The coordination sites of phosphorothioate OligoG$_{10}$ with Cd^{2+} and CdS nanoparticles

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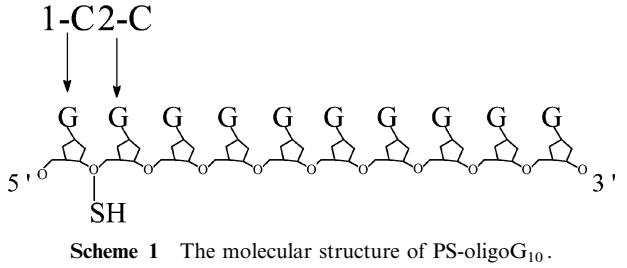
The coordination sites of phosphorothioate oligoG$_{10}$ (PS-oligoG$_{10}$) with Cd^{2+} and CdS nanoparticles are studied by UV-visible, Raman and XPS spectroscopies. It is found that after coordination with the phosphate group of the DNA, Cd^{2+} ions can destroy the guanine–guanine hydrogen bond of the quadruplex assembly of PS-oligoG$_{10}$. After addition of sodium sulfide, a TEM image shows that CdS nanoparticles with diameters of about 5 nm was obtained. As a result, the coordination between Cd^{2+} and the PO_2^- group of the DNA is cleaved and the coordination site of the DNA with the CdS nanoparticle is found to transfer to the guanine residue of the DNA.

Introduction

Inorganic nanoparticles are particularly attractive building blocks for functional nanostructures due to their interesting optical, electronic and catalytic properties.[1–3] Many different approaches have been developed for preparation of inorganic nanoparticles with required properties.[4,5] Inorganic nanoparticles can be prepared by coupling and functionalizing with biomolecules.[6–8] Recently the DNA molecule has become a promising construction biomaterial for fabrication of inorganic nanoparticles due to its physicochemical stability, linearity of molecular structure, and mechanical rigidity.[9,10] In order to get the mild and selective coupling techniques that allow the preparation of thermodynamically stable, kinetically inert, and well-defined DNA–nanoparticle complexes, it is important to understand the role of DNA in the formation of the nanopaticles and the interactions between DNA and the nanoparticle after their formation.[11–13]

In this work we report the preparation of CdS nanoparticles by using phosphorothioate oligoG$_{10}$ (PS-oligoG$_{10}$, thiol was modifed at the phosphate site between C1 and C2, Scheme 1) as capping agent. Phosphorothioate oligo-DNA is well known as an antisense DNA, which is widely employed in manipulating the expression of specific gene products.[14,15] It is found that the addition of Cd^{2+} can destroy the hydrogen bonds between guanine–guanine bases of PS-oligoG$_{10}$ through coordination of Cd^{2+} with its phosphate groups. After addition of sodium sulfide, the coordination between Cd^{2+} and the phosphate group of the DNA is cleaved and the coordination site of DNA with the CdS nanoparticle is transferred to the guanine residue of the DNA.



Scheme 1 The molecular structure of PS-oligoG$_{10}$.

Experimental

PS-oligoG$_{10}$ was synthesized by GENEMED SYNTHESIS, INC (USA). Cadmium chloride and sodium sulfide were both of analytical grade and cadmium chloride was recrystallized before use. Water with a conductivity of 18 MΩ cm was used in the whole experiment. PS-oligoG$_{10}$/Cd^{2+} complex solution (8 μmol L^{-1}) was prepared in 4 ml water. 3.2 μl of 10 mM $CdCl_2$ aqueous solution was added to the PS-oligoG$_{10}$ solution under nitrogen flow. Cd^{2+} concentration in the solution was $[Cd^{2+}]/[P] = 0.1$ ($[Cd^{2+}]$ is the concentration of Cd^{2+} ion, and [P] is the concentration of the phosphate group). The mixture was stirred for 12 h at room temperature to ensure complete interaction between PS-oligoG$_{10}$ and Cd^{2+}. 3.2 μl of 10 mM Na_2S aqueous solution was added, leading to the formation of CdS nanoparticles.

UV-visible spectra were recorded on a Shimadzu UV-1602 spectrophotometer. Raman spectra were carried out on a Renisaw System-1000 Raman spectrometer excited with the 514.5 nm line of an argon ion laser. The samples were dropped on a Si plate about 50 times repeatedly and dried in air after each dropping. X-Ray photoelectron energy spectra (XPS) were obtained by using a VG Scientific ESCALAB Mark II spectrometer referenced to C_{1s} at 284.6 eV.

Transmission electron microscopy (TEM) image was observed using a JEOL JEM-2010 electron microscope. PS-oligoG$_{10}$/Cd^{2+} complex solution was deposited on 300 mesh copper grid covered by Formvar film. The grid was put into a stream of osmic acid for 30 min for staining treatment.

Results and discussion

Fig. 1 shows the UV-visible spectra of PS-oligoG$_{10}$ (a) and PS-oligoG$_{10}$/Cd^{2+} complex (b). The absorbance at 252 nm is guanine's characteristic peak associated with a transition dipole in the bases.[16] After coordination with Cd^{2+}, the intensity of the absorbance at 252 nm increased about 50% without any obvious shift of the peak position. It is well known that the change of absorbance intensity of DNA is related to base pairing and unpairing.[17] Extensive studies have shown that inter- and intramolecular parallel or antiparallel quadruplex

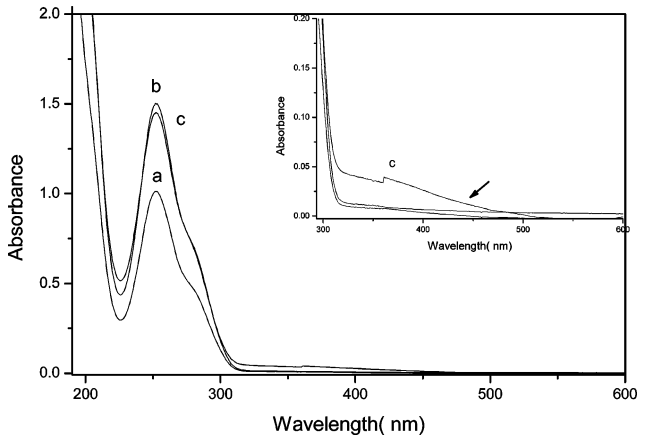


Fig. 1 UV-visible spectra of (a) pure PS-oligoG_{10}, (b) PS-oligoG_{10}/Cd^{2+} complex and (c) PS-oligoG_{10}/CdS. Insert gives amplified spectra of curves in the region of 295–550 nm.

assemblies are readily to be formed for oligonucleotides with multiple G-rich stretches through hydrogen bonds between guanine–guanine bases.[18,19] The increased intensity suggests that the guanine–guanine hydrogen bonding between PS-oligoG_{10} has been destroyed after the addition of Cd^{2+}.

The coordination between PS-oligoG_{10} and Cd^{2+} is further studied by Raman spectroscopy (Fig. 2). For pure PS-oligoG_{10} (a), the band at 1608.1 cm^{-1} is a potentially valuable indicator of guanine N_1–H hydrogen bonding, owing to its origin in N_1–H in-plane bending (Fig. 3a).[20] After the addition of Cd^{2+}, this band shifts to 1599.0 cm^{-1} (Fig. 3b). The band at 1688.5 cm^{-1} is assigned to exocyclic carbonyl band (C=O_6) stretching vibrations of the bases.[21] After coordination with Cd^{2+}, this stretch shifts to lower frequency at 1685.4 cm^{-1}. Such shifts of the N_1–H in-plane bending and C=O_6 stretching vibrations to lower frequencies also indicate that the $N_1H\cdots O_6$ hydrogen bonds in the quadruplex assembly of PS-oligoG_{10} have been destroyed by coordination of Cd^{2+}.[17] The band at 1091.1 cm^{-1} is assigned to the symmetric O–P–O stretching vibration of the nucleic acid phosphodioxy (PO_2^-) group (Fig. 2a).[22] It is seen that the intensity of this band is weakened dramatically after the addition of Cd^{2+}, indicating the coordination between Cd^{2+} and the PO_2^- group of the DNA. The coordination of the PS-oligoG_{10} with Cd^{2+} is further investigated by TEM (Fig. 4). The image shows the DNA/Cd^{2+} complex is observed as nanospheres with diameter of about 2 nm. Before coordination with Cd^{2+}, the DNA is observed as larger aggregates without defined shape as shown by TEM after osmic acid staining treatment.

Fig. 5 shows the TEM image and ED pattern of the formation of the CdS nanoparticles after sodium sulfide was added

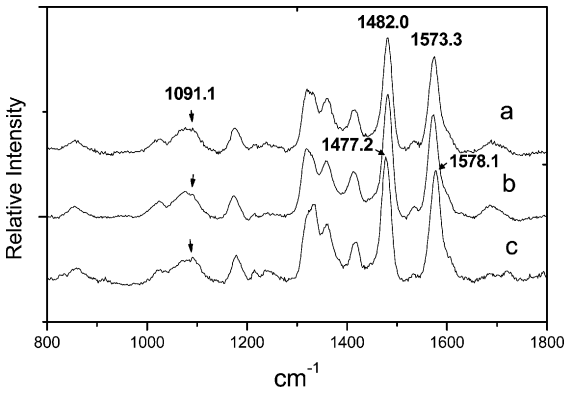


Fig. 2 Raman spectra of (a) pure PS-oligoG_{10}, (b) PS-oligoG_{10}/Cd^{2+} complex and (c) PS-oligoG_{10}/CdS solution dropped on Si substrate.

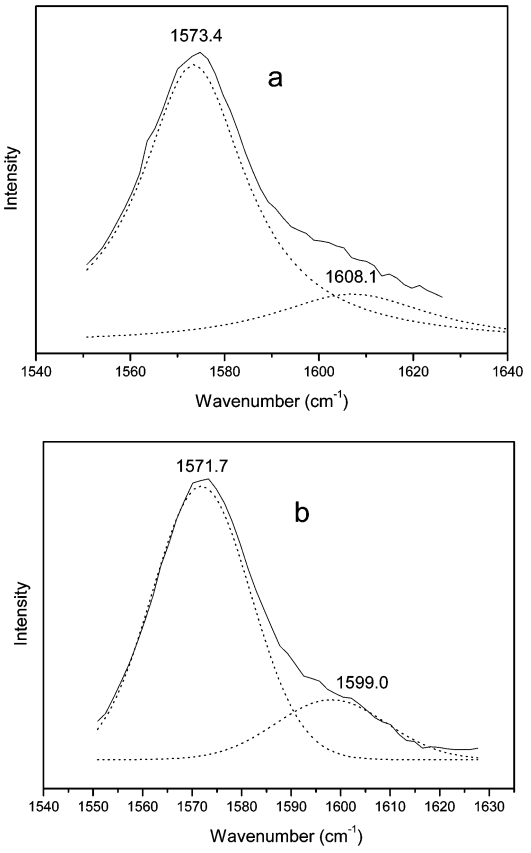


Fig. 3 Fitting results (dotted lines) of the Raman peaks in Fig. 2 in the N–H in-plane bending region. (a) Pure PS-oligoG_{10} and (b) PS-oligoG_{10}/Cd^{2+} ion complex solution.

to the PS-oligoG_{10}/Cd^{2+} complex solution. It reveals the formation of dispersed nanoparticles with diameter of about 5 nm (see Fig. 5b). The ED pattern of the CdS particles shows some dots which indicate that the CdS nanoparticles adopt a crystalline phase and the calculated *d* values are consistent with those of cubic CdS. In addition, the UV-visible spectrum also confirms the formation of the CdS nanopaticles (see Fig. 1c). After addition of sodium sulfide into the PS-oligoG_{10}/Cd^{2+} complex solution, the shift of the edge of the absorption band to about 470 nm (see Fig. 1 insert) indicates that the size of the CdS nanoparticles is about 5 nm.[23]

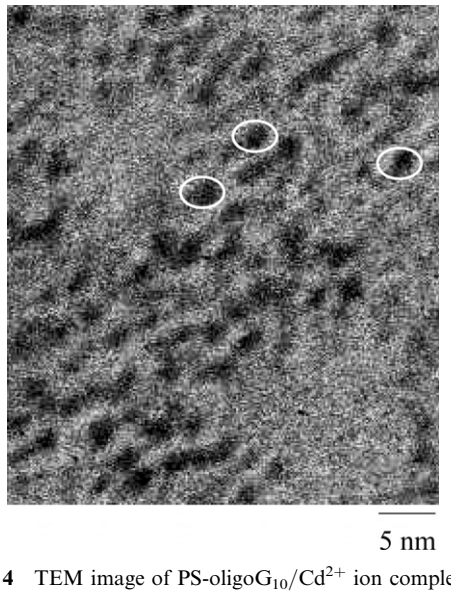


Fig. 4 TEM image of PS-oligoG_{10}/Cd^{2+} ion complexes.

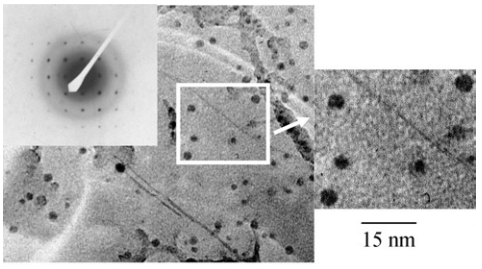


Fig. 5 TEM and electron diffraction pattern of CdS nanoparticles (a), enlarged TEM image of the labeled region in the low magnification image (b). The ED pattern was taken from a region of 100 × 100 nm, coming from a number of nanoparticles within the selected region.

Fig. 6 is the XPS of P_{2p} for pure PS-oligoG_{10} (a), PS-oligoG_{10}/Cd^{2+} complex (b) and PS-oligoG_{10}/CdS (c). For pure DNA, the P_{2p} peak appears at 132.7 eV. The P_{2p} peak shifts to 132.3 eV after the addition of Cd^{2+}, indicating the coordination of Cd^{2+} with the PO_2^- group of the DNA. After addition of sodium sulfide, the P_{2p} binding energy goes back to 132.7 eV. This means the coordination between Cd^{2+} the and phosphate group of PS-oligoG_{10} has been cleaved. The same conclusion can also be drawn from the Raman spectral changes. After the addition of sodium sulfide, the band of the PO_2^- group recovers to its original intensity (see Fig. 3c). In the Raman spectra, the band at 1482.0 cm^{-1} is assigned to a vibration of the guanine residue involving a large displacement of N7 and C8 atoms and the frequency is sensitive to the N7 environment.[20] The 1573.3 cm^{-1} band of the DNA also results from a contribution from guanine residues.[20] Before addition of sodium sulfide, the frequency of the guanine residue in the PS-oligoG_{10}/Cd^{2+} complex experiences little shift. This means

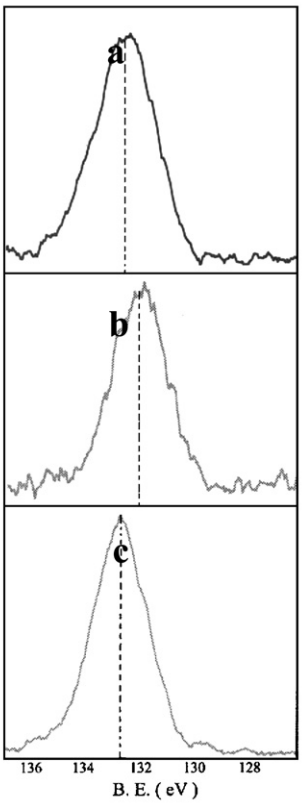
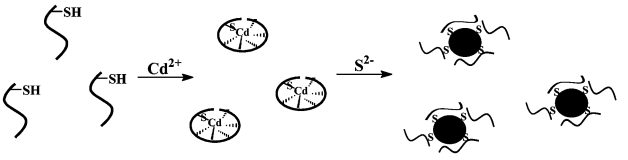


Fig. 6 XPS of P_{2p} for pure PS-oligoG_{10} (a), PS-oligoG_{10}/Cd^{2+} (b) and PS-oligoG_{10}/CdS (c) dropped on a Si substrate.



Scheme 2 Schematic illustration of the coordination sites of PS-oligoG_{10} with Cd^{2+} ions and CdS nanopsrticles.

there are almost no interactions between the Cd^{2+} ions and the guanine residues of the DNA. After addition of sodium sulfide, the band at 1482.0 cm^{-1} shifts to 1477.2 cm^{-1} and the band at 1573.3 cm^{-1} shifts to 1578.1 cm^{-1}. These spectral changes suggest that the coordination site of the DNA with CdS nanoparticle is transferred to the guanine residue of the DNA.

It is known that for oligo DNA without thiol modification, Cd^{2+} can interact with the bases and break the hydrogen bonds between the DNA. For our thiol modified oligo DNA, it is expected that the coordination of Cd^{2+} with the thiol group of PS-oligoG_{10} modified at the phosphate site is prior to that between Cd^{2+} and other groups.[24] The introduction of the thiol group facilitates the coordination of Cd^{2+} with other phosphate groups, resulting in the destruction of the hydrogen bonds between the PS-oligoG_{10}. As a result, individual nanospheres with diameter about 2 nm are observed as shown by TEM. After addition of sodium sulfide, the coordination between Cd^{2+} and the phosphate group of PS-oligoG_{10} is cleaved. The coordination site of the DNA with the CdS nanoparticle is transferred to the guanine residue of the DNA. Based on the above discussion, a schematic representation for the coordination sites of PS-oligoG_{10} with Cd^{2+} ions and CdS nanoparticles is given in Scheme 2.

4. Conclusion

In this work, the coordination sites of DNA with Cd^{2+} and CdS nanoparticles were investigated. The addition of Cd^{2+} can destroy the hydrogen bonds between guanine–guanine bases of PS-oligoG_{10} through coordination of Cd^{2+} with its phosphate groups. After addition of sodium sulfide, the coordination between Cd^{2+} and the phosphate group of the DNA is cleaved and the coordination site of the DNA with the CdS nanoparticle is transferred to the guanine residue of the DNA. Such a study will be helpful for the synthesis of stoichiometrically defined nanoparticle–DNA hybrid materials.

Acknowledgements

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