



Radical Cage Effects: Comparison of Solvent Bulk Viscosity and Microviscosity in Predicting the Recombination Efficiencies of Radical Cage Pairs

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Supporting Information

ABSTRACT: This study reports the results of experiments that probed how solvents affect the recombination efficiency (F_{cP}) of geminate radical cage pairs. The macroviscosity of solvents has traditionally been used to make quantitative predictions about F_{cP} , but experiments reported here show that F_{cP} varies dramatically for solvent systems with identical macroviscosities. Experiments show that F_{cP} correlates with the solvent microviscosity: five different solvent systems (consisting of a solvent and a structurally similar viscogen) were examined, and F_{cP} was the same for all five solvent systems at any particular microviscosity. The translational diffusion coefficient of the radicals (measured by DOSY) in the solvent system.

A goal of our research is to uncover the underlying principles that govern radical cage effects so we can understand radical reactivity better. We report here that solvent microviscosity is more appropriate than macroviscosity (bulk viscosity) for describing the "strength" of the solvent cage and for quantifying the recombination efficiency of radical cage pairs. The term "radical cage effect" refers to the phenomenon that the probability of recombination of a radical pair is greater in solution than in the gas phase.¹⁻³ The origin of this effect is the solvent "cage," a term introduced by Franck and Rabinowitch in 1934 for a hole in the solvent that temporarily traps a pair of reactive molecules causing them to remain as colliding neighbors for a short period of time before random motion allows their separation (Scheme 1).^{4,5} Radical cage

Scheme 1. Photodissociation of a General Molecule (R-R)That Results in a Radical Cage Pair

$$R-R \xrightarrow{h_{V}} [R, R] \xrightarrow{k_{d}} 2 R \xrightarrow{T = trap} 2 R-T$$
cage pair free radicals

effects have an enormous impact on chemical reactivity in solution.^{6,7} In particular, they are necessary to explain a host of kinetic observations and fundamental reaction phenomena. For example, cage effects are necessary to explain magnetic isotope^{8,9} and CIDNP^{10,11} effects, rate-viscosity correlations,¹² variations in products and yields as a function of medium,^{13,14} variations in quantum yields as a function of medium,¹⁵ and regio- and stereochemical control.^{16–18} Examples of important

reactions where cage effects are necessary to explain the kinetics include the initiation, propagation, and termination steps of radical polymerization reactions, ^{19–24} the reactions of coenzyme B₁₂ and its model complexes, ^{8,25–29} the reactions of hemes with O₂, ³⁰ and various electron transfer reactions. ^{31–34} New observations of cage effects and their impact on reactivity are reported regularly. ^{35–56}

With reference to the radical cage pair formed by the bond homolysis in Scheme 1, the "cage recombination efficiency" (F_{cP}) is defined as $F_{cP} = k_c/(k_c + k_d)$.⁵⁷ For quantitative purposes (e.g., in radical polymerization initiator kinetics) it is necessary to know the value of F_{cP} . Although F_{cP} is intuitively related to the viscosity of the solution, numerous studies have shown that bulk viscosity is utterly inadequate for predicting the value of $F_{\rm cP}$ and, in general, for quantitatively describing how solvents affect the dynamics of the cage effect.^{4,6} As shown below, F_{cP} for the same radical cage pair can have remarkably different values in different solvents having the same bulk viscosity.⁵⁸ Various models have been proposed that attempt to quantify F_{cP} and the cage effect in terms of solvent parameters other than bulk viscosity. For example, models involving internal pressure, cohesive energy density, and solvent density have all been proposed. 5^{9-61} However, all of these models inadequately rely on bulk solvent parameters. Furthermore, several of these parameters are exceedingly complex and not conveniently measured. As a result, there is still no good model that adequately relates the strength of the solvent cage to the physical properties of the solvent⁵⁵

Because the solvent cage effect is a localized phenomenon, we hypothesized that local viscosity (i.e., microviscosity) is more appropriate than bulk viscosity for describing the cage effect and, in particular, for predicting $F_{\rm cP}$. In this communication, we present the results of a study that tested the hypothesis that microviscosity is a more appropriate predictor of $F_{\rm cP}$ than macroviscosity.

Solvent-caged radical pairs were generated by irradiation ($\lambda = 532 \text{ nm}$) of the Cp'₂Mo₂(CO)₆ molecule (Cp' = η^{5} -CH₃C₅H₄) in the solvent systems described below (Scheme 2).^{58,62-67} Prior work in our laboratory established methods for measuring F_{cP} for photochemically generated radical cage pairs.^{58,67-69} In brief, the quantum yields for the reaction of Cp'₂Mo₂(CO)₆ with CCl₄ (Scheme 2) were measured as a function of solvent bulk viscosity. (The viscosity was changed by adding a viscogen

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Scheme 2. Photolysis of $Cp'_2Mo_2(CO)_6$ Results in a Caged Radical Pair



to the solvent. In order to avoid selective solvation, the viscogen was chosen so that it has a similar chemical structure and composition to the solvent. For example, IR-grade paraffin oil was added to hexane to increase the bulk viscosity of the hexane solution.) From the resulting plots of quantum yields vs bulk viscosity (see Supporting Information), it is possible to calculate $F_{\rm cP}$ as a function of bulk viscosity by the method reported in our prior papers.^{58,63,68}

Plots of F_{cP} as a function of macroviscosity for five solvent systems are shown in Figure 1. The five solvent systems



Figure 1. Plot of cage recombination efficiency (F_{cP}) as a function of solvent system bulk viscosity (cP). Each sample contains 20 wt % CCl_{4j} error bars are $1\sigma_j$ and the curves are only a visual guide.

(solvent/viscogen) are (1) hexane/paraffin oil; (2) hexane/ polybutenes ($M_n = 3200$); (3) toluene/1,1-bis(3,4dimethylphenyl)ethane (abbreviated "DXE"); (4) toluene/ polystyrene ($M_w = 45,000$); and (5) hexamethyldisiloxane/ poly(dimethylsiloxane) ($M_w = 3800$) (abbreviated HMDS and PDMS, respectively). CCl₄ (20% by weight) was added to each sample as the radical trapping agent (Scheme 2).⁷⁰ Note in the figure that, at any selected bulk viscosity, the F_{cP} values in the five solvent systems are all different. These results illustrate the point made above that F_{cP} can be dramatically different in different solvent systems with the same macroviscosity.

To investigate the hypothesis that microviscosity is a better parameter for describing and interpreting F_{cP} , it was necessary to find a measurable solvent property that tracks with microviscosity. In studies of biological molecules (e.g., protein folding studies), there is a general consensus that rotational diffusion coefficients, obtained from NMR T_1 measurements, are correlated with the local viscosity of the solvent environment.⁷¹ For technical reasons, T_1 measurements were not possible with the molecules and radicals used in this study.⁷² However, other studies have shown that rotational and translational diffusion coefficients can be interchanged when probing the microenvironment of biological molecules,^{73–76} and therefore, we used translational diffusion coefficients.⁷⁷ The translational diffusion coefficients of the radicals in the five solvent systems used in this study were measured using NMR diffusion ordered spectroscopy (DOSY) (Table 1). More

Table 1. Solvents and Visco	gens Used in This Study
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solvent	viscogen	bulk viscosity range (cP)	microviscosity range $(\times 10^9 \text{ s/m}^2)$	
<i>n</i> -hexane	paraffin oil	0.36-20.61	0.28-6.08	
	poly(butenes)	0.36-18.27	0.28-2.31	
toluene	DXE	0.61-8.02	0.57-5.05	
	poly(styrene)	0.62-30.22	0.61-0.83	
HMDS	PDMS	0.54-18.21	0.41-1.94	
^a Each sample contained 20 wt % CCl ₄ .				

specifically, the translational diffusion coefficients were measured using a stable organometallic surrogate for the highly reactive $[Cp'Mo(CO)_3]$ radicals. $(C_6H_6)Cr(CO)_3$ was chosen as the probe because F_{cP} is related to the radical mass and size according to the Noyes equation $(F_{cP} \propto mass^{1/2}/radius^2)$, and the $Cp'Mo(CO)_3$ and $(C_6H_6)Cr(CO)_3$ species are reasonably similar in mass and size.^{58,78,79} (The relevant physical parameters for $(C_6H_6)Cr(CO)_3$ and the $[Cp'Mo(CO)_3]$ radical are presented in the Supporting Information, along with a more detailed justification for using $(C_6H_6)Cr(CO)_3$ as a surrogate for $[Cp'Mo(CO)_3]$ radical.) According to the Stokes–Einstein equation,⁸⁰ viscosity is inversely proportional to the translation diffusion coefficient (D) so 1/D was taken as the solvent parameter representing microviscosity.⁸¹

The F_{cP} values in the five solvent systems in Figure 1 are shown replotted as a function of the microviscosity (1/D) in Figure 2. Note that the F_{cP} values for all five solvent systems are



Figure 2. Cage recombination efficiency (F_{cP}) plotted as a function of microviscosity (1/D). Each sample contains 20 wt % CCl₄, error bars are 1σ ; and the curves are only a visual guide.

nearly the same for identical values of the microviscosity. This result shows that microviscosity provides the best correlation to date between the solvent and the value of $F_{\rm cP}$. Restated, the microviscosity is the parameter of choice when probing solvent effects on the radical cage effect.

Radical-radical recombination requires that the two radicals have the correct orbital orientation to react. Therefore, it might seem that, in addition to being a function of 1/D, the microviscosity should also be a function of a parameter related to the rate of radical rotation such as the rotational correlation time, τ_{c} . However, as noted above, studies of biological

molecules have shown that the rotational and translational diffusion coefficients can be used interchangeably to probe the microenvironment of biological molecules. Thus, in a description of microviscosity involving both 1/D and τ_c , the τ_c term can be written as a function of D to yield an expression for microviscosity involving only D.

In conclusion, the experiments reported here suggest that for nonpolar solvent systems quantitative discussions pertaining to $F_{\rm cP}$ should be based on microviscosity rather than bulk viscosity. In essence, if the translational diffusion coefficient for a particular radical in a cage pair is known then an accurate cage recombination efficiency is predictable, independent of the solvent system. This predictive power will be useful wherever quantitative knowledge of radical reactivity is necessary. It is noted that the method described above can be applied in reverse. That is, if F_{cP} is known then the diffusion coefficient of the molecule can be determined; in turn, the microviscosity of the local environment around the caged molecules can be probed. This reverse application would provide a method for determining the microviscosity in complex systems such as active sites of enzymes or in heterogeneous reactions. Polar solvent systems and hydrogen-bonding solvent systems are currently being investigated in our laboratory to determine if the results obtained above with nonpolar solvents are also applicable in these types of solvents.

ASSOCIATED CONTENT

S Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/jacs.6b05432.

Detailed methods for determining micro- and macroviscosity, cage efficiencies, and a discussion on relevant kinetics (PDF)

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Notes

The authors declare no competing financial interest.

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