

# Comments Concerning "The Effect of Temperature on the Fluorescence Quenching of Perylene by Tetrachloromethane in Mixtures with Cyclohexane and Benzene"

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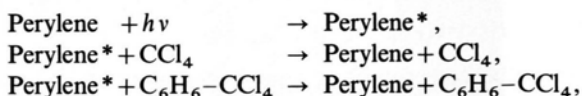
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An indirect spectrofluorometric probe method is developed for calculating equilibrium constants for formation of heterogeneous solvent-solvent molecular complexes from measured fluorescence emission intensities in select systems that exhibit parabolic-shaped Stern-Volmer quenching plots.

In a recent paper, Wicz and Latowski [1] examined the effect of temperature on the fluorescence quenching of perylene by tetrachloromethane in mixtures with cyclohexane and benzene. The authors observed an unusual "parabolic-shaped" curve in the case of the binary tetrachloromethane + benzene system when plotting the ratio of fluorescent quantum yields,  $\phi_0/\phi$ , versus the stoichiometric molarity of tetrachloromethane,  $[\text{CCl}_4]_{\text{total}}$ . The quantities  $\phi_0$  and  $\phi$  refer to measured quantum yields in the absence and in the presence of tetrachloromethane, respectively. Alternatively the authors could have plotted the ratio of experimental fluorescence intensities,  $F_0/F$ , versus  $[\text{CCl}_4]_{\text{total}}$ . Observed non-linearity and the parabolic shape in the  $\phi_0/\phi$  versus  $[\text{CCl}_4]_{\text{total}}$  Stern-Volmer plot was rationalized in terms of two quenchers being present in solution, the free *uncomplexed*  $\text{CCl}_4$  and a presumed  $\text{C}_6\text{H}_6\text{-CCl}_4$  molecular complex. The complex was assumed to be more effective in quenching the fluorescence emission of perylene.

The purpose of the present communication is not to criticize the excellent work of Wicz and Latowski. Rather, I wish to show how their ideas, when combined with a reasonable thermodynamic solution model and simplifying approximations, can lead to the development of an experimental method for determining equilibrium constants of presumed heterogeneous solvent-solvent molecular complexes based upon measured fluorescence emission intensities. For

simplicity, I will assume that the *uncomplexed*  $\text{CCl}_4$  molecules and the  $\text{C}_6\text{H}_6\text{-CCl}_4$  complex both act as dynamic quenchers:



where  $k_{\text{CCl}_4}$  and  $k_{\text{C}_6\text{H}_6\text{-CCl}_4}$  denote the two quenching rate constants. The ratio of the fluorescent quantum yields,  $\phi_0/\phi$ , is given by [2, 3]

$$\begin{aligned} (\phi_0/\phi) - 1 &= (F_0/F) - 1 \\ &= k_{\text{CCl}_4} [\text{CCl}_4]_{\text{free}} + k_{\text{C}_6\text{H}_6\text{-CCl}_4} [\text{C}_6\text{H}_6\text{-CCl}_4] \end{aligned} \quad (1)$$

or by

$$\begin{aligned} [(\phi_0/\phi) - 1] (X_{\text{CCl}_4}^0 V_{\text{CCl}_4} + X_{\text{C}_6\text{H}_6}^0 V_{\text{C}_6\text{H}_6}) \\ = [(F_0/F) - 1] (X_{\text{CCl}_4}^0 V_{\text{CCl}_4} + X_{\text{C}_6\text{H}_6}^0 V_{\text{C}_6\text{H}_6}) \\ = k_{\text{CCl}_4} r_{\text{CCl}_4, \text{free}} + k_{\text{C}_6\text{H}_6\text{-CCl}_4} r_{\text{comp}}, \end{aligned} \quad (2)$$

where

$$r_{\text{CCl}_4, \text{free}} = \frac{\text{moles of free CCl}_4}{(\text{moles of CCl}_4 + \text{moles of C}_6\text{H}_6)}, \quad (3)$$

$$r_{\text{comp}} = \frac{\text{moles of C}_6\text{H}_6\text{-CCl}_4}{(\text{moles of CCl}_4 + \text{moles of C}_6\text{H}_6)}, \quad (4)$$

if one converts the molarities to mole numbers by multiplying by the molar volume of the solution,  $V_{\text{solution}} = X_{\text{CCl}_4}^0 V_{\text{CCl}_4} + X_{\text{C}_6\text{H}_6}^0 V_{\text{C}_6\text{H}_6}$ . The fluorophore is at ca.  $10^{-5}$  Molar (or less) and its presence has a negligible contribution on the solution volume. Mole fractions are denoted as  $X_i$ , and the superscript  $(^0)$  indicates the original stoichiometric binary solvent compositions, calculated as if the molecular complex were not present. Also, it is assumed that the molar volume of the  $\text{C}_6\text{H}_6\text{-CCl}_4$  molecular complex equals the sum of the molar volumes of benzene and tetrachloromethane, and that  $\Delta V$  of mixing equals zero. Equations (1) and (2) also apply if both  $\text{CCl}_4$  and  $\text{C}_6\text{H}_6\text{-CCl}_4$  act as static quenching agents; however, in this latter case the two rate constants would be replaced by equilibrium constants for the formation of nonfluorescent ground state perylene- $\text{CCl}_4$  and perylene- $\text{C}_6\text{H}_6\text{-CCl}_4$  complexes. The mathematical treatment of fluorescence quenching in the case of a combined static-dynamic quenching mechanism is discussed elsewhere [4–6] and will not be considered in the present communication.

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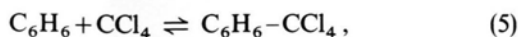
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Formation of the presumed benzene-tetrachloromethane molecular complex is described by



$$K_{\text{eq}} = X_{\text{C}_6\text{H}_6 - \text{CCl}_4} / (X_{\text{C}_6\text{H}_6}^{\text{free}} X_{\text{CCl}_4}^{\text{free}}),$$

with the corresponding equilibrium constant being expressed in mole fraction concentration units, which would be consistent with the Ideal Associated Solution (IAS) thermodynamic model [7–13] and Raoult's law definition of solution ideality. Stoichiometric mole fractions of benzene and tetrachloromethane must sum to unity,  $X_{\text{CCl}_4}^0 + X_{\text{C}_6\text{H}_6}^0 = 1$ , and are related to the mole fractions of the *uncomplexed*, free  $\text{CCl}_4$  and free  $\text{C}_6\text{H}_6$  via

$$X_{\text{CCl}_4}^{\text{free}} = (X_{\text{CCl}_4}^0 - r_{\text{comp}}) / (1 - r_{\text{comp}}), \quad (6)$$

$$X_{\text{C}_6\text{H}_6}^{\text{free}} = (X_{\text{C}_6\text{H}_6}^0 - r_{\text{comp}}) / (1 - r_{\text{comp}}), \quad (7)$$

$$X_{\text{C}_6\text{H}_6 - \text{CCl}_4} = r_{\text{comp}} / (1 - r_{\text{comp}}), \quad (8)$$

simple mass balance constraints.

Equations (5)–(8) are combined to give the expression for the  $\text{C}_6\text{H}_6 - \text{CCl}_4$  association constant

$$K_{\text{eq}} = r_{\text{comp}} (1 - r_{\text{comp}}) / [(X_{\text{CCl}_4}^0 - r_{\text{comp}}) (X_{\text{C}_6\text{H}_6}^0 - r_{\text{comp}})], \quad (9)$$

which after suitable mathematical manipulations is rearranged to

$$K_{\text{eq}} X_{\text{CCl}_4}^0 X_{\text{C}_6\text{H}_6}^0 - K_{\text{eq}} r_{\text{comp}} + K_{\text{eq}} r_{\text{comp}}^2 = r_{\text{comp}} - r_{\text{comp}}^2, \quad (10)$$

$$X_{\text{CCl}_4}^0 X_{\text{C}_6\text{H}_6}^0 / r_{\text{comp}} \quad (11)$$

$$= -[(K_{\text{eq}} + 1)/K_{\text{eq}}] r_{\text{comp}} + (K_{\text{eq}} + 1)/K_{\text{eq}},$$

Similarly, (2) is rewritten as

$$\begin{aligned} [(F_0/F) - 1] (X_{\text{CCl}_4}^0 V_{\text{CCl}_4} + X_{\text{C}_6\text{H}_6}^0 V_{\text{C}_6\text{H}_6}) \\ = k_{\text{CCl}_4} X_{\text{CCl}_4}^0 + r_{\text{comp}} [k_{\text{C}_6\text{H}_6 - \text{CCl}_4} - k_{\text{CCl}_4}], \end{aligned} \quad (12)$$

$$\begin{aligned} r_{\text{comp}} [k_{\text{C}_6\text{H}_6 - \text{CCl}_4} - k_{\text{CCl}_4}] \\ = [(F_0/F) - 1] (X_{\text{CCl}_4}^0 V_{\text{CCl}_4} + X_{\text{C}_6\text{H}_6}^0 V_{\text{C}_6\text{H}_6}) - k_{\text{CCl}_4} X_{\text{CCl}_4}^0. \end{aligned} \quad (13)$$

Every term on the right-hand side of (13) is known, either from direct experimental fluorescence measurements ( $F$  and  $F_0$ ), or known from the initial binary solvent compositions ( $X_{\text{CCl}_4}^0$  and  $X_{\text{C}_6\text{H}_6}^0$ ), or known from properties of the pure components ( $V_{\text{CCl}_4}$  and  $V_{\text{C}_6\text{H}_6}$ ). The quenching rate constant  $k_{\text{CCl}_4}$  is calculated from (12) as  $k_{\text{CCl}_4} = [(F_0/F_{\text{CCl}_4}) - 1] V_{\text{CCl}_4}$ , using the fluorescence emission intensity of perylene measured in pure tetrachloromethane,  $F_{\text{CCl}_4}$ . For notational simplicity, the entire right-hand side of (13) is denoted as  $Y$ , giving  $r_{\text{comp}} [k_{\text{C}_6\text{H}_6 - \text{CCl}_4} - k_{\text{CCl}_4}] = Y$ .

Substituting  $r_{\text{comp}} = Y / [k_{\text{C}_6\text{H}_6 - \text{CCl}_4} - k_{\text{CCl}_4}]$  into (11), the following expression is derived:

$$\begin{aligned} (X_{\text{CCl}_4}^0 X_{\text{C}_6\text{H}_6}^0) / Y \\ = -\{[(K_{\text{eq}} + 1)/K_{\text{eq}}] / [k_{\text{C}_6\text{H}_6 - \text{CCl}_4} - k_{\text{CCl}_4}]\}^2 Y \\ + [(K_{\text{eq}} + 1)/K_{\text{eq}}] / [k_{\text{C}_6\text{H}_6 - \text{CCl}_4} - k_{\text{CCl}_4}]. \end{aligned} \quad (14)$$

Careful examination of (14) reveals that a plot of  $X_{\text{CCl}_4}^0 X_{\text{C}_6\text{H}_6}^0 / Y$  versus  $Y$  should be linear, with slope  $= -[(K_{\text{eq}} + 1)/K_{\text{eq}}] / [k_{\text{C}_6\text{H}_6 - \text{CCl}_4} - k_{\text{CCl}_4}]^2$  and intercept  $= [(K_{\text{eq}} + 1)/K_{\text{eq}}] / [k_{\text{C}_6\text{H}_6 - \text{CCl}_4} - k_{\text{CCl}_4}]$ . Numerical values of the perylene- $\text{C}_6\text{H}_6 - \text{CCl}_4$  quenching constant,  $k_{\text{C}_6\text{H}_6 - \text{CCl}_4}$ , and the equilibrium constant for complex formation,  $K_{\text{eq}}$ , can be determined from the least-squares slope and intercept as  $k_{\text{C}_6\text{H}_6 - \text{CCl}_4} - k_{\text{CCl}_4} = -(\text{intercept}/\text{slope})$  and as  $(K_{\text{eq}} + 1)/K_{\text{eq}} = -[(\text{intercept})^2/\text{slope}]$ . The preceding discussion clearly shows that in certain instances spectrofluorometric probe quenching measurements can provide a convenient, independent experimental method for studying heterogeneous solvent-solvent molecular complexes in fluid solution.

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