An Efficient Procedure for the Synthesis of Crystalline Aryldiazonium Trifluoroacetates – Synthetic Applications

Christophe Colas[a] and Maurice Goeldner*[a]

Keywords: Crystalline diazonium trifluoroacetate salts / Quinone diazides / Pd-catalyzed C–C coupling

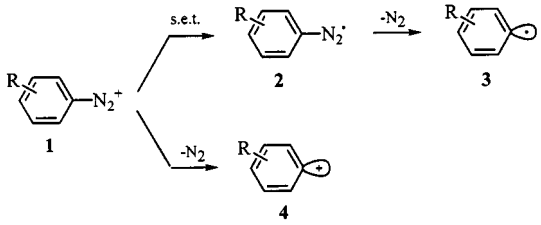
We have developed a very mild procedure for the synthesis of crystalline aryldiazonium trifluoroacetate salts in high yields under anhydrous conditions. Over thirty mono- or polyfunctional aniline derivatives have been diazotized by this method, including water- and acid-sensitive substrates. The *o*- and *p*-hydroxyaryldiazonium salts, derived from the corresponding anilines, could be deprotonated by treatment with K_2CO_3 to yield pure diazoquinones. NMR and UV/Vis spectra have been recorded for all the synthesized salts; the data are in good agreement with the rather limited published data and constitute a first extensive report of ^{13}C-NMR chemical shifts in diazonium salts. An excellent linear relationship emerged between Brown's substituent constants s^+_p and the $^{13}C_{ipso}$ chemical shifts. The diazonium salts obtained proved to be much more soluble in organic solvents than their tetrafluoroborate counterparts. They were tested in Pd-mediated coupling reactions of various carbon–carbon double bonds, and were found to give good yields within short reaction times under very mild conditions. We believe that diazonium trifluoroacetates represent a very attractive alternative to diazonium tetrafluoroborates.

Introduction

Aromatic diazonium compounds **A** are reagents of broad synthetic utility, undergoing a wide variety of reactions[1] that may or may not involve loss of the dinitrogen moiety. In recent studies, they were regarded as donor/acceptor complexes between a phenyl cation and a dinitrogen molecule.[2][3]

Dediazoniation of **1** can generate two types of intermediates (Scheme 1), either the aryl radical **3** formed via the corresponding diazenyl radical **2** (for a review, see ref.[4]), or the highly reactive aryl cation **4**, generated either chemically[5] or photochemically.[6] The intermediate **3** is invoked in several classical procedures (base-catalysed Gomberg–Bachman reaction, Sandmeyer reaction, Meerwein arylation), as well as in some more recent ones.[7][8] The cation **4** has been the subject of recent theoretical studies,[2,3,9] and has been shown to be involved in fluorination (Schiemann reaction), photolithography, affinity/photoaffinity labelling,[10] and DNA cleavage.[11] Finally, Matsuda and coworkers have developed a very powerful synthetic application for aromatic diazonium salts, namely a Pd-mediated ("Heck-like") coupling to various olefinic substrates.[12] This reaction has been extended to many other substrates (see ref.[13] and references cited therein) and has attracted great interest by virtue of its mildness and simplicity. Aryldiazonium salts therefore constitute a very attractive alternative to the expensive aryl iodides, triflates, or bromides.

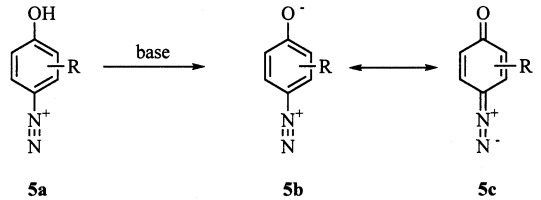
On the other hand, coupling reactions[14] proceeding by nucleophilic addition at the β-nitrogen atom furnish the industrially important azo dyes. Coupling is also possible



Scheme 1. Schematic representation of dediazoniation pathways; s. e. t. = single electron transfer

through activated methylene groups (Japp–Klingemann reaction) and by electrocyclic reactions leading to nitrogen-containing heterocycles,[15][16] exploiting the dienophile or dipolarophile character of some diazonium salts.[17]

The *p*- and *o*-hydroxyaryldiazonium salts exhibit a particular property: Upon deprotonation they adopt quinonoid structures, depicted as quinone diazides **5c**, i.e. cyclic vinyl analogues of α-diazo ketones (Scheme 2). These compounds have been extensively studied in the literature,[18–20] including with regard to their interesting photochemical properties.[21–23]



Scheme 2. Deprotonation of *p*-hydroxydiazonium salts

Numerous methods involving the diazotization of anilines exist for synthesizing aryldiazonium salts.[24–28] Tetrafluoroborate salts are by far the most synthesized compounds due to their enhanced stability compared to other salts (e.g. Cl^-). Their synthesis is generally achieved using

[a] Faculté de Pharmacie, Université L. Pasteur, Strasbourg,
B. P. 24, F-67401 Illkirch Cedex, France
Fax: (internat.) + 33-3/88678891
E-mail: goeldner@bioorga.u-strasbg.fr

  1434–193X/99/0606–1357 $ 17.50+.50/0

sodium nitrite in concentrated aqueous fluoroboric acid solution, from which the diazonium salt precipitates. Alternative procedures operating under anhydrous conditions make use of either moisture-sensitive reagents such as nitrosonium tetrafluoroborate,[25] or of in situ generated nitrosyl fluoride, formed by reaction of *tert*-butyl nitrite with boron trifluoride–diethyl ether.[27] A third method uses trimethylsilyl derivatives of anilines in conjunction with the sensitive nitrosyl halides;[28] however, it has only been applied to aniline and 4-nitroaniline.

To facilitate the usage of arenediazonium salts in organic chemistry, we have developed a general practical method for the synthesis of diazonium trifluoroacetate salts under anhydrous conditions. In actual fact, our reaction produces one equivalent of water, but this was found not to be deleterious under the conditions employed. The very mild procedure, amenable to larger quantities, has been applied to an extensive series of aniline derivatives, using controlled amounts of trifluoroacetic acid and isoamyl nitrite as a nitrosating species. The method has been extended to the synthesis of *ortho*- and *para*-hydroxyaryldiazonium derivatives, for which a practical deprotonation procedure has been elaborated. All compounds were characterized spectroscopically, by their UV, ^{1}H- and ^{13}C-NMR data. Finally, we used the diazonium trifluoroacetate salts in Heck-like coupling reactions with various olefinic bonds.

Results and Discussion

Diazotization Conditions

We sought a general diazotization method that would allow the synthesis of diazonium salts as pure precipitates in anhydrous organic media. We used isoamyl nitrite because it is transformed into volatile side-products during the course of the diazotization, and trifluoroacetic acid (TFA), because of its miscibility with most organic solvents. Diazonium trifluoroacetates have been described previously,[29][30] but the procedure given involved aqueous conditions, gave only moderate yields (ca. 50%), and was only applied to a limited range of anilines. Some of the substituted diazonium salts synthesized here proved to be acid- and/or moisture-sensitive, necessitating the use of a limited amount of acid and anhydrous conditions. It turned out that the use of 2.1 equivalents of TFA was sufficient for the diazotization reaction to proceed smoothly. This can be related to the known stoichiometry of diazonium trifluoroacetates as double salts (ArN_2^+, CF_3COO^-, CF_3COOH[29][30]). Besides, the use of TFA allows reactions to be commenced from *N*-Boc-protected anilines in a one-pot procedure involving a preliminary TFA-mediated deprotection step.

Using a concentration of 0.7 M for the starting aniline derivatives, we tested the influence of various organic solvents on this diazotization procedure using *para*-hydroxyaniline as the substrate, which allowed a convenient UV-spectrophotometric analysis of the reaction. Promising candidates were acetonitrile, ethanol, and dichloromethane, but only the latter permitted satisfactory precipitation of the product upon addition of anhydrous diethyl ether to the reaction medium. This result, established for a specific substrate, could, of course, only be extended to other anilines with caution, in view of the known influence of the substituent on the dediazoniation rate constant. Nevertheless, dichloromethane was found to be suitable for most of the diazonium salts synthesized here.

Tables 1, 2 and 3 summarize the diazotization reactions performed on *para*-, *meta*-, *ortho*-, and poly-substituted aniline derivatives. The results demonstrate the efficiency and generality of our diazotization procedure.

A great variety of substituents, irrespective of their position on the ring, were found to be compatible with these very mild reaction conditions. In the case of anilines bearing electron-withdrawing groups, a lowering of the reaction temperature to −15 °C was found to be necessary to avoid partial decomposition of the resulting diazonium salt. Otherwise, decomposition products could be detected in the NMR spectra of the crude reaction mixtures. In such cases, a 2:1 mixture of CH_2Cl_2 and CH_3CN (conditions B, see legends to tables) was found to give better results than pure CH_2Cl_2 since nitroanilines and aminobenzoic acids are only sparingly soluble in the latter. On the other hand, carrying out the reaction in the CH_2Cl_2/CH_3CN mixture led to an increase in the solubilities of the diazonium salts, even at −78 °C, thereby leading to a slight decrease in the reaction yields due to incomplete precipitation upon addition of diethyl ether.

Benzenediazonium trifluoroacetate was found to be difficult to isolate as a result of its moderate stability at room temperature;[31][32] this necessitated a lowering of the temperature to −78 °C during the stage of washing with diethyl ether. Accordingly, the ^{13}C-NMR spectrum of this compound and those of some other derivatives (*p*-$COCH_3$, *m*-NO_2, *m*-Cl, *m*-Br, *o*-NO_2, and compound **8**) had to be recorded at −15 °C in order to reduce dediazoniation during acquisition (see below).

The *m*-iodo- and *m*-methoxyaryldiazonium salts could not be isolated by this method, as might have been expected in view of their high instabilities owing to spontaneous dediazoniation,[31] the underlying reason for this behaviour remaining controversial.[9,33–35] Moreover, aryldiazonium trifluoroacetates have been reported to be more reactive than their tetrafluoroborate counterparts (vide infra). Nevertheless, most of the diazonium trifluoroacetate salts could be kept for several months at −18 °C without noticeable decomposition, provided that they were protected from light.

Table 3 illustrates the applicability of our method to several polysubstituted anilines, further demonstrating the synthetic utility of the procedure (see Scheme 3).

Of particular interest was the diazotization of the methacrylate ester **10**, this substrate being both acid- and water-sensitive (fast hydrolysis leading to compound **12b**); no problems were encountered under the reaction conditions employed. Our method also proved compatible with oxi-

Table 1. UV- (in methanol) and ^{13}C-/^{1}H-NMR-spectroscopic data (in CD_3OD unless otherwise stated) of isolated *p*-substituted diazonium trifluoroacetates; data are compared with published results (conditions A: CH_2Cl_2, 4°C; conditions B: CH_2Cl_2/CH_3CN, 2:1, −15°C)

Derivative	λ_m	ε	$\delta^{13}C$ (*ipso*)	d^1H (*ortho*)	Conditions	Yield (%)
p-NO_2	254	14000	123.3	9.07	B	70
	395	1700	123.0[a]	8.85[b]		
			121.8[c]			
p-CO_2H	261	14400	120.8[d]	8.82	B	75
	366	1300		8.93[b]		
				(acetone)		
p-CN	261	15130	120.8	8.86	B	90
	370	2200	(acetone)	(acetone)		
p-$COCH_3$	266	13600	120.9[d]	8.96	B	70
H	259	10500	115.1[d]	8.69	B	95
	259[e]	5640[e]	115.2[c]	8.43[b]		
				(acetone)		
	261[f]	12300[f]	115.8[a]			
	296[f]	1900[f]				
p-CH_3	278	15200	112.4	8.64	A	95
			113.3[g]	8.52[b]		
			109.1[a]			
			111.5[c]			
p-Cl	280	12400	115.2	8.71	A	95
	281[h]	15600[h]	113.2[a]	8.58[b]		
p-Br	290	19400	115.6	8.62	A	96
	293[h]	15100[h]	114.8[a]	8.45[b]		
			114.2[c]			
			(DMSO)			
p-I	324	15400	115.9	8.45	A	92
	327.5[h]	10900[h]				
	326[i]	12500[i]				
p-OCH_3	313	27600	103.4	8.68	A	85
	315[h]	19200[h]	105.0[a]	8.45[b]		
	313[i]	23500[i]	103.1[c]			
	313[j]	24600[j]				
p-OH	313	23400	99.0	8.48	A	95
			102.1[g]			
p-NHAc	338	33000	105.2	8.56	A	83
	339[k]	30200[k]				
p-NH-Boc	338	33000	103.0	8.51	A	96
p-$N(CH_3)_2$	379	37500	89.8	8.21	A	95
	378[l]	36100[l]	88.7[m]			
	380[h]	28100[h]	89.3[c]			

[a] Ref.[41], in liquid SO_2. – [b] Ref.[27], in CH_3CN unless otherwise stated. – [c] Ref.[40], in CH_3CN unless otherwise stated. – [d] Spectra recorded at −15°C. – [e] Ref.[39], in ethanol. – [f] Ref.[71], in water. – [g] Ref.[42], in $CDCl_3$ supplemented with 18-crown-6. – [h] Ref.[37], in water. – [i] Ref.[72], in aqueous phosphate buffer, pH = 7.2. – [j] Ref.[38] – [k] Ref.[73] – [l] Ref.[74] – [m] Ref.[75], in CD_3NO_2.

dation-sensitive substrates, such as 3-aminobenzhydrol (data not shown), while substrates such as *p*-NH-Boc-phenyldiazonium could be used to sequentially generate two diazonium functions (see below). Taken together, these results illustrate the versatility of the method, allowing the synthesis of a broad range of polyfunctional and/or sensitive diazonium salts.

Spectral Analysis

UV/Vis data were recorded using methanol as solvent, and, when possible, were compared with published data. A good overall agreement was found. No quantitative relationship between the electronic nature of the substituent and the UV parameters could be delineated, though a qualitative correlation in the *p*-substituted series was evident. Some publications have dealt with the precise analysis of UV/Vis spectra of aryldiazonium salts, attempting to assign the observed absorptions to specific transitions.[36–39] These studies focused only on π-donating groups, but revealed a complexity in the origin of the variations of the absorption maxima. Such variations could arise from intramolecular charge transfer, or from so-called "local excitation" within the aromatic ring framework, for instance. The types of transitions involved varied with the nature of the substituents, preventing the authors from establishing any simple rules. Since we are dealing with π-donors as well as π-acceptors in the three positions on the ring, we cannot rationalize the observed variations in λ_m and ε in a quantitative manner either. Generally, however, *p*-substituted diazonium salts show simple absorption spectra with one maximum, whereas their *m*- and *o*-substituted counterparts show a more complex pattern. In the case of the coumarin derivative **9**, we noticed that the extinction coefficient varies with concentration, possibly due to intermolecular interactions between individual diazonium ions.

For the collection of NMR data, the diazonium trifluoroacetates were found to be sufficiently soluble in three solvents, namely [D_6]acetone, [D_3]acetonitrile, and [D_4]methanol. Acetonitrile proved to be a good solvent for these

Table 2. UV- (in methanol) and ^{13}C-/^{1}H-NMR-spectroscopic data (in CD_3OD unless otherwise stated) of isolated *m*- and *o*-substituted diazonium trifluoroacetates; data are compared with published results (ND: not determined; conditions A: CH_2Cl_2, 4°C; conditions B: CH_2Cl_2/CH_3CN, 2:1, −15°C)

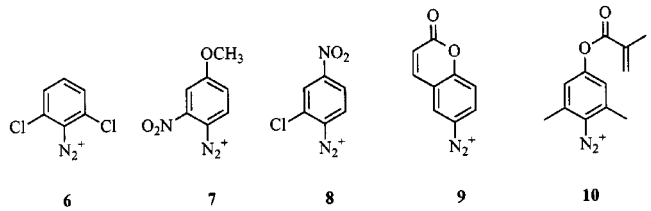
Derivative	λ_m	ε	$\delta^{13}C$ (*ipso*)	d^1H (*ortho*)	Conditions	Yield (%)
m-NO_2	254 318	11500 4400	119.8[a]	9.11; 9.63 8.53[b]	B	84
m-CO_2H	256	11100	118.1	8.84; 9.27	B	54
m-CN	254	10000	118.4	9.01; 9.15	A	89
m-Cl	ND 266[c] 317[c]	ND 14500[c] 2000[c]	118.8	8.80; 8.67	B	
m-Br	265 319 268.5[c] 323[c] 268[d] 323[d]	5900 1700 4200[c] 900[c] 7000[d] 1400[d]	118.7	8.70; 8.93	A	68
o-NO_2	258	9400	118.5[a] 108.2[e]	9.19 8.87[b]	B	75
o-CO_2H	252	7300	113.6	8.83 8.83[b] (DMSO)	A	72
o-CN	262	5600	120.0	8.51	A	74
o-Cl	263 319	6100 1800	117.4	8.85	B	90
o-Br	266 330	5500 1900	119.7	8.82	B	94
o-OCH_3	265 321 264[f]	4900 2100 4900[f]	103.0 99.4[d]	8.49	B	93
o-OH	264 361	8400 2800	93.5	7.77	B	93

[a] Spectra recorded at −15°C. − [b] Ref.[27], in CH_3CN unless otherwise stated. − [c] Ref.[36], in water. − [d] Ref.[72], in aqueous phosphate buffer. − [e] Ref.[41], in liquid SO_2. − [f] Ref.[38] in acetonitrile.

Table 3. UV- (in methanol) and ^{13}C-/^{1}H-NMR-spectroscopic data (in CD_3OD unless otherwise stated) of isolated polysubstituted diazonium trifluoroacetates (conditions A: CH_2Cl_2, 4°C; conditions B: CH_2Cl_2/CH_3CN, 2:1, −15°C)

Derivative	λ_m	ε	$\delta^{13}C$-1[a]	d^1H_o[a]	Conditions	Yield (%)
6	273 342	5600 2500	118.4	−	A	78
7	256 338	13300 10300	99.4	9.01; 8.34	B	93
8	260 335	8100 2500	123.6[b]	9.14[b]	A	82
9	273 (7 μM)[c] 256 (30 μM)[c]	15000 (7 μM)[c] 28700 (30 μM)[c]	111.0	9.08; 8.79	A	94
10	281	14500	112.6		A	91

[a] C-1 is the N_2-bearing carbon atom, H_o is the *ortho* position to the N_2 moiety. − [b] Spectra recorded at −15°C. − [c] See text.



6 7 8 9 10

Scheme 3. Structures of the studied polysubstituted aromatic diazonium trifluoroacetates (see Table 3)

salts, but was not entirely satisfactory for NMR as its ^{13}C peak at δ = 114.5 falls within the range of chemical shifts of the N_2^+-bearing carbon atoms, leading to signal overlap. Methanol was therefore preferred, other than where a lack of solubility necessitated the use of acetone. For some electron-deficient derivatives, partial decomposition was sometimes unavoidable on the timescale of the ^{13}C acquisition at room temperature, necessitating acquisition at −15°C. On the other hand, in the case of *meta*-cyano-substituted derivatives, 2D-heteronuclear correlations (under field gradients) were required in order to make unambiguous chemical shift assignments. Since most trifluoroacetates are very soluble in alcohols, no additives such as crown ethers were necessary to increase their solubilities. Other than for quinone diazides, for which a strong solvent dependence of the chemical shifts has previously been demonstrated,[20] com-

parison of our chemical shift values with those reported in the literature showed a very good correlation. This was somewhat surprising, since the solvents and counteranions used differ greatly (DMSO,[20][40] CH_3CN,[27][41] SO_2,[41] acetone,[27] and sometimes 18-crown-6/chloroform[42][43]). Most of the data collected in methanol solutions match the published data to within a few ppm. Since variations in ^{13}C chemical shifts can be qualitatively related to differences in solvation, the aforementioned observations might suggest that solvation of diazonium salts does not vary greatly among donor solvents.

Notably, in the ^{13}C-NMR spectra, only two quadruplets at $\delta \approx 117.5$ and $\delta \approx 161.5$ were observed, which correspond to the two carbon atoms of a trifluoroacetate. The proposed composition of these diazonium salts, however, requires one trifluoroacetate and one trifluoroacetic acid molecule. This observation shows that the two fluorinated molecules are magnetically equivalent, which would be consistent with a total dissociation of the diazonium salt and deprotonation of the trifluoroacetic acid equivalent, as has previously been mentioned for aqueous solutions of these salts.[29]

The series of ^{13}C chemical shifts obtained for the N_2^+-bearing carbon atoms allowed us to evaluate a possible linear relationship with Brown's parameters for the corresponding *para* substituents, as proposed by Ustynyuk et al.[40] From Figure 1, it is clear that linearity is also observed for $\delta(C_{ipso})$ of the trifluoroacetates in CD_3OD solution. Linearization gives Equation 1.

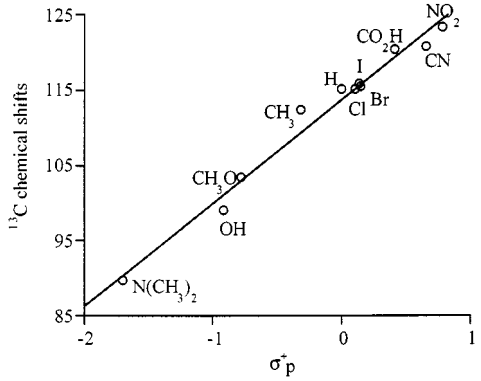


Figure 1. Plot of the recorded chemical shifts for *p*-substituted aryldiazonium salts against Brown's constants

$$\delta(C_{ipso}) = 113.7 + 13.7 \times \sigma^+_p \quad (1)$$

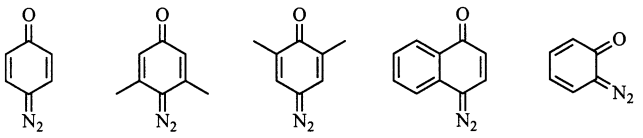
A linearity coefficient of 13.7 (which is of the same order of magnitude as that described by Ustynyuk: 15.7) with an excellent correlation coefficient ($r = 0.990$) was found. This linear relationship may allow the determination of s^+_p values for other substituents, e.g. a value of -0.78 was estimated for the N(H)Boc group. The significance of the linear variation is not clear and remains controversial;[2,44,45] even though the shielding of C_{ipso} increases regularly with the donating ability of the *para* substituent, no quantitative conclusions can be drawn concerning the electronic density on the diazonium-bearing carbon atoms. The variations of $d^{13}C$ parameters do not show any direct correlations to reactivity patterns either, since the benzenediazonium salt, for instance, is found to decompose in methanol more rapidly than the 4-cyanobenzenediazonium salt (see ref.[31] for an overview).

Quinone Diazides

In the syntheses described above, *N*-Boc-amino-protected derivatives were used as starting materials. These precursors were obtained by treatment of the aminophenol with Boc_2O (which allowed an efficient purification of the commercial products) in the case of **11a** and **11d**, or by catalytic hydrogenation of the corresponding nitroso or nitro compound in the presence of the Boc_2O reagent (**11b** and **11c**, respectively).

Compounds **11a–e** were then treated with pure TFA, isolated as anilinium trifluoroacetates, and submitted to diazotization (see above) to give the corresponding hydroxydiazonium derivatives.

A method allowing their deprotonation under anhydrous conditions needed to be developed. While the use of Ag_2O in ethanolic solution requires chromatography on alumina,[46] we found that simple treatment with K_2CO_3 in CH_2Cl_2 offered comparable results, allowing for a selective solubilization of quinone diazides in CH_2Cl_2. Since the formed CF_3CO_2K is hygroscopic, this procedure can be expected to maintain an anhydrous reaction medium. The hydroxy-substituted substrates **11a–d** were treated as described and gave the quinone diazides **12a–d** in solution, their isolation requiring simple filtration of the inorganic salts and evaporation of the solvent. This method represents an improvement on the existing procedure, avoiding in particular a chromatographic separation of the final diazo compounds. Good to excellent overall yields, calculated for the three steps (deprotection, diazotization, and deprotonation), were obtained (Scheme 4, Table 4).



12a **12b** **12c** **12d** **12e**

Scheme 4. Structures of the studied quinone diazide derivatives (see Table 4)

Synthetic Applications

The Heck-like carbon–carbon coupling reaction represents a recent synthetic application for aryldiazonium salts (see ref.[13] and references cited therein). The idea is to substitute "classical" nucleofuges in Heck-like coupling reactions such as triflates or iodides by the diazonium moiety. We decided to take advantage of the better solubility of diazonium trifluoroacetate salts in organic solvents com-

Table 4. UV- (in methanol) and ^{13}C-/^{1}H-NMR-spectroscopic data (in CD_3OD unless otherwise stated) of isolated quinone diazides

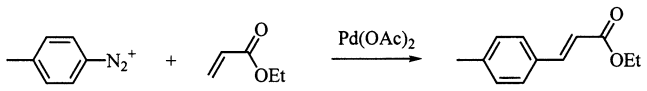
Derivative	λ_m	ε	$\delta^{13}C$-1[a]	$d^{13}C$-4[a]	$d^{1}H_o$[a]	$d^{1}H_m$[a]	Yield (%)
12a	350	30000	80.6 73.6[b,e] 75.2[b] (DMSO) 79.8[d]	184.0 182.2[b] 181.56[e]	7.88 7.78[c]	6.44 6.17[c]	82
12b	347	27000	83.5 77.8 (acetone)[b]	184.0 181.8 (acetone)[b]	–	6.26	94
12c	363	33600	77.36 72.6 (DMSO)[b]	183.6 180.5 (DMSO)[b]	7.66	–	97
12d	269	9100	78	180.9			
12e	389 262 264[f] 396 402[f]	24800 8600 6300[f] 6000 5000[f]	74.9[b] 90.5	181.0[b] 180.2	8.24 7.50 7.38[b]	6.59 6.68 6.66[b]	83 76

[a] C-1 is the N_2-bearing carbon atom, C-4 the carbonyl carbon atom; H_o is the *ortho* position to the N_2 moiety, H_m the *meta* position; data are compared with published results. – [b] Ref.[20]; in $CDCl_3$ unless otherwise stated. – [c] Ref.[46] – [d] Ref.[42] – [e] Ref.[40] – [f] Ref.[76]

pared to the tetrafluoroborates generally used for such reactions. Recent studies[47] described the use of in situ generated diazonium salts from acidolysis of arylmorpholinotriazenes in carbon–carbon coupling reactions.

We first set up the reaction conditions, focusing on the coupling of the tolyldiazonium cation with ethyl acrylate (Scheme 5). Various solvents were used for palladium-mediated coupling reactions of diazonium salts with electron-deficient olefins, such as alcohols,[47][48] water,[49] acetonitrile,[12][50] CH_2Cl_2/acetone,[51] and dioxane.[13] Table 5 shows the results we obtained on testing ethanol, acetonitrile, dichloromethane, and dioxane in coupling reactions with $Pd(OAc)_2$ as the catalyst.

The results revealed a dramatic influence of the solvent, the reaction only proceeding well in ethanol. We did not test other alcohols, since we wished to avoid transesterification reactions. Previous studies on the stabilities of diazonium salts in acidic alcoholic solutions[32,52,53] have shown that two dediazoniation reaction pathways can occur (see Scheme 1), depending on the substrates (nature of substituents on the aromatic ring) and the conditions (the presence or absence of oxygen; temperature). The 4-nitrophenyldiazonium cation was found to decompose almost exclusively by homolytic cleavage, while the *p*-tolyldiazonium cation decomposes almost exclusively according to a heterolytic pathway. For most other substrates, these two processes are generally in competition, depending on the conditions used. Oxygen is known to inhibit the radical pathway, thereby favoring the ionic process, which would be better suited for our synthetic purposes. However, the use of N_2 or Ar is recommended because of the known sensitivity of organopalladium species to air. The use of trifluoroacetate salts led to a reduction in the reaction times at room temperature compared to those with tetrafluoroborates,[47,50,54] thereby rendering the coupling reactions much faster than any spontaneous dediazoniation. This again illustrates the mildness of the proposed methodology. In fact, the apparent greater reactivity of diazonium trifluoroacetates has been mentioned previously in the literature.[55] Comparing the thermal decomposition of benzenediazonium trifluoroacetate and tetrafluoroborate in water, higher yields of phenol, at lower temperatures, were obtained with the former.



Scheme 5. Pd-mediated coupling of *p*-tolyldiazonium trifluoroacetate with ethyl acrylate (see Table 5)

Table 5. Coupling yields obtained in the reaction of the *p*-tolyldiazonium cation with ethyl acrylate

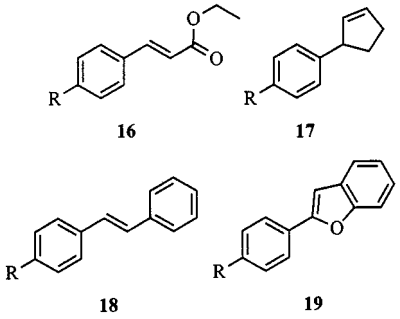
Solvent	Dioxane	EtOH	CH_3CN	CH_2Cl_2
Yield (%)	0	98	9	30

The mechanism of the reaction has been proposed to involve a general catalytic cycle, as illustrated for example for boronic acids.[13] An initially formed palladium(II) complex is reduced, thereby forming a nucleophilic Pd^0 center, which then undergoes insertion into the diazonium cation in place of the dinitrogen moiety. Subsequent nucleophilic attack by the olefin regenerates a Pd^{II} complex, liberating the coupled product through a *cis*-elimination process.

The role of nucleophiles in spontaneous dediazoniations, originating either from the solvent[5][56] or from added substances,[34][52] has been well documented. In particular, bases (such as tertiary amines, carboxylates, or carbonates) as well as phosphanes[57] are known to react rapidly with diazonium salts at the β-nitrogen atom, thereby initiating radical chain reactions. Indeed, attempts to use phosphane coordinated to transition metal ions (Rh^{II}, Pd^{II}, Pd^0) failed to give any coupling products, but essentially only hydrodediazoniation products instead. Consequently, even though these ligands are commonplace in Heck-like reactions, we only used $Pd(OAc)_2$ in our trials.

The coupling reaction was attempted with various C−C multiple bonds to further investigate the scope of the trifluoroacetate salts. It turned out that neither phenylacetylene nor allyl alcohol gave satisfactory results under the conditions used, as was previously found by Matsuda et al. with tetrafluoroborates.[12] However, the reaction worked well with cyclopentene, styrene, and to a lesser extent with 2,3-benzofuran. The results are presented in Scheme 6 and Table 6. In the case of electron-rich diazonium cations, they compare favorably with previously published results.[58]

In this study, we did not try to optimize the reaction conditions, but rather tested the general applicability of diazonium trifluoroacetates in Pd-mediated couplings under the conditions established for the coupling of the *p*-tolyldiazonium cation with ethyl acrylate.



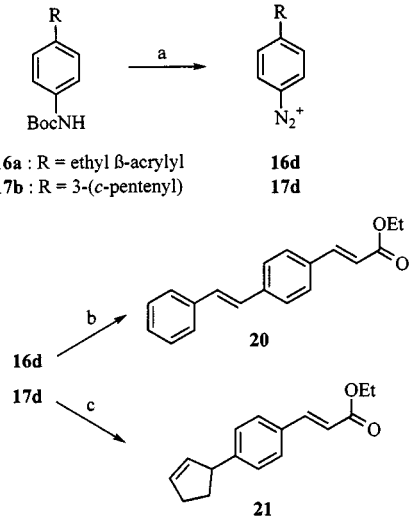
Scheme 6. Structures of compounds synthesized by Pd-mediated coupling reactions using different aromatic trifluoroacetates (see Table 6)

Table 6. Yields (indicated in%) of couplings between diazonium trifluoroacetates and ethyl acrylate, cyclopentene, styrene, and benzofuran, under $Pd(OAc)_2$ catalysis

Coupling product	**a**: R = N(H)Boc	**b**: R = CH_3	**c**: R = NO_2
16	63	99	45
17	77	89	32
18	90	98	41
19	24	43	20

In general, the results parallel the propensity of the tested diazonium salts to follow heterolytic decomposition pathways. In all cases, the *p*-nitrophenyldiazonium salt gave the lowest yields, which can be related to its known tendency to undergo homolytic dediazoniation reactions forming nitrobenzene as a major side-product.[51][59] As expected, the *p*-methyl- and *p*-(Boc-amino)aryldiazonium salts gave much better results. In the case of the cyclopentene derivative, migration of the double bond was observed, which could be rationalized in terms of the mechanism of the *cis* elimination from the σ-Pd complex. However, the NMR spectra of the cyclopentene adducts showed a slight contamination (average 5%) by the 2-aryl-substituted isomer. The case of benzofuran shows that even electron-rich double bonds may presumably be used as substrates in these coupling reactions.

The *p*-Boc-amino-substituted aryldiazonium cation merits its special comment: Subsequent deprotection of the obtained coupling products would generate new aniline derivatives, which could be diazotized and further used in coupling sequences. In order to evaluate this latter possibility, we submitted compounds **16a** and **17b** to a deprotection step in pure TFA, followed by a diazotization step. ^{1}H-NMR monitoring of the intermediate anilines and diazonium salts indicated that both reactions proceeded satisfactorily. We then used the latter compounds in coupling reactions with styrene and ethyl acrylate (with compounds **16d** and **17d**, respectively, Scheme 7). The conditions used were strictly identical to those used previously. Work-up of the reaction mixtures led to the isolation of the expected products, **20** (75%) and **21** (47%), respectively. Neither the deprotection nor the diazotization steps led to polymerization of the starting alkene, which is especially noteworthy in the case of the unconjugated C=C bond in **17b**. In this latter compound, no isomerization of the double bond could be observed either, which further emphasizes the utility of the described method. Yields are moderate, but again we did not try to optimize the reaction conditions.



Scheme 7. a: TFA 30 min, room temp., then *i*-AmONO (1.2 equiv.), TFA (1.1 equiv.), −15°C, 1 h, CH_2Cl_2; b: styrene (1.2 equiv.), $Pd(OAc)_2$ 0.01 mol-%, room temp., 1 h, EtOH; c: ethyl acrylate (1.2 equiv.), $Pd(OAc)_2$ (0.01 mol-%), room temp., 1 h, EtOH

In summary, this sequential coupling procedure demonstrates that the use of aryldiazonium salts constitutes a good alternative approach to Wittig-like reactions in the syntheses of substituted alkenes. This strategy leads to unsymmetrically substituted compounds, potentially allowing the synthesis of "push-pull"-type derivatives, for example, which are widely used in non-linear optical materials and organic conducting polymers.

Experimental Section

General: ***CAUTION:*** Besides their well-documented photosensitivity, aryldiazonium salts are subject to spontaneous ignition or explosion hazards, especially in the presence of nucleophilic counteranions. This behaviour is never observed in solution, but violent shock or heat could, in principle, initiate their explosive decomposition in the solid state. This was not encountered with the salts presented here, though we routinely manipulated them with a met-

allic spatula, even on a gram scale. Since spontaneous decomposition cannot, however, be excluded, we recommend that manipulation of solid diazonium salts should be kept to a minimum and that suitable precautions should be taken (no contact with rough surfaces). Isoamyl nitrite should be handled in inert atmosphere and protected from light to avoid explosive decomposition. – ^{1}H- and ^{13}C-NMR spectra were recorded at room temperature with Bruker AC200 or DPX300 spectrometers, equipped with 5-mm dual probes for routine acquisition. Low-temperature measurements were made with the AC200 instrument using a 10-mm probe. Relaxation delay was set at 0 s for ^{1}H and at 500 µs for ^{13}C. In some cases, the N_2^+-bearing carbon atoms relaxed very poorly, even under these conditions. [D_4]Methanol, [D_3]acetonitrile, and [D_6]acetone were purchased from CEA, Saclay, France. HMQC and HMBC acquisitions, where required, were recorded under field gradients using the Bruker inv4gs and inv4lplrnd programs, respectively. For HMBC, 70 µs was often found to be a convenient value for 1/2 *J*. ^{1}H-NMR signals were referenced against the CHD_2OD signal in methanol (δ = 3.35), while ^{13}C signals were referenced against the CD_3OD signal set at δ = 49.3. – UV spectra were recorded with a double-beam Uvikon 860 spectrophotometer. Methanolic solutions of the diazonium salts were prepared immediately prior to use and were stored over ice to minimize possible dediazoniations. The λ_m and ε values quoted are mean values from at least 4 measurements. Solvents used for synthesis were of analytical grade. They were kept dry by continuous distillation from CaH_2 (CH_2Cl_2 and acetonitrile) or benzophenone/sodium (diethyl ether). TFA (98%) was purchased from Fluka. Isoamyl nitrite was purchased from Aldrich and used as received; $Pd(OAc)_2$ was purchased from Lancaster Synthesis. Solid aniline derivatives were used as received; liquid compounds were redistilled under reduced pressure prior to use. All the described syntheses were carried out under N_2 or Ar with protection from direct light.

Diazotization Procedure: The appropriate aniline (6 mmol) was dissolved in 8 mL of dry CH_2Cl_2 at room temp. under inert atmosphere. If the solubility was too low, a 2:1 CH_2Cl_2/CH_3CN mixture was used instead. Under vigorous stirring, 1 mL (2.1 equiv.) of TFA was then added dropwise by means of a syringe. In some cases, a voluminous precipitate appeared, which redissolved during the course of the reaction. The mixture was then equilibrated at the chosen temperature, and isoamyl nitrite (1 mL, 1.2 equiv.) was added to the well-stirred reaction mixture over a period of 10 min by means of a syringe. The reaction was allowed to proceed for 1 h at the chosen temperature. For strongly electron-deficient anilines, the addition of a further 0.3 equivalents of isoamyl nitrite during this period was found to improve the yields. At the end of the reaction, the mixture was often found to be brown in color. The reaction flask was then cooled to −78°C and, with vigorous stirring, a threefold volume excess of precooled, dry diethyl ether was immediately added. The resulting precipitate was stirred for a few minutes, then left to settle (at −78°C). The supernatant was removed with a syringe or by cannulation, and a further threefold volume excess of cold diethyl ether was added to the remaining precipitate. After stirring and decantation, the supernatant was again discarded. This washing procedure was repeated once more. Alternatively, after the first precipitation, the slurry could simply be filtered through cotton (***CAUTION:*** Never use a sintered funnel – explosion hazard!) and rinsed with cold diethyl ether. This latter procedure was, however, found to be less well suited for sensitive diazonium salts (increased temperature; water condensation). The finally recovered precipitate was dried under reduced pressure without any heating, giving the pure diazonium trifluoroacetate.

Deprotonation Procedure: The obtained hydroxydiazonium salt was resuspended in dry CH_2Cl_2 (20 mL) at room temp., together with 2.1 equivalents of K_2CO_3, and the mixture was stirred for 1 h under an inert atmosphere. The liquid phase turned orange-brown. After decantation, the supernatant was collected and the precipitate was washed twice with 10 mL of fresh CH_2Cl_2. The combined supernatants were concentrated, yielding the pure quinone diazide.

General Procedure for Palladium-Mediated Coupling Reactions: The chosen diazonium trifluoroacetate (1 mmol) was dissolved in 10 mL of ethanol (dried over 3-Å molecular sieves) under inert atmosphere and with protection from light. The appropriate unsaturated nucleophile (1.2 equiv.) was then added to the stirred solution, followed by the $Pd(OAc)_2$ catalyst (0.01 equiv.) as a freshly prepared solution in dry CH_2Cl_2. After 10–60 min, the reaction was stopped simply by filtration through Celite. The filtrate was concentrated in vacuo, the residue was redissolved in diethyl ether, and the resulting solution was washed twice with water and brine. After drying with $MgSO_4$, the organic layer was adsorbed onto silica gel and subjected to chromatography. The optimal eluents were found to be diethyl ether/pentane and dichloromethane/pentane.

Deprotection Procedure: The appropriate Boc-protected aniline was dissolved in pure TFA (final concentration in the molar range) and the solution was stirred at room temperature under inert atmosphere for ca. 30 min. The solvent was then evaporated in vacuo and the residue was triturated twice with anhydrous diethyl ether. The resulting precipitate was subjected to the classical diazotization procedure, except that only 1.2 equivalents of TFA were added to the dichloromethane solution.

Ethyl 4-(Boc-amino)cinnamate (16a):[60] Pale-yellow crystals, m.p. 91–93°C (ref. 92–94°C[60]). – ^{1}H NMR ($CDCl_3$): δ = 1.33 (t, ^3J = 7.13 Hz, 3 H, CH_3), 1.52 [s, 9 H, $C(CH_3)_3$], 4.25 (q, ^3J = 7.19 Hz, 2 H, CH_2), 6.34 (d, ^3J = 6.08 Hz, 1 H, H_α), 6.79 (br. s, 1 H, NH), 7.39 (d, ^3J = 9.14 Hz, 2 H, 3′-H), 7.45 (d, ^3J = 9.12 Hz, 2 H, 2′-H), 7.63 (d, ^3J = 15.72 Hz, 1 H, H_β). – ^{13}C NMR ($CDCl_3$): δ = 15.08 (CH_3), 29.03 [$C(CH_3)_3$], 61.14 (CH_2), 81.70 [$OC(CH_3)_3$], 117.16 (C_α), 119.04 (C-3′), 127.26 (C-1′), 129.78 (C-2′), 141.10 (C-4′), 144.89 (C_β), 153.14 [OC(=O)NH], 168.01 (C=O ester). – MS (70 eV); *m*/*z* (%): 291 (16) [M^+], 235 (100) [$M^+ - H_2C=CMe_2$], 191 (28) [$M^+ - H_2C=CMe_2 - CO_2$], 190 (23) [$M^+ - OCOCMe_3$], 172 (33) [$M^+ - HOCMe_3 - OEt$].

Ethyl 4-Methylcinnamate (16b):[61–63] Colorless liquid. – ^{1}H NMR ($CDCl_3$): δ = 1.34 (t, ^3J = 7.12 Hz, 3 H, CH_2CH_3), 2.37 (s, 3 H, $ArCH_3$), 4.27 (q, ^3J = 7.06 Hz, 2 H, CH_2CH_3), 6.40 (d, ^3J = 16.06 Hz, 1 H, H_α), 7.19 (d, ^3J = 8.04 Hz, 2 H, 3′-H), 7.43 (d, ^3J = 9.12 Hz, 2 H, 2′-H), 7.67 (d, ^3J = 16.10 Hz, 1 H, H_β). – ^{13}C NMR ($CDCl_3$): δ = 15.08 (CH_3), 22.18 ($ArCH_3$), 61.14 (CH_2), 117.88 (C_α), 128.77 (C-2′), 130.33 (C-3′), 132.46 (C-1′), 141.36 (C-4′), 145.34 (C_β), 167.95 (C=O ester). – MS (70 eV); *m*/*z* (%): 190 (64) [M^+], 162 (11) [$M^+ - C_2H_4$], 145 (100) [$M^+ - OEt$], 115 (53), 91 (27) [$CH_3C_6H_4^+$].

Ethyl 4-Nitrocinnamate (16c):[62][64] Yellow crystals, m.p. 137–138°C (ref. 136–137°C[63]). – ^{1}H NMR ($CDCl_3$): δ = 1.34 (t, ^3J = 7.14 Hz, 3 H, CH_3), 4.28 (q, ^3J = 7.14 Hz, 2 H, CH_2), 6.55 (d, ^3J = 16.20 Hz, 1 H, H_α), 7.67 (d, ^3J = 8.79 Hz, 1 H, 2′-H), 7.70 (d, ^3J = 16.17 Hz, 1 H, H_β), 8.23 (d, ^3J = 8.79 Hz, 1 H, 3′-H). – ^{13}C NMR ($CDCl_3$): δ = 14.98 (CH_3), 61.72 (CH_2), 123.31 (C_α), 124.89 (C-3′), 129.34 (C-2′), 141.31 (C-1′), 142.32 (C_β), 149.18 (C-4′), 166.73 (C=O). – MS (70 eV); *m*/*z* (%): 221 (28) [M^+], 193 [$M^+ - C_2H_4$], 176 (100) [$M^+ - OEt$].

3-(4′-Boc-aminophenyl)cyclopentene (17a): White crystals, m.p. 94–95°C. – ^{1}H NMR ($CDCl_3$): δ = 1.52 [s, 9 H, $C(CH_3)_3$],

1.61−1.78 (m, 1 H, 4-H), 2.29−2.56 (m, 2 H, 5-H), 3.79−3.90 (m, 1 H, 3-H), 5.73−5.78 (m, 1 H, 1-H), 5.90−5.95 (m, 1 H, 2-H), 6.47 (br. s, 1 H, NH) 7.11 (d, ^3J = 8.40 Hz, 2 H, 3′-H), 7.28 (d, ^3J = 8.40 Hz, 2 H, 2′-H). − ^{13}C NMR ($CDCl_3$): δ = 29.11 [C(*C*H$_3$)$_3$], 33.21 (C-4), 34.60 (C-5), 51.44 (C-3), 81.12 [O*C*(CH$_3$)$_3$], 119.59 (C-3′), 128.42 (C-2′), 132.61 (C-1), 135.12 (C-2), 137.00 (C-4′), 142.08 (C-1′), 153.59 [O*C*(=O)NH]. − MS (70 eV); *m*/*z* (%): 259 (31) [M$^+$], 203 (100) [M$^+$ − H$_2$C=CMe$_2$], 159 (10) [MH$^+$ − H$_2$C=CMe$_2$ − CO$_2$], 158 (10) [M$^+$ − O=COCMe$_3$].

3-Tolylcyclopentene (17b):[65][66] Colorless liquid. − ^{1}H NMR ($CDCl_3$): δ = 1.73−1.83 (m, 1 H, 4-H), 2.39 (s, 3 H, CH$_3$), 2.42−2.61 (m, 3 H, 4-H and 5-H), 3.89−3.96 (m, 1 H, 3-H), 5.81−5.85 (m, 1 H, 1-H), 5.97−6.01 (m, 1 H, 2-H), 7.13−7.21 (m, 4 H, aromatic). − ^{13}C NMR ($CDCl_3$): δ = 21.72 (CH$_3$), 33.24 (C-5), 34.62 (C-4), 51.68 (C-3), 127.84 (C-3′ or C-2′), 129.80 (C-3′ or C-2′), 132.42 (C-1), 135.27 (C-2), 136.16 (C-4′), 144.25 (C-1′). − MS (70 eV); *m*/*z* (%): 158 (69) [M$^+$], 157 (100) [M$^+$ − H], 143 (91) [M$^+$ − CH$_3$].

3-(4′-Nitrophenyl)cyclopentene (17c):[12] Yellow liquid. − ^{1}H NMR ($CDCl_3$): δ = 1.64−1.77 (m, 1 H, 4-H), 2.40−2.58 (m, 3 H, 4-H and 5-H), 3.94−4.03 (m, 1 H, 3-H), 5.74−5.77 (m, 1 H, 1-H), 6.03 (dt, ^3J = 2.21 Hz, $^3J'$ = 5.76 Hz, 1 H, 2-H), 7.36 (d, 2 H, ^3J = 8.79 Hz, 2 H, 2′-H), 8.14 (d, ^3J = 8.52 Hz, 2 H, 3′-H). − ^{13}C NMR ($CDCl_3$): δ = 33.21 (C-5), 34.36 (C-4), 51.91 (C-3), 124.44 (C-3′), 128.72 (C-2′), 133.45 (C-1), 134.26 (C-2), 147.14 (C-4′), 155.12 (C-1′). − MS (70 eV); *m*/*z* (%): 189 (95) [M$^+$], 172 (32) [M$^+$ − OH], 142 (96) [M$^+$ − HNO$_2$].

4-(Boc-amino)stilbene (18a): White crystals, m.p. 184−185°C. − ^{1}H NMR ($CDCl_3$): δ = 1.58 [s, 9 H, C(CH$_3$)$_3$], 7.08 (d, ^3J = 18.24 Hz, 1 H, C$_\alpha$-H or C$_\beta$-H), 7.09 (d, ^3J = 18.24 Hz, 1 H, C$_\alpha$-H or C$_\beta$-H), 7.29 (m, 1 H, 4′-H), 7.38 (d, ^3J = 8.97 Hz, 2 H, 3′-H), 7.41 (d, ^3J = 10.50 Hz, 2 H, 3-H), 7.50 (d, ^3J = 10.23 Hz, 2 H, 2-H), 7.55 (d, ^3J = 10.23 Hz, 2 H, 2′-H). − ^{13}C NMR ($CDCl_3$): δ = 29.08 [C(*C*H$_3$)$_3$], 81.41 [O*C*(CH$_3$)$_3$], 119.30 (C-3), 127.09 (C-2′), 127.93 (C-2 and C$_\alpha$-H), 128.10 (C-4′), 128.85 (C$_\beta$-H), 129.40 (C-3′), 132.96 (C-1), 138.21 (C-1′), 138.56 (C-4′), 153.37 [O*C*(=O)NH]. − MS (70 eV); *m*/*z* (%): 295 (12) [M$^+$], 239 (100) [MH$^+$ − H$_2$C=CMe$_2$], 221 (61) [M$^+$ − HOCMe$_3$], 195 (88) [MH$^+$ − H$_2$C=CMe$_2$ − CO$_2$].

4-Methylstilbene (18b): White crystals, m.p. 118−119°C (ref. 119°C[61][67]). − ^{1}H NMR ($CDCl_3$): δ = 2.42 (s, 3 H, CH$_3$), 7.14 (s, 2 H, H$_\alpha$ and H$_\beta$), 7.22 (d, ^3J = 8.02 Hz, 2 H, 3-H), 7.32 (t, ^3J = 9.20 Hz, 1 H, 4′-H), 7.39 (d, ^3J = 7.66 Hz, 2 H, 3′-H), 7.48 (d, ^3J = 8.02 Hz, 2 H, 2-H), 7.56 (d, ^3J = 8.04 Hz, 2 H, 2′-H). − ^{13}C NMR ($CDCl_3$): δ = 22.04 (CH$_3$), 127.18 (C-2 and C-2′), 128.16 (C-4′), 128.45 (C$_\beta$-H), 129.36 (C-3′), 129.44 (C$_\alpha$-H), 130.16 (C-3), 135.30 (C-4), 138.24 (C-1′ and C-1). − MS (70 eV); *m*/*z* (%): 194 (98) [M$^+$], 179 (99) [M$^+$ − CH$_3$], 178 (100) [M$^+$ − CH$_4$].

4-Nitrostilbene (18c):[61][67] Pale-yellow crystals, m.p. 155−156°C (ref. 155°C[67]). − ^{1}H NMR ($CDCl_3$): δ = 7.14 (d, ^3J = 16.06 Hz, 1 H, H$_\alpha$), 7.29 (d, ^3J = 16.44 Hz, 1 H, H$_\beta$), 7.34−7.46 (m, 3 H, 3′-H, 4′-H), 7.57 (d, ^3J = 7.86 Hz, 2 H, 2′-H), 7.64 (d, ^3J = 7.86 Hz, 2 H, 2-H), 8.23 (d, ^3J = 7.86 Hz, 2 H, 3-H). − ^{13}C NMR ($CDCl_3$): δ = 124.92 (C-3), 127.04 (C$_\alpha$), 127.61 (C-2), 127.81 (C-2′ and C-3′), 129.66 (C-4′), 134.08 (C$_\beta$), 136.94 (C-1′), 144.62 (C-1), 147.51 (C-4). − MS (70 eV); *m*/*z* (%): 225 (100) [M$^+$], 178 (44) [M$^+$ − HNO$_2$].

2-[(4′-Boc-amino)phenyl]benzo[*b*]furan (19a): White crystals, m.p. 208−210°C. − ^{1}H NMR ($CDCl_3$): δ = 1.55 [s, 9 H, C(CH$_3$)$_3$], 6.62 (br. s, 1 H, NH), 6.94 (d, ^4J = 0.72 Hz, 1 H, 3-H), 7.22 (d, ^3J = 7.80 Hz, 2 H, 5-H or 6-H), 7.25 (d, ^3J = 8.00 Hz, 2 H, 5-H or 6-H), 7.46 (d, ^3J = 8.76 Hz, 2 H, 3′-H), 7.51 (d, ^3J = 8.20 Hz, 2 H, 7-H), 7.56 (d, ^3J = 8.80 Hz, 2 H, 4-H), 7.80 (d, ^3J = 8.76 Hz, 2 H, 2′-H). − ^{13}C NMR ($CDCl_3$): δ = 29.11 [C(*C*H$_3$)$_3$], 81.64 [*C*(CH$_3$)$_3$], 101.05 (C-3), 111.82 (C-7), 119.27 (C-3′), 121.46 (C-4), 123.66 (C-5 or C-6), 124.73 (C-5 or C-6), 126.05 (C-9), 126.52 (C-2′), 130.13 (C-1′), 139.45 (C-4′), 153.31 [O*C*(=O)NH], 155.48 (C-8), 156.55 (C-2). − MS (70 eV); *m*/*z* (%): 309 (5) [M$^+$], 253.1 (30) [M$^+$ − H$_2$C=CMe$_2$], 235.1 (56) [M$^+$ − HOCMe$_3$], 209.1 (100) [MH$^+$ − H$_2$C=CMe$_2$ − CO$_2$].

2-Tolylbenzo[*b*]furan (19b):[67] Light-yellow crystals, m.p. 128−129°C (ref. 128−129°C[68]). − ^{1}H NMR ($CDCl_3$): δ = 2.46 (s, 3 H, CH$_3$), 7.02 (d, ^4J = 0.81 Hz, 1 H, 3-H), 7.26−7.37 (m, 4 H, aromatic H), 7.59 (dt, ^3J = 6.84 Hz, ^4J = 1.08 Hz, 1 H, 7-H), 7.64 (dt, ^3J = 6.87 Hz, ^4J = 1.08 Hz, 1 H, 4-H), 7.83 (d, ^3J = 8.22 Hz, 2 H, 2′-H). − ^{13}C NMR ($CDCl_3$): δ = 22.14 (CH$_3$), 101.31 (C-3), 111.85 (C-7), 121.5 (C-4), 123.61 (C-5 or C-6), 124.75 (C-5 or C-6), 125.64 (C-2′), 128.50 (C-8), 130.11 (C-1′), 130.23 (C-3′), 139.31 (C-4′), 155.52 (C-9), 156.95 (C-2). − MS (70 eV); *m*/*z* (%): 208 (100) [M$^+$], 178 (10) [M$^+$ − CO].

2-(4′-Nitrophenyl)benzo[*b*]furan (19c): Yellow crystals, m.p. 177−178°C (ref. 182−184°C[69]). − ^{1}H NMR ($CDCl_3$): δ = 7.25 (s, 1 H, 3-H), 7.29 (dd, ^4J = 1.28 Hz, ^3J = 7.32 Hz, 1 H, 5-H), 7.38 (ddd, ^3J = 8.04 Hz, $^3J'$ = 7.30 Hz, ^4J = 1.46 Hz, 1 H, 6-H), 7.57 (ddd, ^3J = 8.12 Hz, ^4J = 1.93 Hz, $^4J'$ = 1.10 Hz, 1 H, 7-H), 7.66 (ddd, ^3J = 7.40 Hz, ^4J = 1.73 Hz, $^4J'$ = 1.10 Hz, 1 H, 4-H), 8.01 (d, ^3J = 9.14 Hz, 2 H, 2′-H), 8.32 (d, ^3J = 9.12 Hz, 2 H, 3′-H). − ^{13}C NMR ($CDCl_3$): δ = 105.87 (C-3), 110.58 (C-5), 122.39 (C-4), 124.29 (C-7), 125.07 (C-3′), 125.97 (C-2′), 126.6 (C-6), 129.40 (C-8), 137.03 (C-1′), 147.97 (C-4′), 154.01 (C-2), 156.17 (C-7). − MS (70 eV); *m*/*z* (%): 239 (100) [M$^+$], 209 (20) [M$^+$ − NO], 193 (10) [M$^+$ − NO$_2$], 165 (18) [M$^+$ − NO$_2$ − CO].

Ethyl 4-Styrylcinnamate (20):[61][70] White crystals, 75% from **16a**, m.p. 141−143°C (lit. 144.5°C[70]). − ^{1}H NMR ($CDCl_3$): δ = 1.40 (t, ^3J = 7.15 Hz, 3 H, CH$_2$C*H*$_3$), 4.32 (q, ^3J = 7.13 Hz, 2 H, C*H*$_2$CH$_3$), 6.49 (d, ^3J = 16.02 Hz, 1 H, =CHCO), 7.14 (d, ^3J = 16.36 Hz, 1 H, C$_6$H$_5$CH=C*H*), 7.21 (d, ^3J = 16.38 Hz, 1 H, C$_6$H$_5$C*H*=CH), 7.33 (dt, ^3J = 6.86 Hz, ^4J = 1.50 Hz, 1 H, 4′-H), 7.42 (dd, ^3J = 6.86 Hz, ^4J = 1.60 Hz, 2 H, 3′-H), 7.56−7.60 (m, 6 H, 2′-H, 3-H and 2-H), 7.73 (d, ^3J = 16.00 Hz, 1 H, C*H*=CHCO). − ^{13}C NMR ($CDCl_3$): δ = 15.09 (CH$_3$), 61.25 (CH$_2$), 118.53 (=*C*HCO), 127.42 (C-3′), 127.65 (C-2), 128.48 (C$_6$H$_5$CH=*C*H), 128.77 (C-4′), 129.23 (C-3), 130.33 (C-3′), 129.50 (C-2′), 130.78 (C$_6$H$_5$*C*H=CH), 134.35 (C-1), 137.67 (C-1′), 140.03 (C-4), 144.80 (*C*H=CHCO), 167.82 (C=O ester). − MS (70 eV); *m*/*z* (%): 279 [MH$^+$] (20), 278 (64) [M$^+$], 233 (18) [M$^+$ − OEt], 204 (20) [M$^+$ − OEt − CO], 203 (37) [M$^+$ − Ar], 202 (38) [M$^+$ − Ar], 178 (30) [M$^+$ − CH$_2$=CH−CO$_2$Et].

Ethyl 4-(3′-Cyclopentenyl)cinnamate (21): Yellowish oil, 47% from **17b**. − ^{1}H NMR ($CDCl_3$): δ = 1.435 (t, ^3J = 7.15 Hz, 3 H, CH$_2$C*H*$_3$), 1.69−1.82 (m, 1 H, 4′-H$_{cis}$), 2.37−2.57 (m, 3 H, 4′-H$_{trans}$ and 5′-H), 3.87−3.97 (m, 1 H, 3′-H), 4.27 (q, ^3J = 7.11 Hz, 2 H, C*H*$_2$CH$_3$), 5.77 (dd, ^3J = 5.76 Hz, ^4J = 2.00 Hz, 1 H, 2′-H), 5.98 (dd, ^3J = 5.52 Hz, ^4J = 2.20 Hz, 1 H, 1′-H), 6.41 (d, ^3J = 16.04 Hz, 1 H, =CHCO), 7.21 (d, ^3J = 8.28 Hz, 2 H, 3-H), 7.46 (d, ^3J = 8.02 Hz, 2 H, 2-H), 7.68 (d, ^3J = 16.04 Hz, 1 H, C*H*=CHCO). − ^{13}C NMR ($CDCl_3$): δ = 15.10 (CH$_2$*C*H$_3$), 33.26 (C-5′), 34.40 (C-4′), 51.96 (C-3′), 61.19 (*C*H$_2$CH$_3$), 118.08 (=*C*HCO), 128.42 (C-3), 128.98 (C-2), 133.13 (C-1), 133.26 (C-1′), 134.46 (C-2′), 145.32 (*C*H=CHCO), 149.97 (C-4), 167.96 (C=O ester). − MS (70 eV); *m*/*z* (%): 243 (19) [MH$^+$], 242 (100) [M$^+$], 213 (83) [M$^+$ − C$_2$H$_5$], 197 (142) [M$^+$ − OEt], 181 (33), 169 (69) [M$^+$ −

$CO_2 - C_2H_5$], 168 (60) [$M^+ - CO - C_2H_5OH$], 167 (70) [$M^+ - H_2O - CO - C_2H_5$], 153 (47), 141 (40).

Acknowledgments

We wish to thank the Ministère de l'Education Nationale de la Recherche et de la Technologie and the Centre National de la Recherche Scientifique for financial support.

[1] D. S. Wulfman in *The Chemistry of Diazonium and Diazo Groups*, vol. 1 (Ed.: S. Patai), John Wiley and Sons, New York, **1978**, p. 247−339.
[2] R. Glaser, C. J. Horan, *J. Org. Chem.* **1995**, *60*, 7518−7528.
[3] R. Glaser, C. J. Horan, H. Zollinger, *Angew. Chem. Int. Ed. Engl.* **1997**, *36*, 2210−2213.
[4] C. Galli, *Chem. Rev.* **1988**, *88*, 765−792.
[5] H. Zollinger, *Angew. Chem. Int. Ed. Engl.* **1978**, *17*, 141−220.
[6] S. M. Gasper, C. Devadoss, G. B. Schuster, *J. Am. Chem. Soc.* **1995**, *117*, 5206−5211.
[7] P. Allongue, M. Delamar, B. Desbat, O. Fagebaume, R. Hitmi, J. Pinson, J. M. Saveant, *J. Am. Chem. Soc.* **1997**, *119*, 201−207.
[8] D. Kosynkin, T. M. Bockman, J. K. Kochi, *J. Am. Chem. Soc.* **1997**, *119*, 4846−4855.
[9] A. Nicolaides, D. M. Smith, F. Jensen, L. Radom, *J. Am. Chem. Soc.* **1997**, *119*, 8083−8088.
[10] F. Kotzyba-Hibert, I. Kapfer, M. Goeldner, *Angew. Chem. Int. Ed. Engl.* **1995**, *34*, 1296−1312.
[11] J.-P. Behr, *J. Chem. Soc.*, *Chem. Commun.* **1989**, 101−103.
[12] K. Kikukawa, T. Matsuda, *Chem. Lett.* **1977**, 159−162.
[13] S. Darses, T. Jeffery, J. L. Brayer, J. P. Demoute, J. P. Genet, *Bull. Soc. Chim. Fr.* **1996**, *133*, 1095−1102.
[14] H. Mayr, M. Hartnagel, K. Grimm, *Liebigs Ann.* **1997**, 55−69.
[15] B. A. Carlson, W. A. Sheppard, O. W. Webster, *J. Am. Chem. Soc.* **1975**, *97*, 5291−5293.
[16] J. V. Jollimore, K. Vaughan, *J. Org. Chem.* **1996**, *61*, 210−214.
[17] F. Bronberger, R. Huisgen, *Tetrahedron Lett.* **1984**, *25*, 57−60, 61−64, 65−68.
[18] P. Grünader *Methoden Org. Chem. (Houben-Weyl)*, **1980**, vol. VII/3b, p. 359−394.
[19] M. Regitz, G. Maas, in *Diazo Compounds − Properties and Synthesis* (Eds.: M. Regitz, G. Maas), Academic Press, Inc., Orlando, **1986**, p. 596.
[20] W. Sander, G. Bucher, P. Komnick, J. Morawietz, P. Bubenitschek, P. G. Jones, A. Chrapkowski, *Chem. Ber.* **1993**, *126*, 2101−2109.
[21] B. R. Arnold, J. C. Scaiano, G. F. Bucher, W. W. Sander, *J. Org. Chem.* **1992**, *57*, 6469−6474.
[22] G. Bucher, W. Sander, *J. Org. Chem.* **1992**, *57*, 1346−1351.
[23] A. Reiser, H.-Y. Shih, T.-F. Yeh, J.-P. Huang, *Angew. Chem. Int. Ed. Engl.* **1996**, *35*, 2428−2440.
[24] A. Roe in *Organic Reactions*, vol. V (Ed.: R. Adams), Wiley, New York, **1949**, 193−216.
[25] U. Wannagat, G. Hohlstein, *Chem. Ber.* **1955**, *88*, 1839−1846.
[26] K. Schank in *The Chemistry of Functional Groups: The Chemistry of Diazonium and Diazo Groups*, vol. 2 (Ed.: S. Pataï), John Wiley and Sons, New York, **1978**, p. 645−658.
[27] M. P. Doyle, W. J. Bryker, *J. Org. Chem.* **1979**, *44*, 1572−1574.
[28] R. Weiß, K. G. Wagner, M. Hertel, *Chem. Ber.* **1984**, *117*, 1965−1972.
[29] M. R. Pettit, M. Stacey, J. C. Tatlow, *J. Chem. Soc.* **1953**, 3081−3084.
[30] M. R. Pettit, J. C. Tatlow, *J. Chem. Soc.* **1954**, 1941−1947.
[31] M. L. Crossley, R. H. Kienle, C. H. Benbrook, *J. Am. Chem. Soc.* **1940**, *62*, 1400−1404.
[32] D. F. DeTar, T. Kosuge, *J. Am. Chem. Soc.* **1958**, *80*, 6072−6077.
[33] R. W. Taft, I. R. Fox, I. C. Lewis, *J. Am. Chem. Soc.* **1961**, *83*, 3349−3350.
[34] C. G. Swain, J. E. Sheats, K. G. Harbinson, *J. Am. Chem. Soc.* **1975**, *97*, 783−790.
[35] J. D. Dill, P. v. R. Schleyer, J. A. Pople, *J. Am. Chem. Soc.* **1977**, *99*, 1−8.
[36] M. Sukigara, S. I. Kikuchi, *Bull. Chem. Soc. Jpn.* **1967**, *40*, 1082−1086.
[37] M. Sukigara, S. I. Kikuchi, *Bull. Chem. Soc. Jpn.* **1967**, *40*, 1077−1081.
[38] E. M. Evleth, R. J. Cox, *J. Chem. Phys.* **1967**, *71*, 4082−4089.
[39] M. Sukigara, S. I. Kikuchi, *Bull. Chem. Soc. Jpn.* **1967**, *40*, 461−466.
[40] Y. A. Ustynyuk, O. A. Subbotin, L. M. Buchneva, V. N. Gruzdneva, L. A. Kazitsyna, *Dokl. Akad. Nauk. SSSR*, *Engl. Transl.* **1975**, *227*, 175−177.
[41] G. A. Olah, J. L. Grant, *J. Am. Chem. Soc.* **1975**, *97*, 1546−1548.
[42] D. O. Duthaler, H. G. Förster, J. R. Roberts, *J. Am. Chem. Soc.* **1978**, *100*, 4974−4979.
[43] S. H. Korzeniowski, A. Leopold, J. R. Beadle, M. F. Ahern, W. A. Sheppard, R. K. Khanna, G. W. Gokel, *J. Org. Chem.* **1981**, *46*, 2153−2159.
[44] M. Karplus, J. A. Pople, *J. Chem. Phys.* **1963**, *38*, 2803−2807.
[45] G. L. Nelson, G. C. Levy, J. D. Cargioli, *J. Am. Chem. Soc.* **1972**, *94*, 3089−3094.
[46] M. Puza, D. Doetschman, *Synthesis* **1971**, *9*, 481−482.
[47] S. Sengupta, S. K. Sadhukhan, S. Bhattacharyya, *Tetrahedron* **1997**, *53*, 2213−2218.
[48] M. Beller, K. Kühlein, *Synlett* **1995**, 441−442.
[49] S. Sengupta, S. Bhattacharyya, *Tetrahedron Lett.* **1995**, *36*, 4475−4478.
[50] K. Kikukawa, K. Nagira, F. Wada, T. Matsuda, *Tetrahedron* **1981**, *37*, 31−36.
[51] K. Kikukawa, K. Nagira, N. Terao, F. Wada, T. Matsuda, *Bull. Chem. Soc. Jpn.* **1979**, *52*, 2609−2610.
[52] T. V. Broxton, J. F. Bunnett, C. H. Paik, *J. Org. Chem.* **1977**, *42*, 643−649.
[53] J. F. Bunnett, C. Yijima, *J. Org. Chem.* **1977**, *42*, 639−643.
[54] S. Bhattacharyya, R. Mukherjee, S. Sengupta, *Synth. Commun.* **1995**, *25*, 651−657.
[55] N. Kamigata, R. Hisada, H. Minato, M. Kobayashi, *Bull. Chem. Soc. Jpn.* **1973**, *46*, 1016−1018.
[56] I. Szele, H. Zollinger, *Helv. Chim. Acta* **1978**, *61*, 1721−1729.
[57] S. Yasui, M. Fujii, C. Kawano, Y. Nishimura, K. Shioji, A. Ohno, *J. Chem. Soc.*, *Perkin Trans. 2* **1994**, 177−183.
[58] K. Kikukawa, K. Maemura, K. Nagira, F. Wada, T. Matsuda, *Chem. Lett.* **1980**, 551−552.
[59] K. Kikukawa, K. Kono, F. Wada, T. Matsuda, *J. Org. Chem.* **1983**, *48*, 1333−1336.
[60] R. Rai, J. A. Katzenellenbogen, *J. Med. Chem.* **1992**, *35*, 4150−4159.
[61] D. Christoforou, D. A. R. Happer, *Aust. J. Chem.* **1983**, *36*, 2083−2094.
[62] R. F. Silver, A. A. Kerr, P. D. Frandsen, S. J. Kelley, H. L. Holmes, *Can. J. Chem.* **1967**, *43*, 2585.
[63] O. Tsuge, K. Sone, S. Urano, K. Matsuda, *J. Med. Chem.* **1982**, *47*, 5171−5177.
[64] W. M. Phillips, D. J. Currie, *Can. J. Chem.* **1969**, *47*, 3137−3146.
[65] C. H. DePuy, G. F. Morris, J. S. Smith, R. J. Smat, *J. Am. Chem. Soc.* **1965**, *87*, 2421−2428.
[66] N. Kamigata, A. Satoh, T. Kondoh, M. Kameyama, *Bull. Chem. Soc. Jpn.* **1988**, *61*, 3575−3580.
[67] O. H. Wheeler, H. N. Batlle de Pabon, *J. Org. Chem.* **1965**, *30*, 1473−1477.
[68] A. Kasahara, T. Izumi, M. Yodono, R. Saito, T. Takeda, T. Sugawara, *Bull. Chem. Soc. Jpn.* **1973**, *46*, 1220−1225.
[69] A. Hercouet, M. Le Corre, *Tetrahedron* **1981**, *37*, 2867−2873.
[70] D. Christoforou, D. A. R. Happer, *Aust. J. Chem.* **1982**, *35*, 729−738.
[71] C. D. Ritchie, D. J. Wright, *J. Am. Chem. Soc.* **1971**, *93*, 2429−2432.
[72] B. L. Kieffer, M. P. Goeldner, C. G. Hirth, *J. Chem. Soc.*, *Chem. Commun.* **1981**, 398−399.
[73] L. C. Anderson, B. Manning, *J. Am. Chem. Soc.* **1955**, *77*, 3018−3019.
[74] R. J. Cox, P. Bushnell, E. M. Evleth, *Tetrahedron Lett.* **1970**, 207−210.
[75] D. Ströhl, S. Thomas, E. Kleinpeter, R. Radeglia, J. Brunn, *Monatsh. Chem.* **1992**, *123*, 769−777.
[76] A. Schweig, H. Baumgartl, R. Schultz, *J. Mol. Struct.* **1991**, *247*, 135−172.

Received October 2, 1998
[O98440]