chains destabilizes the T state so effectively that unliganded (Co, Fe) tetramers are not fully T_0 in the absence of IHP and that the T_2 state of the doubly liganded (Co, Fe) tetramers is strongly destabilized even in the presence of IHP. This indicates that the values of L_0 ($\approx 10^5$ in HbA[2]) and of L_2 have each been reduced by orders of magnitude through Co replacement in only two chains. Thus, although the structures of the Zn(II) and Co(II) porphyrins are more alike[15,16] than, e.g., the Mn(II) and Zn(II) porphyrins,[13,15] the incremental stereochemical differences between the Co(II) and Zn(II) complexes clearly lead to a hemoglobin with quite different properties from those of HbA. This observation explains the anomalous features in equilibrium measurements of O_2 binding to (Co, Fe) hybrids and the reduced cooperativity of O_2 binding to coboglobin.[17]

These experiments show that mixed-metal hybrid hemoglobins can be used to measure the allosteric properties of and the extent of chain inequivalence within the unliganded and diliganded hemoglobin tetramer; analogous measurements with O_2 as ligand are underway.[3] The use of a series of metals further confirms that the hemoglobin allosteric mechanism does not rely on the details of ferroheme structure in a simple fashion;[18] the dependence appears monotonic, although probably not linear.[19] On the other hand, the results for all three replacement metals show that the CO binding rates of an Fe chain within the Hb molecule are not influenced by the metal occupying the complementary chain.

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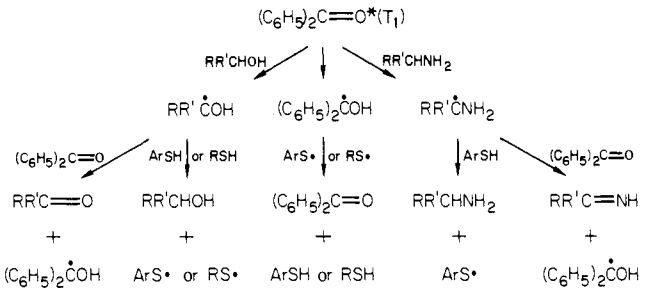
Catalysis by Aliphatic Thiol of Photoreduction of Benzophenone by Primary and Secondary Amines

Sir:

Quantum yields for photoreduction of benzophenone by amines may be substantially increased by aliphatic thiols, and decreased by aromatic thiols,[1] while quantum yields for photoreduction by alcohols are decreased by both aromatic and aliphatic thiols.[2] The decreases have been shown, by deuterium labeling and thiol–disulfide equilibration, to occur by hydrogen-transfer reactions which convert radical intermediates to starting materials (Scheme I).[1,2]

Reduction by amines appears to proceed via initial charge transfer. It was proposed that this would be followed either by proton transfer (k_h) or by regeneration of starting materials (k_e) (Scheme II).[3,4] On this basis. the quantum yield for photoreduction of ketone would depend on the relative importance of the

Scheme I



Scheme II

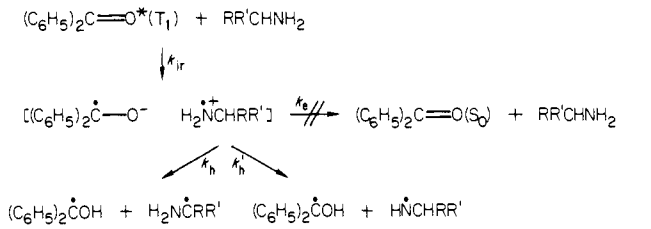


Table I. Photoreduction of 0.06 M Benzophenone by Amines in Benzene. Effect of 1-Pentanethiol and *tert*-Butylamine (TBA)

expt no	reductant compd	M	$(CH_3)_3CNH_2$ M	$(CH_3)_3CNH_2$ trip,[a] %	1-$C_5H_{11}SH$ M	1-$C_5H_{11}SH$ trip,[b] %	φ
1			4.1	100			~0.06
2					0.1–1.0		~0.03
3	$C_2H_5CH(NH_2)CH_3$	0.10					0.79
4	$C_2H_5CH(NH_2)CH_3$	0.10			0.023	1.0	1.20
5	$C_2H_5CH(NH_2)CH_3$	0.10	4.1	92			~0.06
6	$C_2H_5CH(NH_2)CH_3$	0.10	4.1	92	0.020	0.8	1.04
7	$(i\text{-}C_3H_7)_2NH$	0.06					0.56
8	$(i\text{-}C_3H_7)_2NH$	0.06			0.10	1.1	1.29
9	$(i\text{-}C_3H_7)_2NH$	0.06	5.5	78			0.22
10	$(i\text{-}C_3H_7)_2NH$	0.06	5.5	78	0.10	0.2	1.07
11	$(i\text{-}C_3H_7)_2NC_2H_5$	0.06					1.11
12	$(i\text{-}C_3H_7)_2NC_2H_5$	0.06			0.09	0.7	1.02
13	$(i\text{-}C_3H_7)_2NC_2H_5$	0.06	5.5	70			0.36
14	$(i\text{-}C_3H_7)_2NC_2H_5$	0.06	5.5	70	0.02	0.04	0.64

[a] Percent of reacting triplet trapped by TBA. [b] Percent of reacting triplet trapped by the thiol.

k_h and k_e processes, and it was suggested that aliphatic thiol increased quantum yield by catalyzing hydrogen transfer in the charge-transfer complex.[1] However, it has recently been found that reactions of benzophenone with common aliphatic amines, including *tert*-butylamine (TBA) and triethylamine, which have only –NH and α-CH, respectively, form benzophenone ketyl radical with quantum yield $\varphi = 0.9$–1.0; thus, the quenching process (k_e) does not occur significantly.[5] Loss of quantum efficiency must be due to subsequent reactions of the initially formed radicals, and the accelerating effect of aliphatic thiol, like the retarding effect, would involve reactions with these radicals. This has been borne out in studies with TBA (Table I).

Irradiations were carried out, as described previously,[1] on a rotating wheel, along with a secondary actinometer, 0.06 M benzophenone, and 1.2 M 2-aminobutane in benzene, $\varphi = 1.17$. The fraction of triplet reacting with each component was calculated from the rate constants (k_{ir}) and the concentrations. Values of k_{ir}, from phosphorescence quenching,[6] were TBA, 7.0×10^7; 2-aminobutane, 2.5×10^8; and 1-pentanethiol, 1.3×10^7 M^{-1} s^{-1}. The values for diisopropylamine, 1.9×10^9 M^{-1} s^{-1}, and diisopropylethylamine, 2.9×10^9 M^{-1} s^{-1}, were obtained by quenching

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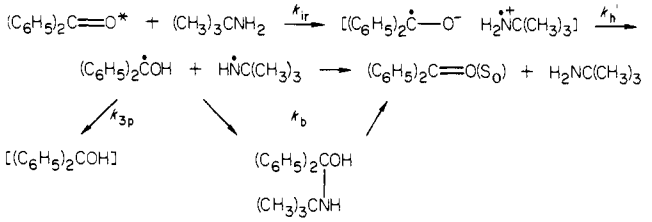
Scheme III



by naphthalene of photoreduction of benzophenone by the amines, based on $k_q = 6 \times 10^9$ M^{-1} s^{-1}. The rapid reaction of 0.06 M benzophenone, 0.1 M 2-aminobutane, 4 M TBA, and 0.1 M 1-pentanethiol led to benzopinacol, 90%, and *N*-2-butylidene-2-aminobutane,[7] 76% yield. The slow reduction of 0.06 M benzophenone by 4 M TBA did not go to completion; the reduction of 0.01 M ketone led to benzopinacol.

Reaction of benzophenone triplet with TBA forms ketyl radical with $\varphi = 0.96$.[5] However, TBA has no α H, and quantum yield for net reduction of ketone is low, $\varphi \sim 0.06$ (experiment 1, Table I), indicating that ketyl and aminyl radicals disproportionate, either directly or after combination, much more rapidly than ketyl radicals dimerize (Scheme III). A low rate constant for aminyl coupling would lead to a high steady-state concentration of aminyl radical and contribute to a high rate of ketyl–aminyl reaction.

2-Aminobutane and diisopropylamine, containing both NH and α-CH, may lead to both α-aminoalkyl and alkylaminyl radicals (Scheme II, k_h and k'_h). The former reduces ground-state ketone and is necessary for efficient photoreduction; the latter would disproportionate with ketyl radical (Scheme III, k_b), regenerate starting materials, and reduce quantum yields.

1-Pentanethiol, which interacts directly with little of the triplet and is a very inefficient reducing agent ($\varphi \sim 0.03$, experiment 2), increases reduction by 2-aminobutane and diisopropylamine, from $\varphi = 0.79$ and 0.56 (experiments 3 and 7) to $\varphi = 1.20$ and 1.29 (experiments 4 and 8). Reduction by the tertiary amine is decreased slightly by thiol (experiments 11 and 12). When 4–5 M TBA is added to these three amines (experiments 5, 9, and 13), quantum yields are greatly decreased. Then, addition of 0.02–0.1 M 1-pentanethiol (experiments 6, 10, and 14) increases the quantum yields of the TBA-retarded reductions, tenfold in the case of 2-aminobutane, fivefold for the secondary amine, and nearly twofold for the tertiary amine.

The retardations by TBA (experiments 5, 9, and 13) are consistent with the extent to which it reacts with triplet and lead to little net reduction (Scheme III). We propose that the thiol counters this effect by catalyzing conversion of an aminyl radical to an α-aminoalkyl radical. The aminyl radical abstracts hydrogen from the thiol, and the thiyl radical abstracts hydrogen from the α-carbon of the reducing amines (eq 1 and 2a). Catalysis by thiol

$$(CH_3)_3CNH\cdot + RSH \rightarrow (CH_3)_3CNH_2 + RS\cdot \quad (1)$$

$$RS\cdot + \text{>CHN<} \underset{2b}{\overset{2a}{\rightleftharpoons}} RSH + \text{>}\dot{C}\text{N<} \quad (2)$$

in the absence of TBA (experiments 4 and 8) would be caused similarly, as alkylaminyl radicals from primary and secondary amines (Scheme II, k'_h) may be converted to aminoalkyl radicals by a sequence corresponding to eq 1 and 2a. The tertiary amine leads only to aminoalkyl radicals, and inefficient retardation is observed, via eq 2b. α-Aminoalkyl radicals are more stabilized than α-hydroxyalkyl radicals by overlap of the unpaired electron with nonbonding electrons of the heteroatom. They may abstract hydrogen from S of thiols less rapidly than do α-hydroxyalkyl radicals,[1,8] in competition with their being oxidized by ground-state ketone (Scheme I).[9,10] Thus, aromatic thiols retard photoreduction by amines, but less effectively than that by alcohols,[1] and aliphatic thiols, with stronger S–H bonds, may show very weak retardation, which is observed only with the tertiary amine (experiment 12).

In reduction by alcohols, direct abstraction from α C occurs, and alkoxyl radicals are generally not formed. In reduction by amines, the charge-transfer mechanism and the lower bond energy of N–H vs. O–H allow formation of alkylaminyl radicals from primary and secondary amines, which then may regenerate starting material. However, H· is readily abstracted from S of thiols, even by triphenylmethyl radical,[11] and the unstabilized aminyl radicals may also do this rapidly (eq 1) in competition with disproportionation with ketyl. Thiols have unusual properties in that although H· may be abstracted very rapidly from S the resulting thiyl radicals are highly reactive, notably, but not only, in abstracting H·, in this case from α C of amines, forming stabilized α-aminoalkyl radicals (eq 2a). Such hydrogen transfers from and to sulfur compete effectively with other possible hydrogen abstractions and with radical combination.[12] They may lead to inhibition,[2] or to change of products,[13] as in photoreduction by alcohols, or to catalysis, as in the change of identity of radicals[14] and in the decarbonylation of aldehydes.[15] In the present case, catalysis by the sequence of hydrogen transfers is further favored, as combination of thiyl and ketyl radicals and thiyl and α-aminoalkyl radicals regenerates thiol, and disulfide is reduced by ketyl radical to thiol and thiyl radical.[8]

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Ion–Molecule Complexes in Unimolecular Fragmentations of Gaseous Cations. Cyclization of Unsaturated Carbocations in the Gas Phase

Sir:

The cyclization exemplified by reaction 1 constitutes a major pathway in terpene biosynthesis.[1] This intramolecular electrophilic addition represents an endocyclic closure,[2] since both sp^2 carbons at the unsaturated terminus of cation **1** are incorporated into the

(1)

1

ring that is formed. Although there are some exceptions,[3] most of the reported examples form six-membered ($n = 3$) or larger rings, a result that has led to the suggestion that endocyclic attack of double bonds is disfavored for shorter chain lengths.[2] A major

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