Figure 2 shows such a calculated curve for $k_4 = 3 \times 10^9$ M^{-1} s^{-1} together with the experimental data obtained at 360 MHz.

Lower values for the deprotonation rates were found when buffers with lower pK_a values were used (acetate, formate). Since in these cases the reaction rates are also likely to be diffusion controlled, this decrease in deprotonation efficiency can probably be described by the equation due to Eigen et al.,[11] $k = k_0 10^{\Delta pK}(1 + 10^{\Delta pK})^{-1}$, where k_0 is the diffusion controlled rate constant and $\Delta pK = pK_A - pK_D$, the difference in pK_a's of proton acceptor and donor. Under this assumption a value for the pK_a of the AMP derived radical cation (pK_a = 4.0 ± 0.2) was found. Buffers with pK_a values lower than 3 (mono-, di-, and trichloroacetate, the $H_2PO_4^-$ ion) were unable to cause sufficiently rapid deprotonation to be observable on the CIDNP time scale, as predicted by the Eigen equation.

In summary the following conclusions can be drawn: (1) The quenching of the flavin triplet by 5′-AMP involves electron transfer from the adenine ring. (2) In the presence of a suitable base catalyst fast deprotonation of the primarily formed AMP radical cation leads to the observation of a radical-pair substitution effect in the CIDNP experiment. (3) Since both radical pairs lead to the same diamagnetic products (ground-state flavin and AMP), this pair substitution modulates the CIDNP signals observed for the aromatic protons in AMP. (4) The deprotonation of the AMP radical cation (pK_a = 4.0 ± 0.2, measured in ^2H_2O) by phosphate occurs with a rate constant of (4 ± 2) × 10^9 M^{-1} s^{-1}, which is close to the diffusion controlled limit.

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Addition of Diphenylphosphine Oxide to Arenesulfonylhydrazones: Novel Adducts from Tosylhydrazones and a New Synthesis of Alkyldiphenylphosphine Oxides from Trisylhydrazones

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There are precious few high-yield additions to arenesulfonylhydrazones.[1] Such additions have the potential for becoming as important to organic synthesis as the chemistry derived from the discovery of conditions for α-proton removal,[2] which extended the usefulness of arenesulfonylhydrazones from diazoalkane and carbene precursors[3] to invaluable intermediates for regiospecific alkylation[4] and olefin formation.[5] Secondary phosphine oxides have been reported to add to the C–N double bonds of hydrazones;[6] however, following the literature method, we were unable to prepare adducts of diphenylphosphine oxide (**1**) and tosylhydrazones **2**. Therefore we have developed conditions which give the analytically pure adducts, **3** (Scheme I), in good to excellent yields. The adducts from ketone tosylhydrazones are very delicate; acid, base, and heat decompose them rapidly back to starting material in what appears to be the most facile E_i reaction reported for a phosphine oxide. Conditions also have been found under which sulfinic acid and nitrogen are eliminated to yield alkyldiphenylphosphine oxides in the mildest method extant for these synthetically useful compounds.

No adducts could be isolated when **1** and **2a** or **1** and cyclohexanone phenylhydrazone were stirred in methanol or ethanol, either at room temperature or at reflux.[6] In contrast, treatment of some representative aldehyde and ketone tosylhydrazones with **1** in ethereal solvents at 20–25 °C allows the adducts to be isolated by simple filtration in 58–100% yields (see Table I). The ^{13}C NMR spectra all lacked the resonance due to the C doubly bonded to N characteristic of **2** (δ 155–165)[7] and all contained instead a doublet for the carbon bonded to nitrogen and phosphorus (see Table I for spectral parameters). The alternative structure for the adducts in which the oxygen of **1** has bonded to the imino carbon of **2** would give a smaller ^{13}C–^{31}P coupling constant.[8]

Under the same conditions that are successful for **2a**, cyclohexanone mesitylenesulfonylhydrazone[9] and cyclohexanone trisylhydrazone are unreactive. The ^{13}C NMR resonances due to the imino carbons of these three hydrazones are δ 162.7, 160.9, and 160.5, respectively.[7] The similarity of these values indicates that steric effects, not electronic ones,[10] are responsible for the lack of reactivity of the trimyl-[9] and trisylhydrazones. The imino resonance of cyclohexanone phenylhydrazone, which also does not give an adduct, is shifted upfield to δ 150.6, so that the lack of reactivity in this case is an electronic effect.[10] The trimylhydrazone[9] of cyclohexanecarboxaldehyde does form an adduct, but the yield (55%) is lower than that of the corresponding tosylhydrazone (**2f**) under the same conditions.

The adducts **3** decompose back to **1** and **2** when exposed to acid, base, or heat. The sensitivity to base explains why basic catalysis is not helpful, as it is for the addition to carbonyl compounds.[11,12] The ketone tosylhydrazone adducts are much less stable toward acid and heat than those derived from aldehyde tosylhydrazones. In solution the former decompose thermally at 35 °C in a matter of hours whereas the latter decompose at a comparable rate at 65 °C. This order of reactivity parallels the order of stability of the corresponding carbenium ions (benzylic > secondary > primary). This correlation explains why no adduct was observed with benzaldehyde tosylhydrazone. The facility of the thermal elimination of **1** from the ketone tosylhydrazone adducts is extraordinary, considering the fact that alkyldiphenylphosphine oxides, even those with γ-carbonyl groups,[13] are remarkably resistant to

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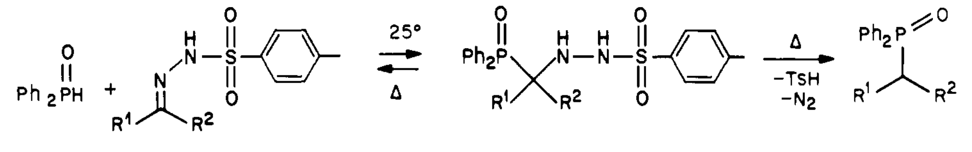
Scheme I



1 2 3 4

Table I

2, tosylhydrazone of compd[a]	3, % yield[b] (days)	solvent[c]	analysis[d]	δP-^{13}C-N (J_{CP}, Hz)
cyclohexanone (2a)	100 (8)	Et_2O	$C_{25}H_{29}N_2O_3PS$	62.0 (67.7)
	86 (8)[e]	Et_2O	Calcd: C, 64.09; H, 6.24; N, 5.98; P, 6.61; S, 6.84	
	90 (3)[f,g]	THF	Found: C, 63.93; H, 6.22; N, 5.90; P, 6.75; S, 6.85	
	79 (12)[e,g]	THF		
acetone (2b)	88 (6)	dioxane	$C_{22}H_{25}N_2O_3PS$	58.6 (76.5)
	74 (12)[e]	dioxane	Calcd: C, 61.67; H, 5.88; N, 6.54; P, 7.23; S, 7.48	
			Found: C, 61.66; H, 5.98; N, 6.52; P, 7.23; S, 7.38	
bicyclo[4.2.0]octan-7-one (2c)	58 (29)[h]	Et_2O	$C_{27}H_{31}N_2O_3PS$	62.1 (67.3)
			Calcd: C, 65.57; H, 6.32; N, 5.66; P, 6.26; S, 6.48	
			Found: C, 64.89; H, 6.21; N, 5.59; P, 6.30; S, 6.54	
3-methylpentanal (2d)	86 (4)[e]	Et_2O	$C_{25}H_{31}N_2O_3PS$	57.4 (67.6)
			Calcd: C, 63.81; H, 6.64; N, 5.95; P, 6.58; S, 6.81	
			Found: C, 63.77; H, 6.72; N, 5.88; P, 6.77; S, 6.83	
2-methylpropanal (2e)	86 (9)	Et_2O	$C_{23}H_{27}N_2O_3PS$	64.2 (67.6)
	79 (9)[e]	Et_2O	Calcd: C, 62.43; H, 6.15; N, 6.33; P, 7.00; S, 7.25	
			Found: C, 62.41; H, 6.22; N, 6.35; P, 6.98; S, 7.17	
cyclohexanecarboxaldehyde (2f)	91 (13)[e]	Et_2O	$C_{26}H_{31}N_2O_3PS$	65.2 (66.2)
			Calcd: C, 64.71; H, 6.48; N, 5.80; P, 6.42; S, 6.64	
			Found: C, 64.87; H, 6.58; N, 5.59; P, 6.38; S, 6.73	

[a] All starting materials were analytically pure. [b] Analytically pure products isolated for 2-9 mmol of starting materials. [c] Distilled from sodium benzophenone ketyl. [d] Galbraith Laboratories, Knoxville, TN 37921. [e] 1.0 equiv of pyridine was present. [f] 0.1 equiv of pyridine was present. [g] Product contained 1 equiv of THF, not removed in vacuum. [h] Total yield from three crops.

Table II

product 4[a]	carbonyl compd	arenesulfonylhydrazone[b]	1, equiv (time, days)	reflux solvent	yield,[c] %
$R_1R_2 = (CH_2)_5$ (4a)	cyclohexanone	trisyl	1.1 (1)	THF	83
$R_1 = R_2 = CH_3$ (4b)	acetone	trisyl	1.1 (1)	THF	90
$R_1 = C_6H_5$, $R_2 = H$ (4c)	benzaldehyde	tosyl	1.1 (1)	dioxane	62
$R_1 = n\text{-}C_5H_{11}$, $R_2 = CH_3$ (4d)	2-heptanone	trisyl	1.5 (2)	THF	88
$R_1 = n\text{-}C_4H_9$, $R_2 = CH_2CH_3$ (4e)	3-heptanone	trisyl	1.5 (5)	THF	45
$R_1 = R_2 = n\text{-}C_3H_7$ (4f)	4-heptanone	trisyl	1.5 (5)	THF	46
$R_1 = n\text{-}C_6H_{13}$, $R_2 = H$ (4g)	heptaldehyde	trisyl	2.0 (1)	THF	32[d]
$R_1 = c\text{-}C_6H_{11}$, $R_2 = CH_3$ (4h)	cyclohexyl methyl ketone	trisyl	1.5 (8)	THF	21

[a] Satisfactory microanalysis (or exact mass) and spectral data were obtained for new compounds (4e,f,h). The rest were characterized by comparison of physical properties with literature values or those of authentic samples made by the literature method. [b] All starting materials were analytically pure, except for heptaldehyde trisylhydrazone, which slowly decomposed at room temperature with loss of gas. [c] Isolated by silica gel chromatography on a 1-mmol scale. [d] Starting material decomposed under reaction conditions, see *b*.

the E_i elimination, which is a synthetically useful reaction in the cases of amine oxides, sulfoxides, and selenoxides.[14] Since the related adducts from **1** and acetone[11] or from dimethoxyphosphine oxide and ketones[15] or ketimines[16] are much more stable, decomposing at 100-200 °C, the extraordinarily easy elimination of **1** from **3a** ($t_{1/2} \sim 2$ h at 35 °C) may be attributable to an α effect[17] of neighboring lone pairs of electrons on the hydrazine moity.

While brief heating suffices to decompose the adducts to starting materials, prolonged refluxing in THF converts the starting materials into new phosphine oxides **4**. For example, refluxing **2a** with 6 equiv of **1** in THF for 12 days gives a 23% yield of cyclohexyldiphenylphosphine oxide (**4a**), presumably by the elimination of *p*-toluenesulfinic acid and nitrogen from a small equilibrium concentration of **3a**. Therefore two modes of elimination from **3** are observable; that of **1** is fast and reversible, whereas that of *p*-toluenesulfinic acid is slow but irreversible. The yield is improved by using a hydrazone with a better leaving group. Refluxing cyclohexanone trisylhydrazone with 1.1 equiv of **1** in THF for 1 day yields 83% of **4a**, previously prepared in 65% yield by adding a cyclohexyl Grignard reagent to diphenylphosphinoyl chloride,[18] in 84% yield by adding sodium diphenylphosphinite to cyclohexyl bromide,[19] and in 90% yield by the addition of diphenylphosphine to cyclohexanone in refluxing concentrated HCl.[20] Benzyldiphenylphosphine, which we prepare in 62% yield by refluxing benzaldehyde tosylhydrazone with **1** in dioxane, previously has been made by treating benzyl chloride with lithium diphenylphosphide followed by oxidation with hydrogen peroxide,[21] by hydrolyzing benzyldiphenylphenoxyphosphonium chloride in boiling water,[22] as well as by the Grignard method,[23] and the

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acid-catalyzed reaction of diphenylphosphine and benzaldehyde.[20] Our method is by far the mildest one available, as it is anhydrous and avoids strong acids, bases, and oxidizing agents, making it the one of choice for complex molecules,[24] which are likely to contain functionality sensitive to at least one of these conditions. The other results in Table II show that this new reaction is also useful for dialkyl ketone trisylhydrazones, especially methyl ones, provided there is no α branching. Such selectivity can be a desirable feature.

Aliphatic and aromatic six-membered rings are common in natural as well as man-made substances, and this new reaction will undoubtedly prove useful in the synthesis of such compounds. The diphenylphosphinoyl group is becoming an important activating group in organic synthesis,[18,25] which adds to the significance of this new addition reaction of arenesulfonylhydrazones.

Acknowledgment. We thank M. L. M. Schilling for the ^{13}C NMR spectra reported.

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Radical-Like Reactions of Singlet Fluorenylidene. Hydrogen and Halogen Abstraction[1]

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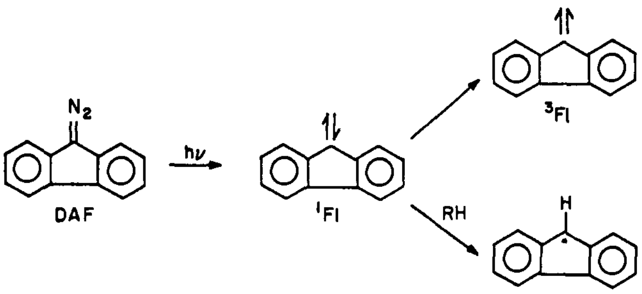
During the last few years there have been several reports of absolute rate constants[2] for the reactions of carbenes in solution.[3-6] Most recently, Zupancic and Schuster have reported rate constants for the reactions of singlet (^{1}Fl) and triplet (^{3}Fl) fluorenylidene with a variety of olefins[7] as well as activation parameters for intersystem crossing.[8] However, in these studies a major reaction pathway for the decay of ^{1}Fl was not included in the mechanism proposed when acetonitrile was used as solvent, namely, that ^{1}Fl readily abstracts hydrogen from the solvent to give the 9-fluorenyl radical. This reaction has a significant bearing on the interpretation of the kinetic data.



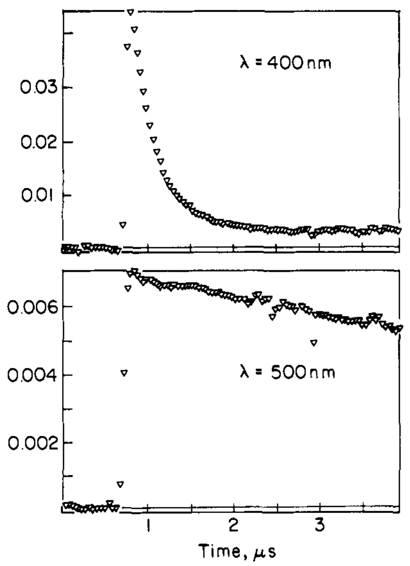


Figure 1. Traces obtained at 400 and 500 nm in the presence of diethyl fumarate (0.025 M). Conditions: T = 300 K, [DAF] = 0.008 M, solvent: acetonitrile.

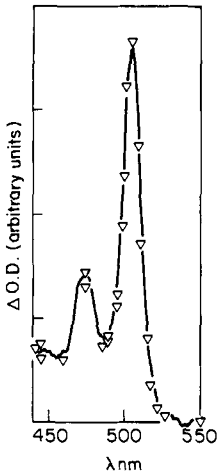


Figure 2. Absorption spectrum of the 9-fluorenyl radical in benzene solvent at 25 °C. Continuous trace was obtained by a modulation spectrometer. The point spectrum was obtained by laser flash photolysis. The two spectra have been overlapped for ease of comparison.

Laser flash photolysis of diazofluorene (DAF; 8 × 10^{-4} M) in acetonitrile leads, as was previously reported,[7] to the formation of a short-lived transient (λ_{max} 470 nm; lifetime = 27 ns) which is assigned to ^{1}Fl.[9] As this species decays, two other bands are produced at λ_{max} 400 (broad) and 500 nm (very sharp) for which the lifetime of *formation* is 27 ns (in good agreement with the *half-life* of 17 ns reported by Schuster[7]), indicating that these bands are derived from ^{1}Fl decay. As a result of this observation and by comparison with earlier literature reports,[7,8] both bands were assigned to ^{3}Fl which was formed with high efficiency and the lifetime observed was found to represent the kinetics for intersystem crossing, i.e., $^1\mathrm{Fl} \rightarrow {}^3\mathrm{Fl}$. However, if ^{1}Fl decayed to give two different products, each will *necessarily* be formed with the same lifetime, which is in fact the case in this instance.[11] This agreement between the decay rate at 470 nm and the buildup profiles at 400 and 500 nm is observed under a variety of con-

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