

CHARACTERISTIC EFFECTS IN THE REACTION KINETICS OF POLYMERIC REAGENTS

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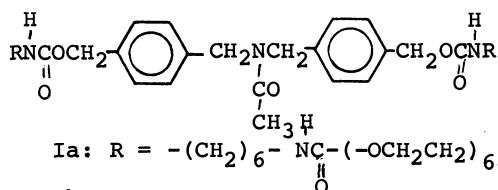
Abstract - Recent advances in studies of the kinetics of chemical processes in dilute polymer solutions include investigations of hindered rotation in the backbone of flexible chain molecules, of ionic reactions in polyelectrolyte solutions, kinetic effects reflecting the local medium in the polymer domain, neighboring group effects in reactions of polysaccharides and diffusion-controlled intramolecular or intermolecular reactions. In addition, some results are presented on the kinetics of reactions of gel-bound reactive groups with reagents in homogeneous solution.

INTRODUCTION

Differences between the reactivity of polymers and analogous small molecules may be due to energetic interactions between the polymer and the second reagent, effects due to the local medium in the polymer domain and neighboring group effects. I have summarized previously studies of these various effects up to 1975 (1) and covered in later reviews more recent results (2,3). Here I wish to draw attention to some investigations dealing with the conformational mobility of polymer chains, effects depending on the nature of the solvent medium in the polymer domain, the effect of the field of a polyion on the interaction of two small ionic species, neighboring group effects in the reaction of polysaccharides and diffusion-controlled reactions involving two polymeric species. Some quantitative data have also become available concerning the kinetics of heterogeneous reactions involving a polymeric phase.

THE MECHANISM OF CONFORMATIONAL TRANSITIONS OF CHAIN MOLECULES IN DILUTE SOLUTION

It has been widely assumed that conformational transitions in the backbone of polymer chains require two near-simultaneous hindered rotations (a "crankshaft-like motion"), so that only a short segment of the chain has to move through the viscous solvent medium (4-7). However, if this is indeed the mechanism of conformational transitions in polymer chains, then the activation energy should be nearly twice as large as in small analogous molecules where hindered rotation around one bond only is required. Until recently, no method was available which would allow us to compare the rate of hindered rotation with a low energy barrier around a well defined bond in a polymer and a similar process in an analogous small molecule. The phenomenon of intramolecular excimer formation has now provided us with the necessary tool to subject the assumption of crankshaft-like motions to a critical test. When a molecule such as N,N-dibenzylacetamide is excited, two fluorescence bands are observed, one corresponding to the emission from an isolated phenyl residue, while the other is due to emission from a sandwich-like complex formed from an excited and a ground state phenyl group (the "excimer"). It can be shown that under certain conditions the ratio of the intensities of excimer and "monomer" emission reflects the probability that the hindered rotation required for excimer formation takes place during the lifetime of the excited state (8). Since this lifetime is of the order of 10^{-8} sec, we have a means of studying the rates of conformational transitions with energy barriers of 3-4 kcal/mole. Using this technique we have recently compared the emission spectrum of polymer Ia and the analogous small molecule Ib(9):



In dilute solution these emission spectra were virtually identical showing that the conformational transition necessary for excimer formation in the dibenzylacetamide residue was not significantly impeded when this group was incorporated into the center of a poly(ethylene oxide) chain. We believe that this result proves that conformational transitions cannot involve two correlated hindered rotations in dilute polymer solutions.

REACTIONS OF EXCITED $\text{Ru}(\text{bpy})_3^{++}$ IN POLYANION SOLUTIONS

Some time ago, studies in our laboratory were concerned with the fluorescence quenching of excited UO_2^{++} (10) or quinone cations (11) by Fe^{++} in the presence of poly(vinylsulfonic acid) (PVSA). We found that at low Fe^{++} concentrations, the polyion increased by a large factor the quenching efficiency, since both the fluorescing and the quenching ions were concentrated in the polyion domain. However, when the Fe^{++} concentration was increased beyond a certain point, the fluorescence intensity increased dramatically. This was interpreted as being due to the displacement of the fluorescing cations from the polymer domain into a region of low quencher concentration, assuming that the exchange of bound and free counterions is slow on the time scale of the excited state. This interpretation has now been confirmed in a study of the fluorescence of the ruthenium tripyridyl complex, $\text{Ru}(\text{bpy})_3^{++}$, by Cu^{++} in PVSA solution. As long as both the $\text{Ru}(\text{bpy})_3^{++}$ and the Cu^{++} could be accommodated in the polymer domain, the fluorescence intensity following a laser flash followed a simple exponential decay. However, at higher Cu^{++} concentrations, this decay was biphasic corresponding to the distinct behavior of excited $\text{Ru}(\text{bpy})_3^{++}$ within and without the polyion domain (12).

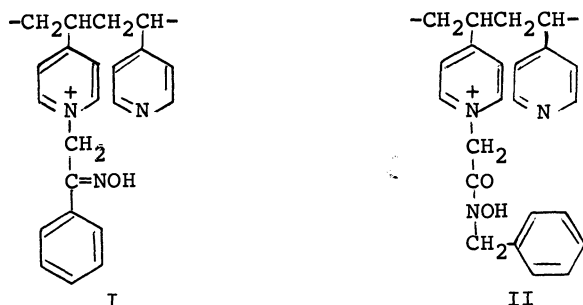
The excited $\text{Ru}(\text{bpy})_3^{++}$ is a strong electron donor leading, in the presence of an electron acceptor X, to the $\text{Ru}(\text{bpy})_3^{++*}$ species which is a sufficiently powerful oxidizing agent to decompose water. The excitation of $\text{Ru}(\text{bpy})_3^{++}$, which absorbs in the visible spectrum, has, therefore, been considered by a number of investigators as a possible means of providing an energy source from sunlight. Unfortunately, the process $[\text{Ru}(\text{bpy})_3^{++*}] + \text{X} \rightleftharpoons \text{Ru}(\text{bpy})_3^{++} + \text{X}^-$ is reversible and the yields of $\text{Ru}(\text{bpy})_3^{++*}$ are poor due to the reverse reaction before the products can diffuse out of the solvent cage. It was, however, observed that this separation can be substantially accelerated in PVSA solution, since the polyanion attracts one and repels the other reaction product (13).

EFFECTS DUE TO THE MICROENVIRONMENT IN THE POLYMER DOMAIN

The effective solvent medium in the immediate vicinity of a macromolecule may differ considerably from the solvent in bulk and this will lead to kinetic effects if the reactivity of a functional group attached to a polymer is sensitive to solvation. Such effects have been known for some time, and several new examples have been reported recently.

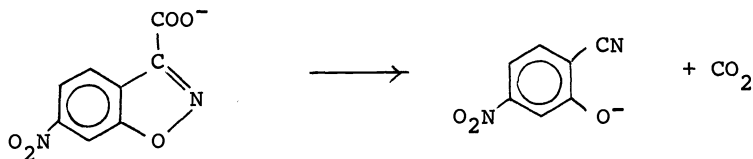
When styrene, methyl acrylate or N,N-dimethylacrylamide copolymers containing a small number of nitrophenyl acrylate residues were subjected to benzylaminolysis in dioxane solution, the rate constants were found to be in the ratio of 1:13:230, demonstrating that the effective reaction medium was largely determined by the polymer chain (14). It was also observed that a change in the solvent had a much smaller effect on the reaction rate of the polymer-bound reagent than on the reaction rate of an analogous small molecule (15).

Another interesting observation concerned copolymers which catalyze the solvolysis of active esters. Substances I (16) and II (17) were found to be particularly active acyl acceptors since the pK of the oxime and hydroxamic acid was lowered below their usual value without reducing the nucleophilicity of the oximate and hydroxamate. This was believed to be due to desolvation of the zwitterionic structure in the hydrophobic environment. The catalytic effect of these copolymers depends then on a two-state process, i.e., the active ester transfers first its acyl group to the oximate or hydroxamate and the acyl group is then released due to nucleophilic action of



the pyridine residues.

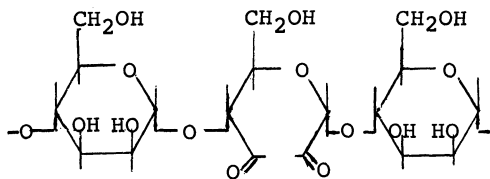
Another example of the effect of a hydrophobic medium within a polymer domain in enhancing a reaction efficiency was reported for the process



which was found to be 1300 times as fast in the presence of polyethyleneimine partially acylated with lauryl groups with the remainder of the amines fully quaternized (18).

NEIGHBORING GROUP EFFECTS IN THE OXIDATION OF POLYSACCHARIDES

In many reactions of chain molecules, the reactivity of a functional group appended to the polymer depends on whether the two neighboring groups have or have not reacted. In the simplest case the reactivity of such a polymer may be characterized by three rate constants k_0 , k_1 and k_2 , pertaining to reactive groups with 0, 1 or 2 reacted neighbors and the reaction pattern obtained for this case has been known for some time (19). A more complicated situation is encountered in the periodate oxidation of polysaccharides. With alginate, the aldehydes formed during the oxidation react rapidly with hydroxyls of neighboring sugar residues forming hemiacetals and this leads to complete inhibition of the oxidation of these neighboring units (20). However, in the case of amylose, hemiacetal formation is incomplete, since it competes with the hydration of the aldehyde (23). Moreover, as can be seen from the structure of a triplet of glycoside units in which the central unit has been oxidized, the two neighbors are not equivalent and



computer simulation has shown, in fact, that this nonequivalence has to be taken into account for the description of the course of this reaction (22). A formal theory of neighboring group effects has been published which takes account of the peculiarities of polysaccharide oxidation (23).

INTRAMOLECULAR AND INTERMOLECULAR DIFFUSION CONTROLLED REACTIONS

When a flexible polymer chain carries substituents at the two chain ends which react with each other in a diffusion-controlled process, the intramolecular reaction will be controlled by the rate of conformational transitions which allow the two chain ends to approach each other. While the theory of such processes has been formulated some time ago (24-25), experimental studies of the dependence of the diffusion-controlled reaction rate of the two chain ends with each other have become available only more recently with the use of various fluorescence techniques (26-27). It seems that for relatively short chains the rate constant for such processes is inversely proportional to the chainlength; for very long chains the chainlength dependence of the rate constant is much smaller. Fluorescence techniques have also been found to provide a powerful tool for the study of diffusion-controlled reactions between ends of two different

polymeric chains. The rate-limiting process of such reactions is the segmental diffusion by which the reactive chain end is brought to the surface of the polymeric coil (28), since the mutual interpenetration of polymeric coils is thermodynamically resisted in good solvent media. Horie and Mita (29,30) studied the dependence of such reaction rates on both the chainlength of the polymer and the solvent power of the medium. They found that the rate constant decreased with increasing solvent power for relatively short chains, but increased with increasing solvation of very long polymer chains. They concluded that with short chains the thermodynamic resistance to coil interpenetration is the dominant effect, while with long chains intramolecular entanglements produced in poor solvent media provide the main impediment to encounters between chain ends.

HETEROGENEOUS POLYMER REACTIONS

Heterogeneous polymer reactions are of great practical importance. One particular aspect which has been investigated in a number of laboratories concerns the catalysis by crosslinked polymers, a field which has recently been beautifully summarized (31). Here I should only try to draw attention to a local medium effect in such a catalysis which is similar to effects described above for homogeneous polymer solutions.

It has been known for some time that weakly solvated ion pairs of an onium salt in a lipophilic environment may increase by a large factor the nucleophilic activity of an anion. This phenomenon may be taken advantage of in "phase transfer catalysis" (32). Usually, a quaternary ammonium detergent is used for this purpose, but this may promote formation of stable emulsions so that isolation of the reaction product becomes difficult. However, similar effects may be obtained when the quaternary ammonium group is attached to a crosslinked polymer. Regen (33) showed that a triphase system containing the polymer, aqueous sodium cyanide and an alkyl halide in benzene solution led rapidly to high yields of the alkyl cyanide. The catalyst could also be used to generate dichlorocarbene from chloroform and aqueous sodium hydroxide.

An important problem arises in connection with polypeptide synthesis on polymer supports as pioneered by Merrifield (34). This technique can succeed only if exposure of the polymer-bound functional groups to an excess of reagents in the solution phase ensures that the reaction will go to completion. It is, therefore, important to determine whether functional groups attached to a crosslinked network are kinetically equivalent. In attempting to study this problem we had to develop an analytical technique which would satisfy two conditions: (a) It had to allow a continuous monitoring of the progress of a reaction in a heterogeneous system. (b) The signal had to be proportional to the amount of unreacted polymer-bound reagent, so that the last 2-3% of the reaction could be followed with high precision. Both these conditions are satisfied by studying a model reaction in which the polymer carries fluorescent substituents whose fluorescence is quenched by reaction with a reagent in the solution phase. The reaction is followed by reflectance fluorescence and if the reagent in the solution phase is in large excess, any deviation from linearity in a plot of the logarithm of fluorescence intensity against time will indicate a kinetic nonequivalence of the polymer-bound reagent.

Using this method, we found (35) that reaction of anilino groups attached to partially swollen polymers with solutions of a large excess of acetic anhydride yields linear first-order plots over seven half-lives. However, introduction of crosslinks into the polymer leads to deviation from first-order kinetics. Surprisingly, these deviations are insensitive to the degree of crosslinking, but quite sensitive to the nature of the polymer to which the anilino groups are attached. Since the reaction of p-toluidine with acetic anhydride was found to be about eighty times faster in cyclohexane than in a number of polar media, we believe that the dispersion of the rate constant of the polymer-bound reagent reflects fluctuations in the local polarity of the crosslinked polymer system. In the absence of crosslinks, the local polarity is averaged over the lifetime of the reaction by microbrownian motions, but this becomes impossible when the linear polymer is converted into a network structure.

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