

## CYCLODEXTRIN NANOTUBE INDUCED BY 4,4'-BIS(2-BENZOAZOLYL) STILBENE

AIHUA WU, XINGHAI SHEN\* and HONGCHENG GAO  
*Department of Applied Chemistry, College of Chemistry and Molecular Engineering  
Peking University, Beijing 100871, P. R. China  
\*xshen@pku.edu.cn*

The formation of  $\beta$ - and  $\gamma$ -cyclodextrin (CD) nanotubes induced by the molecule 4,4'-bis(2-benzoxazolyl) stilbene (BOS) was investigated by fluorescence anisotropy. Using the Perrin–Webber formula, the average number of cyclodextrin ( $n_{CD}$ ) in each nanotube was estimated and the results suggested that the  $n_{CD}$  value in the  $\gamma$ -CD system is larger than that in the  $\beta$ -CD system. Hydrogen-bonding between the hydroxyl groups of neighboring CDs was found to be an important contribution to the formation of cyclodextrin nanotube on the basis of the pH effect study. The temperature effect study showed that this nanotube was thermostable at  $T \leq 303$  K, while it was gradually collapsed at higher temperature.

*Keywords:* Cyclodextrin; nanotube; fluorescence; anisotropy.

### 1. Introduction

Cyclodextrins (CDs), containing six ( $\alpha$ -CD), seven ( $\beta$ -CD), or eight ( $\gamma$ -CD) D-glucose units linked by 1,4- $\alpha$ -glucosidic bonds, are most popular host molecules to construct various molecular assemblies.<sup>1–3</sup> Depending on its size, a CD molecule has room to accommodate one or two guest molecules; if the guest is long enough, more than two or even many CD rings can be threaded along it.<sup>4–6</sup> Li and his co-worker reported the formation of rigid molecular nanotube aggregates of  $\beta$ -CD and  $\gamma$ -CD through linkage by a rod-like molecule, i.e., all-trans-1,6-diphenyl-1,3,5-hexatriene (DPH).<sup>7</sup> Later on, Pistolis *et al.* found that DPH could facilitate the formation of nanotube aggregates when mixed with  $\beta$ - and  $\gamma$ -CD in the appropriate solvents.<sup>8</sup> The results of their further study on the size effect of the homologues of the  $\alpha,\omega$ -diphenylpolyenes series, with two, three and four double bonds, on the formation of nanotubes with  $\gamma$ -CD indicated that the length of guest molecule is a key factor in the course of nanotube formation.<sup>9</sup> Agbaria and Gill discovered that some oxazole molecules, such as 2,5-diphenyl 1,3,4-oxadiazole (PPO), 2-phenyl-5-(4-diphenyl)1,3,4-oxadiazole (PBD), 2,5-diphenyl 1,3,4-oxadiazole (PPD), 2,5-(4,4'-diphenyl) 1,3,4-oxazole (BBOD) could also form nanotubes with  $\gamma$ -CD in aqueous solutions.<sup>10–12</sup> Recently, the results reported by Liu and co-workers indicated that the formation of cyclodextrin nanotube could be induced by 4,4'-dipyridine in the presence of Ni (II).<sup>13</sup> In addition, nanotubular structure can also be formed between a drug molecule and cyclodextrin.<sup>14</sup>

\*Corresponding author.

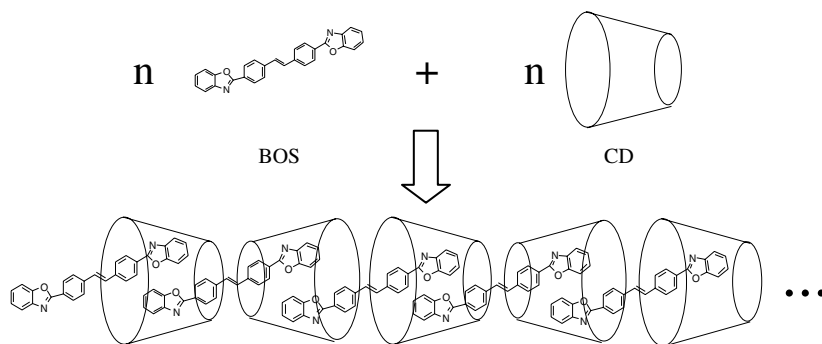


Fig. 1. Illustration of cyclodextrin nanotube induced by BOS.

Our research group has also been focused on the study of the formation of nanotubular structure of cyclodextrin induced by small molecules. So far, several such kind of small molecules have been found.<sup>15–19</sup>

4,4'-bis(2-benzoxazolyl) stilbene (BOS, see Fig. 1) is one of the widely applicable fluorescent whitening agents. Because its fluorescence spectrum containing distinct intensity peaks at characteristic wavelengths, BOS is often used as a fluorescent probe in polymer materials processing.<sup>20,21</sup> Our present study shows that BOS as a good fluorescent bleacher and probe can also induce the formation of cyclodextrin nanotube at high concentrations and form inclusion complex at low concentrations.

## 2. Experimental Section

### 2.1. Materials

BOS (Acros, 99%), and  $\gamma$ -CD (Aldrich, 99%) were used as received.  $\beta$ -CD (Beijing Shuanghuan, China) was recrystallized three times from tridistilled water. All other chemical reagents used in this study were of analytical grade.

### 2.2. Instruments

Steady-state fluorescence and polarization measurements were performed on F-4500 (Hitachi) spectrofluorimeter. Both the excitation and emission bandpasses were 10 nm. Each solution was excited near its maximum absorption wavelength using 1 cm quartz cells. The excitation wavelength was 375 nm. The temperature was monitored by a thermocouple (Checktemp, Hanna, Italy) ( $\pm 0.1^\circ\text{C}$ ).

### 2.3. Methods

Stock solution of BOS was prepared in methanol. In order to prepare the nanotube solution, the following procedures were performed: (1) an aliquot of stock solution of BOS was added to the volumetric flask; (2) required amount of CD was added to give a

certain volume; (3) the above mixture was sonicated for 1 h, and then incubated for one night before carrying out any measurements. Tridistilled water and fresh sample solutions were used throughout the experiments. In the pH studies, pH values were adjusted by adding hydrochloric acid and sodium hydroxide. In the temperature studies, the temperature control was achieved with the sample placed in a water jacketed cell. Water from a thermostated bath was allowed to circulate through the walls of the sample compartment. The final temperature of the sample was measured by a thermocouple.

Steady-state fluorescence anisotropy (polarization) was used to determine the degree of rotation of the BOS/CD complexes. Polarization in emission can be described by the anisotropy  $r$ , measured by front-face excitation, can be given by

$$r = \frac{I_{VV} - GI_{VH}}{I_{VV} + 2GI_{VH}}, \quad (1)$$

where  $I_{VV}$  and  $I_{VH}$  are the intensities when the excitation polarizer has a vertical orientation and the emission polarizer has a vertical or horizontal orientation. The  $G$  factor is defined as

$$G = \frac{I_{HV}}{I_{HH}}, \quad (2)$$

where  $I_{HV}$  and  $I_{HH}$  are the intensities when the excitation polarizer has a horizontal orientation and the emission polarizer has a vertical and horizontal orientation, respectively.  $G$  is an instrumental factor reflecting the polarization characteristics of the photometric system.

### 3. Results and Discussion

Fluorescence excitation and emission spectra of BOS ( $2 \times 10^{-7}$  M) in the aqueous solutions of  $\beta$ - and  $\gamma$ -CD, respectively, are shown in Fig. 2.

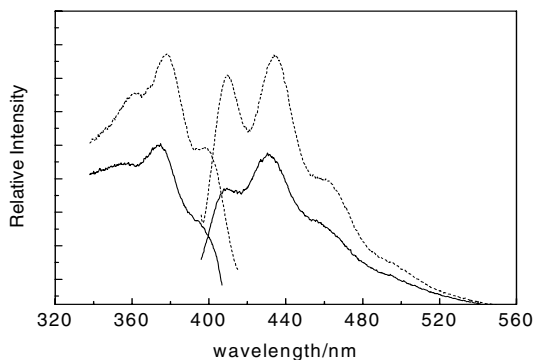


Fig. 2. Fluorescence excitation and emission spectra of BOS ( $2 \times 10^{-7}$  M) in the aqueous solutions of  $\beta$ -CD (10 mM, solid line) and  $\gamma$ -CD (10 mM, dashed line), respectively.

The measurement of the steady-state fluorescence anisotropy provides a method to estimate the relative size of the BOS- $\beta$ -CD nanotube according to Perrin–Webber formula<sup>22</sup>:

$$\frac{r_0}{r} = 1 + \frac{\tau RT}{\eta V}, \quad (3)$$

where  $r_0$  is the maximum value of anisotropy for a certain probe in a frozen state in which it cannot undergo rotational diffusion. For BOS, the measured value of  $r_0$  is 0.288 in the vitrified solution of glycerol.<sup>8</sup>  $\tau$  is the fluorescence lifetime,  $\eta$  is the viscosity of the medium,  $T$  is the absolute temperature and  $R$  is the ideal gas constant. When the fluorescence lifetime and viscosity remain constant, an increase in the anisotropy suggests an increase in the size of the complex. In this way, the relative size of the BOS- $\beta$ -CD nanotube can be estimated by the corresponding values of  $r$ <sup>8</sup>

$$\frac{r_2(r_0 - r_1)}{r_1(r_0 - r_2)} = \frac{V_2}{V_1}, \quad (4)$$

where  $r_1$  and  $r_2$  are the values of the fluorescence anisotropy measured in two different systems,  $V_1$  and  $V_2$  are the effective volumes of these two systems.

To estimate the number of the  $\beta$ -CD molecules in the nanotube, the fluorescence anisotropy values ( $r_2$ ) of BOS ( $1 \times 10^{-6}$  M) at different concentrations of  $\beta$ -CD were investigated. Introducing the value of 1:2 (BOS: $\beta$ -CD) inclusion complex ( $[\text{BOS}] = 2 \times 10^{-7}$  M,  $[\beta\text{-CD}] = 2$  mM,  $r_1 = 0.111$ ), the value of  $2 \times (V_2/V_1)$  is approximated to the number of  $\beta$ -CD molecules in the nanotube. As can be seen in Fig. 3, the fluorescence anisotropy of BOS and the value of the  $n_{\text{CD}}$  were both increased with increasing the concentration of  $\beta$ -CD in aqueous solutions. The maximum number of  $\beta$ -CD molecules in the nanotube was estimated to be 16. The formation of cyclodextrin nanotube induced by BOS was further confirmed by the study of the interactions between  $\gamma$ -CD and BOS. There are essentially two main contributions that can favor the formation of such nanotube in the aqueous solution. Concerning  $\beta$ -CD and BOS, one is

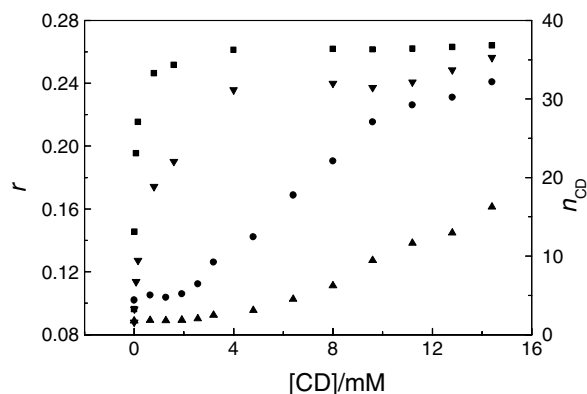


Fig. 3. Steady-state fluorescence anisotropy of BOS at the concentration of  $1 \times 10^{-6}$  M ( $\bullet$   $\beta$ -CD,  $\blacksquare$   $\gamma$ -CD), and the average number of CD in the nanotube ( $\blacktriangle$   $\beta$ -CD,  $\blacktriangledown$   $\gamma$ -CD).

the hydrogen-bonding between the hydroxyl groups of neighboring  $\beta$ -CDs in a tubular stack, the other is the hydrophobic interaction between BOS and the internal hydrophobic  $\beta$ -CD cavity. Considering that the number of  $\gamma$ -CD hydroxyl groups is larger than that of  $\beta$ -CD, we assumed that nanotube could also be formed between  $\gamma$ -CD and BOS and the number of  $\gamma$ -CD in the nanotube would be larger based on the increasing hydrogen-bonding contribution. The result we obtained was in consistent with the assumption. The maximum number of  $\gamma$ -CD molecules in the nanotube was estimated to be 35 (see Fig. 3). The simple illustration that BOS induced the formation of cyclodextrin nanotube was shown in Fig. 1.

The experiment of pH influence on the formation of BOS- $\beta$ -CD nanotube in another way proved the hydrogen-bonding contribution. As can be seen in Fig. 4(a), the  $r$  value was decreased with increasing pH value of the aqueous solution. For the  $\beta$ -CD  $pK_a = 12.20$ ,<sup>23</sup> under that condition all hydroxyl groups of  $\beta$ -CD molecules were changed to negative oxygenic ions. When the pH value was increased beyond 12.00, hydrogen bonding among the  $\beta$ -CDs became ineffective, the driven force for the nanotube formation was vanished and the nanotubular structure was collapsed. This conclusion agrees well with the result in the literature.<sup>8</sup> To discuss the thermostabilization of the cyclodextrin nanotube, we measured the fluorescence anisotropy of BOS as a function of temperature.<sup>24</sup> Figure 4(b) shows that the nanotube induced by BOS and  $\beta$ -CD is thermostable at  $T \leq 303$  K, a higher temperature would cause a gradual collapse of the nanotubular structure.

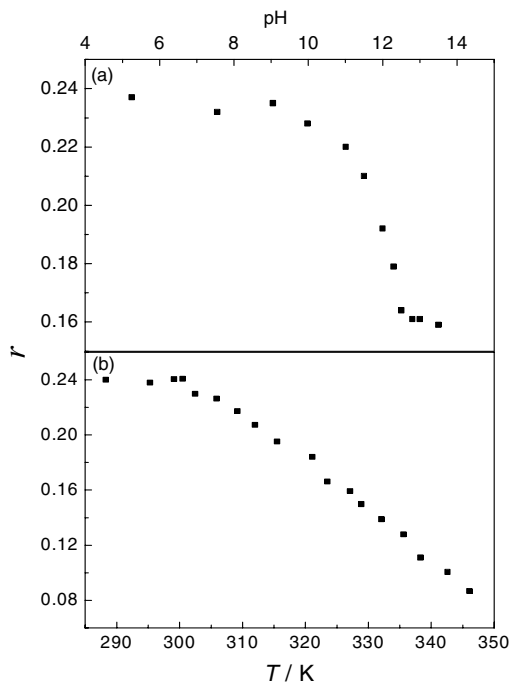


Fig. 4. The steady-state fluorescence anisotropy as a function of (a) pH value and (b) temperature.

In conclusion, BOS is a suitable guest molecule to induce the formation of  $\beta$ - and  $\gamma$ -cyclodextrin nanotubes in the aqueous solution. Further study concerning the influence of other physical or chemical conditions on the formation mechanism of cyclodextrin nanotubes is undergoing in our laboratory.

### Acknowledgments

This work was supported by the National Natural Science Foundation of China (Grant No. 90206020, 29901001) and Doctoral Program Foundation of Education Ministry of China (Grant No. 20010001003).

### References

1. G. Wenz, *Angew. Chem. Int. Ed. Engl.* **33**, 803 (1994).
2. H. J. Schneider, F. Hacket, V. Rudiger and H. Ikeda, *Chem. Rev.* **98**, 1755 (1998).
3. E. Engeldinger, D. Armspach and D. Matt, *Chem. Rev.* **103**, 4147 (2003).
4. G. Wenz and B. Keller, *Angew. Chem. Int. Ed. Engl.* **31**, 197 (1992).
5. X. Shen, M. Belletête and G. Durocher, *J. Phys. Chem. B* **101**, 8212 (1997).
6. A. Harada, J. Li and M. Kamachi, *Nature* **356**, 325 (1992).
7. G. Li and L. B. McGown, *Science* **264**, 249 (1994).
8. G. Pistolis and A. Malliaris, *J. Phys. Chem.* **100**, 15562 (1996).
9. G. Pistolis and A. Malliaris, *J. Phys. Chem. B* **102**, 1095 (1998).
10. A. A. Rezik and D. David, *J. Phys. Chem.* **92**, 1052 (1988).
11. R. A. Agbaria and D. Gill, *J. Photochem. Photobiol. A: Chem.* **78**, 161 (1994).
12. A. A. Kimberly, D. M. Tracy, A. A. Rezik and M. W. Isiah, *J. Photochem. Photobiol. A: Chem.* **91**, 205 (1995).
13. Y. Liu, H. Wang, P. Liang and H.-Y. Zhang, *Angew. Chem. Int. Ed.* **43**, 2690 (2004).
14. X. Wen, M. Guo, Z. Liu and F. Tan, *Chem. Lett.* **33**, 894 (2004).
15. C. Zhang, X. Shen and H. Gao, *Chem. Phys. Lett.* **363**, 515 (2002).
16. C. Zhang, X. Shen and H. Gao, *Prog. Natural Sci.* **15**, 342 (2002).
17. C. Zhang, X. Shen and H. Gao, *Spectrosc. Spect. Anal.* **23**, 217 (2003).
18. K. Xia, T. Hou, X. Xu and X. Shen, *Acta Physico-Chimi. Sinica* **20**, 5 (2004).
19. C. Zhang, Ph.D. Thesis, Peking University, Beijing (2002).
20. A. J. Bur, M. G. Vangel and S. C. Roth, *Polymer Eng. Sci.* **41**, 1380 (2001).
21. W. Majewski and J. Krasinski, *Opt. Commun.* **18**, 255 (1976).
22. J. R. Lakowicz, *Principles of Fluorescence Spectroscopy* (Plenum Press, New York, 1983), Chap. 5, p. 135.
23. S. Li and W. C. Purdy, *Chem. Rev.* **92**, 1457 (1992).
24. K. A. Agnew, T. D. McCarley, R. A. Agbaria and I. M. Warner, *J. Photochem. Photobiol. A: Chem.* **78**, 85 (1994).