figure 6) is significantly influenced by packing effects in the solid

state structures: While quantum-chemically calculated structures of $1^{+}-11^{+}$ stay within a narrow range for the twist angles (gas phase: 26.2 ± 2°; in water: 24.5 ± 2°), the twist angles in the crystals of 1^{+} , 2^{+} , 3^{+} , 5^{+} , and 6^{+} vary unsystematically between 3° and 25° (Table 4, Figure 6).





As depicted in Figure 7, rotation around the C⁺-C_{Ar} bond (that is, the C₁-C₂ or the C₁-C₅ bond) in the benzhydrylium ions **3**⁺ and **1**⁺ gives rise to three different conformers. The conformer (*Z*,*Z*)-**3**⁺, the only **3**⁺ conformer detectable by X-ray analysis, is calculated to be 1.6 and 1.8 kJ/mol more stable than (*E*,*Z*)-**3**⁺ and (*E*,*E*)-**3**⁺, respectively. Calculations show the (*Z*,*Z*)conformer of **1**⁺ also to be the most stable structure, closely followed by the (*E*,*Z*)- and the (*E*,*E*)-conformers (Figure 7). The dislocation observed in the X-ray structure of **1**⁺-BF₄⁻ (Figure 8A) indicates that now two conformers exist in the ratio 55/45, and from the C₂ axis through the center of the carbenium ion, one can derive that it is a mixture of (*Z*,*Z*)- and (*E*,*E*)-**1**⁺.



Figure 7. Conformational analysis of benzhydrylium ions 3^* and 1^* . Conformers having the same relative orientation of the aryl rings are Boltzmann-weighted based on their energies at the B3LYP-D3/6-311+g(d,p) level of theory in aqueous solution (IEF-PCM).

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Table 4. Experimental bond lengths and bond angles in the solid state structures of the benzhydrylium tetrafluoroborates 1^* , 2^* , 3^* , 5^* , and 6^* and quantum-chemically calculated bond lengths and bond angles of structures optimized at the B3LYP-D3/6-311+g(d,p) level of theory in gas-phase and solution (IEF-PCM, water) for 1^*-11^* . Data refer to the most stable conformer (Gibbs energy at 298 K). For atom numbering, see Figure 5.

	Single-crystal X-ray structure				Gas-phase			Water (IEF-PCM)			
	C ₁ -C ₂ [Å]	C₁−C₅ [Å]	averaged C_1 – (C_2/C_5) [Å]	C ₂ -C ₁ -C ₅ [°]	Twist [°]	averaged C_1 – (C_2/C_5) [Å]	C ₂ -C ₁ -C ₅ [°]	Twist [°]	averaged C_1 (C_2/C_5) [Å]	C ₂ -C ₁ -C ₅ [°]	Twist [°]
1⁺	1.4090(19)	1.4090(19)	1.4090(19)	132.6(2)	25.04(6)	1.4097	132.3	26.19	1.4100	132.6	23.71
2 ⁺	1.4153(17)	1.4016(17)	1.4085(17)	134.27(11)	14.63(6)	1.4087	132.1	26.05	1.4090	132.2	24.40
3 * ^[a]	1.410(5) 1.399(4)	1.403(5) 1.415(4)	1.407(5)	135.0(3) 134.8(3)	3.57(14) 5.19(14)	1.4093	132.5	24.57	1.4095	132.6	22.37
4 ⁺						1.4085	132.0	26.34	1.4088	132.3	23.37
5⁺	1.413(3)	1.398(3)	1.406(3)	133.5(2)	21.60(11)	1.4083	132.1	25.93	1.4085	132.2	23.93
6 *	1.412(2)	1.403(2)	1.408(2)	133.6(2)	11.68 (6)	1.4084	131.9	26.33	1.4086	132.1	24.25
7 *						1.4083	131.9	26.13	1.4086	131.7	25.12
8*						1.4078	131.6	25.64	1.4081	131.8	24.18
9⁺						1.4088	131.6	26.15	1.4092	131.3	26.21
10 ⁺						1.4090	131.7	27.32	1.4089	131.6	25.75
11⁺						1.4089	131.6	27.89	1.4094	131.8	26.52

^[a] Two individual units crystallized in the asymmetric unit.



Figure 8. (A) Dislocation in the crystal structure of 1^+ -BF₄⁻. Transparent atoms and fragmentated bonds belong to the species with lower occupation (45%). (B) Close ion contacts towards BF₄⁻ anions in the crystal structure of 1^+ -BF₄⁻. (C) NBO analysis at the B3LYP-D3/6-311+g(d,p) level of theory (gas phase) Italic numbers indicate the values for carbon/nitrogen while standard ones are for hydrogen. The values for CH₂ groups are averaged.

Packing effects in the solid-state structures

In the solid-state structures of **1**^{*}-BF₄⁻, **2**^{*}-BF₄⁻, **5**^{*}-BF₄⁻, and **6**^{*}-BF₄⁻, the benzhydrylium tetrafluoroborates are arranged in flat layers (as shown in Figure 9), which are fixed by π - π stacking and C-H… π interactions between the layers. A different arrangement was only found in the structure of **3**^{*}-BF₄⁻: The layers of cations are not flat but follow a zig-zag pattern (Figure 10).

In the crystal structures of all benzhydrylium tetrafluoroborates the tetrafluoroborate ions take part in C-H···F hydrogen-bonds with H-F distances ranging from 2.35 to 2.55 Å (Figure 8B).^[42,43] Generally, the tetrafluoroborate ions adopt positions within the layer of benzhydrylium ions (Figures 9 and 10) where they occupy the gaps between the individual cations.^[44] There is little preference for the BF₄⁻ anion to be positioned at a certain site of the carbocation, and Fig. 8B shows that C-H···F contacts exist at various sites between 1^+ and its tetrafluoroborate counterion. This can be explained by the

effective delocalization of the positive charge, which is also shown by the quantum-chemically calculated charges in a Natural Bond Orbital (NBO)^[45] analysis (Figure 8C).



Figure 9. Packing within one layer of cations in the crystal structure of 2^+ -BF₄⁻ shown as top and side view. As the structure shows dislocation, only the conformer with the highest occupancy is depicted.



Figure 10. Packing within one layer of cations in the crystal structure of 3^+ - BF_4^- shown as top and side view. As the structure shows dislocation, only the species with the highest occupancy is depicted.

The cation-anion interactions in the X-ray structures of 1^+ -BF₄⁻, 2^+ -BF₄⁻, 3^+ -BF₄⁻, 5^+ -BF₄⁻, and 6^+ -BF₄⁻ and the even distribution of the charge over the cation has previously been observed by ¹H, ¹⁹F HOESY NMR spectroscopy in the CD₂Cl₂ solution of 6^+ -BF₄⁻. ^{[91} Strong F,H interactions were detected that originated

from the proximity of BF_4^- anions and protons of the dimethylamino-group in **6**⁺-BF₄⁻. Additionally, significant interactions of fluorine (of BF_4^-) with the ortho- and meta CH protons of the arene rings could be observed. In analogy to the situation in Figure 8B, only a weak correlation signal of ¹⁹F nuclei in BF_4^- with the C¹–H proton was found by HOESY NMR spectroscopy.^[9]

Conclusion

The discussion of structure-reactivity relationships is often hampered by the fact that an unambiguous separation of steric and electronic effects is not possible. By using *para-* and *meta*substituted benzhydrylium ions as reference electrophiles, we succeeded to vary electrophilicity by 18 orders of magnitude while the steric surroundings of the reaction center were kept constant.^[12–15] The syntheses of methyl-, methoxy-, and halogen-substituted benzhydryl derivatives are well-established, but the preparation of most amino-substituted benzhydrylium ions has not or only vaguely been described previously.^[12] With the optimized procedures given in the Supporting Information of this paper, these compounds now become easily available and can hence be used for systematic investigations of fundamental questions of organic chemistry.

As shown in previous work, amino-substituted benzhydrylium ions cannot only be used for characterizing the reactivities of nucleophiles of intermediate strengths,^[12] but also for the construction of general Lewis basicity scales with respect to carbon-centered Lewis acids.^[18] Due to their well-defined electrophilicities, electrofugalities, and Lewis acidities they allow one to investigate the limits of common concepts of organic reactivity. Whereas typical carbocations are the more reactive, the slower they are formed in S_N1 reactions, this general rule does not any longer hold for amino-substituted benzhydrylium ions, where in many cases variable intrinsic barriers account for the counterintuitive observation that carbocations, which are formed faster in S_N1 reactions also react faster with nucleophiles.^[46,47] The possibility to fine-tune electrophilicity and Lewis acidity of these compounds furthermore allows one to use them for elucidating puzzling regioselectivities in reactions of ambident nucleophiles.^[47,48] In summary, due to their reactivities in between those of ordinary carbocations and neutral acceptorsubstituted π -systems, amino-substituted benzhydrylium ions are unique mechanistic tools,^[49] which have now become easily accessible

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• synthetic methods • X-ray diffraction

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Keywords: carbocations • hydrogen bonds • substituent effects

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Entry for the Table of Contents

Layout 2:

FULL PAPER



Benzhydrylium ions are the backbone of several reactivity and stability scales. The optimized syntheses of eleven *p*-amino-substituted benzhydrylium tetrafluoroborates are reported. The features of these benzhydrylium salts have been investigated in solution (UV-Vis, NMR), solid state (five X-ray structures), and by DFT calculations (in gas phase and aqueous solution).

Benzhydrylium Ions

Robert J. Mayer, Nathalie Hampel, Peter Mayer, Armin R. Ofial,* Herbert Mayr*

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Synthesis, Structure and Properties of Amino-Substituted Benzhydrylium lons – a Link Between Ordinary Carbocations and Neutral Electrophiles