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Nanosized Particles of Organically Modified Silica as Microreactors to Enhance the Regioselectivity in the Photocycloaddition of 9-Substituted Anthracenes

Da-Yong Wu, Bin Chen, Xiao-Gang Fu, Li-Zhu Wu,* Li-Ping Zhang, and Chen-Ho Tung*

Technical Institute of Physics and Chemistry, The Chinese Academy of Sciences, Beijing 100101, China

chtung@ipc.ac.cn

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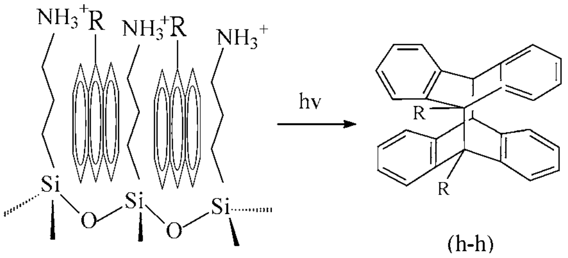
ABSTRACT



Nanosized particles of modified silica with 3-ammoniumpropyl residue have been prepared and successfully used as microreactors to control the regioselectivity of the photocycloaddition of five 9-substituted anthracences [AnCH$_2$N$^+$(CH$_3$)$_3$Br$^-$ (1), AnCH$_2$COO$^-$Na$^+$ (2), AnCH$_2$CH$_2$COOH (3), AnCH$_2$OH (4), AnCH$_3$ (5), where An = 9-anthryl]. While the photocycloaddition of the five substrates in methanol mainly gave rise to their head-to-tail (h–t) photocyclomers, irradiation of 1–4 incorporated in the suspension of the modified silica in methanol almost exclusively yielded the head-to-head (h–h) photocyclomers with high quantum yields.

The development of efficient and highly selective methods for organic synthesis is one of the main topics in organic chemistry, and much effort has been directed toward this goal. Of the various approaches, use of organized and constrained media as microreactors to control reaction pathways has shown considerable promise.[1−6] Here we report the controlled regioselectivity in the photocycloaddition of 9-substituted anthracenes at the interface of organically modified silica particles suspended in methanol.

Nanosized silica particles with a 3-ammoniumpropyl residue were prepared on the basis of a sol−gel method.[7] Typically, the solution of tetraethoxysilane (5.2 g, 25 mmol) in ethanol (100 mL) and that of 3-aminopropyltrimethoxysilane (4.6 g, 25 mmol) were added, simultaneously and dropwise, to the mixture of 900 mL of ethanol and 4 mL of diluted ammonia spirit (pH = 10) under vigorous stirring at room temperature. The stirring was continued for 72 h at 50 °C, yielding an optically clear solution containing silica particles. The particle formation was demonstrated by transmission electron microscopy. The electron micrograph clearly showed that the particles were spherical and polydispersed with diameters ranging from ca. 60 to 80 nm. Removing the solvent from the particle containing solution by evaporation afforded ca. 3.0 g of white solid. The IR spectrum of the solid displayed the expected bands for $-NH_2$

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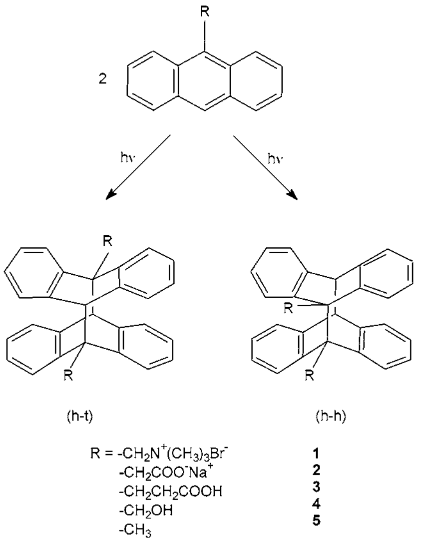
(3425, 3356, 1560, and 692 cm^{-1}), $-(CH_2)_3-$ (2933, 2867 and 1490 cm^{-1}), and Si−C (1140 cm^{-1}), suggesting that the 3-aminopropyl residue is covalently bound onto the silica. The silica particles were acidified with diluted hydrochloric acid to convert the amine into an ammonium group and then resuspended in methanol by sonicating. The resultant suspension was optically clear. Since the particle size and density are known, we could calculate the particle population in the suspension. Because the organic residue in this silica possesses a hydrophilic ammonium group and a hydrophobic alkyl chain, we proposed that the structure of the silica particle in methanol would resemble a "micelle" and could be used as a microreactor for certain organic reactions.

Irradiation of 9-substituted anthracenes in organic solution typically results in cycloaddition of the aromatic rings at the 9,10-positions to yield head-to-tail (h−t) cyclomers (Scheme 1), although evidence for the concomitant formation of head-to-head (h−h) cyclomers has been obtained in some instances.[8−10] This regioselectivity was rationalized in terms of the electrostatic and steric effects of the substituents. When anthracene bearing an ionic or a polar substituent is incorporated within the suspension of organically modified silica particles in methanol as prepared above, one might expect that the substrate would be concentrated at the interface of the micelle-like silica particles and the molecules would be arranged in such a way that the anthracene moiety is located in the hydrophobic "micelle core" with the polar substituent toward the methanol phase. This preorientation would favor the formation of the h−h photocyclomer and the enhancement of the local concentration would increase the quantum yield of the photocycloaddition. We found that photoirradiation of **1**−**3** (Scheme 1) incorporated in the suspensions indeed almost exclusively leads to the h−h photocyclomers in high quantum yields.

Scheme 1. Photocycloaddition of 9-Substituted Anthracene



Compounds **1**−**5** were irradiated in methanol solutions in a Pyrex reactor. Prior to irradiation, the samples were degassed with nitrogen for 15 min. A 500 W high-pressure mercury lamp was used as the light source. The photocycloaddition process was monitored by UV absorption spectroscopy. The h−h and h−t cyclomers were separated by using a Perkin-Elmer HPLC apparatus with a SUPELCOSIL LC-18 column, and methanol/water was used as the eluting solvent. Of particular interest was the ratio of h−t to h−h cyclomers, which was determined both by HPLC measurement and the ^{1}H NMR spectroscopy of the product mixture. The ratios obtained by these two methods were consistent with each other. Irradiation of the 2.0×10^{-3} M degassed solutions of **1**−**5** in methanol led to the formation of the h−t and h−h cyclomers. For all the substrates except **3**, the main products are the h−t cyclomers. Table 1 gives the ratios of the h−t to h−h cyclomers. The preferable production of the h−h cyclomer of **3** is interpreted in terms of formation of hydrogen bonding between the carboxylic acid groups of the substrate molecules in ground state that allows the h−h preorientation of the molecular pairs,[8] although hydrogen bonding is weak in methanol. For all the substrates, the yields of the photocyclomers are close to 100% on the basis of the consumption of the starting materials. The structure proposed for the products as the [4π + 4π] cyclomers rests mainly on their ^{1}H NMR spectra, which are in close agreement with those reported in the literature.[8−11] The assignment of the h−t and the h−h photocyclomers relies on the chemical shifts of the bridgehead protons in their ^{1}H NMR spectra. It has been established[8−11] that the chemical shifts of the bridgehead protons for the h−h cyclomers appear at lower regions compared with those for the corresponding h−t cyclomers. The chemical shifts of the bridgehead protons in the h−t and h−h cyclomers of **1**−**5** are summarized in Table 1.

Table 1. Chemical Shifts (ppm, in CDCl$_3$) of the Bridgehead Protons and the h−t/h−h Ratios of the Photocyclomers of **1**−**5**

	chemical shifts of bridged protons		ratios of h−t to h−h	
compd	δ_{h-t}	δ_{h-h}	methanol	silica/methanol suspension
1	4.38	4.50	83/17	8/92
2	4.80	5.16	80/20	0/100
3	4.44	4.58	42/58	2/98
4	4.55	4.80	86/14	33/67
5	4.00	4.56	66/34	64/36

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The situation for the photocycloaddition of the 9-substituted anthracenes in the silica suspensions as prepared above is completely different. Compounds **1**−**5** could be easily incorporated into the suspensions to give optically transparent solutions. The particle population in the suspension used was equivalent to a molarity of ca. 1.0×10^{-6} M, and the concentration of the substrate was ca. 2.0×10^{-3} M. After irradiation, the suspension was centrifuged. Analyses revealed that most of the products and the unreacted starting material was adsorbed on the silica, and the fraction of the products and starting material in the centrifugate was generally smaller than 5%. This observation is probably due to the fact that the nanosized silica particles provide a vast surface area, and the products and substrate are more soluble in the interface of the micelle-like silica particles than in the bulk methanol. This also explains why high regioselectivity and high quantum yield in the photocycloaddition were obtained in the silica suspensions (see below). The silica obtained from the centrifugation was extracted with methylene chloride. The extract was combined with the centrifugate methanol solution and analyzed by ^{1}H NMR and HPLC as in the case of the samples in methanol solutions. Photocycloaddition of **1**−**3** incorporated in the suspensions almost exclusively resulted in the formation of the h−h cyclomers (Table 1). The h−h cyclomer of **4** was also increased in yield and became the major product. On the other hand, the ratio of the h−t to h−h cyclomers of **5** experienced almost no change compared with the sample in methanol (Table 1). For all the substrates, the mass balance for this photocycloaddition was close to 100%. Furthermore, the quantum yields for the photocycloaddition of **1**−**5** in the suspensions were remarkably greater than those in methanol. For example, after 20 min of irradiation of the suspension sample of **1**, the conversion was ca. 70%. Under identical conditions, 20 min of irradiation of the sample in methanol resulted only in ca. 50% conversion.

The greater quantum yields for the photocycloaddition in the suspensions are evidently due to the higher local concentration. As described above, the substrate molecules are concentrated at the amphiphilic interface of the silica particles. The concentrations of the silica particles (ca. 1.0×10^{-6} M) and the substrate (ca. 2.0×10^{-3} M) in the suspensions used in this work suggest that each particle contains thousands of substrate molecules. In consideration of the small size of the silica particle, the local concentration of the substrate should be very high. The almost exclusive formation of the h−h cyclomers of **1**−**3** is attributed to the preorientation of substrate molecules on the silica particle interface. Because of the hydrophobicity of the anthracene moiety and the charged or polar nature of the substituent, the anthracene chromophores of **1**−**3** should reside in the alkyl layer of the interface of the micelle-like particle, while the substituent is anchored among the ammonium headgroups at the interface and directed toward the methanol phase. Consequently, the photocycloaddition of two neighboring anthracene molecules favors the formation of h−h cyclomers. In contrast, the nonpolar reference substrate **5** lacks such a preorientation, although its molecules are concentrated on the interface of the silica particles. The product distribution for this substrate is comparable with that in methanol (Table 1). However, the quantum yield of its photocycloaddition in silica suspension is evidently greater than in methanol. For the less polar substrate **4**, only a fraction of its molecules are preorientated at the interface of the silica particles. As a result, the ratio of the h−h to h−t cyclomers (Table 1) was observed to be increased compared with that in methanol, but the extent of increase is not as large as those for **1**−**3**.

The above proposal for the interface of the organically modified silica particles being the site for the photocycloaddition is further strengthened by checking the effect of a blank silica on the reaction. Silica particles comprising tetraethoxysilane only (without 3-aminopropyltrimethoxysilane) and their suspensions in methanol were prepared and used as a medium for photocycloaddition of **1**−**5** in a manner similar to that described above. Neither the regioselectivity nor the quantum yield of the photocycloaddition was found to be increased. These observations confirm that the micelle-like structure of the silica particles is crucial for the enhancement of regioselectivity and quantum yield in the photocycloaddition.

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Supporting Information Available: Experimental procedures for preparation of nanosized silica particles with a 3-ammoniumpropyl residue, photoirradiation, and product analysis. This material is available free of charge via the Internet at http://pubs.acs.org.

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