Supplementary Material (ESI) for Chemical Communications
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Supporting Information

Specific Interactions between Silver(I) Ions and Cytosine–Cytosine Pairs in DNA Duplexes

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Additional References

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Preparation of samples for thermal denaturation

Oligonucleotides with or without metals were dissolved in appropriate buffer solutions and heated at 90 °C in a hot water bath for 10 min. The bath temperature was gradually decreased to 4 °C and kept at this temperature for 2 h before thermal denaturation.

T_m of duplexes containing C–C pairs in the presence of $AgNO_3$

T_m versus the Ag(I) ion concentration is shown in Figure S1. Each solution consisted of 1 µM duplex [5’-CACTGCACTGGTCAC-3’: 3’-GTGACGTCACCAGTG-5], 0–2 µM $AgNO_3$ in 10 mM Mops, and 100 mM $NaNO_3$ at pH 7.1. The thermally induced transitions of the duplexes in Figure S1 were monitored on a Beckman DU 7500 spectrophotometer with the T_m analysis accessory. The temperature was ramped at 0.5 ºC min^{-1}.

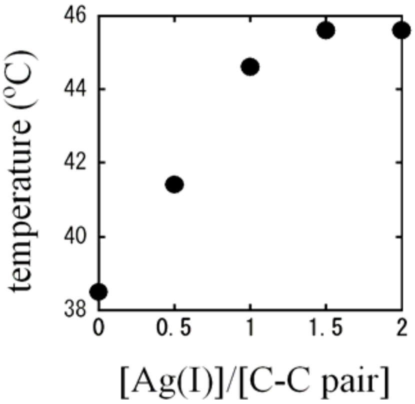
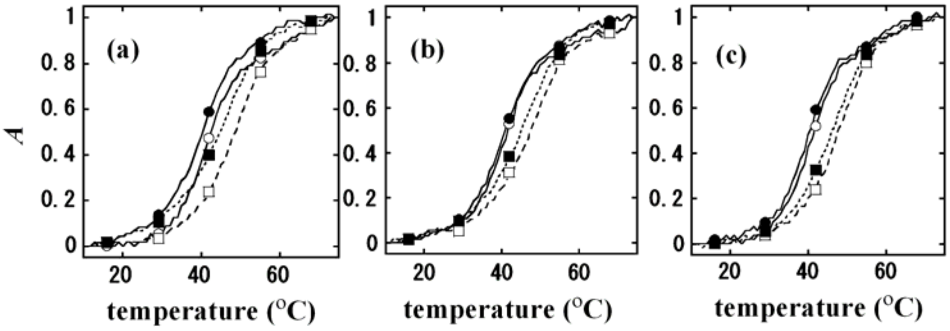


Figure S1

Thermally induced dissociation and association processes of the duplex containing the C-Ag-C pair.

In Figure S2, thermally induced profiles for dissociation and association processes of a duplex containing one C-C pair, [5'-d(CACTGCA**C**TGGTCAC)-3' 5'-(GTGACCA**C**TGCAGTG)-3'] in the presence and the absence of silver ions. In the absence and the presence of silver ions, with the temperature ramp of 0.5 ºC min$_{-1}$, the dissociation and the association curves were not overlapped (Fig. S2a). With the temperature ramps of 0.2 ºC min$_{-1}$ and 0.1 ºC min$_{-1}$, in the absence of silver ions, the dissociation and association curves almost overlapped (Figure S2bc).In contrast, in the presence of silver ion, the association curve was sifted to the lower temperature area compared to the dissociation curve (Figure S2abc). Thus, T_m values in the presence of Ag(I) were not correct in the strict sense of the word “T_m”, the temperature at which 1/2 of the duplex dissociate in an equilibrium state. However, Tm values in the report are sufficiently reliable for detecting the duplex - metal ion binding.



		the temperature ramp of 0.5 °C min-1,	the temperature ramp of 0.2 °C min-1,	the temperature ramp of 0.1 °C min-1,
5'-CACTGCACTGGTCAC-3' 3'-GTGACGTCACCAGTG-5 without Ag (I)	up	○ T_m = 41 °C	○ T_m = 40 °C	○ T_m = 40 °C
	down	● T_m = 40 °C	● T_m = 40 °C	● T_m = 39 °C
5'-CACTGCACTGGTCAC-3' 3'-GTGACGTCACCAGTG-5 with Ag (I)	up	□ T_m = 46 °C	□ T_m = 47°C	□ T_m = 47 °C
	down	■ T_m = 45 °C	■ T_m = 46 °C	■ T_m = 46 °C

Thermally induced transition profiles of DNA duplexes containing the C–C pair mismatch in the presence of metal ions.

The relative absorbance, $A = [(A_{t\,^{\circ}\mathrm{C}} - A_{10\,^{\circ}\mathrm{C}})/(A_{60\,^{\circ}\mathrm{C}} - A_{10\,^{\circ}\mathrm{C}})]$ at 260 nm as a function of temperature for each mixture is shown in Figure S3. Each solution consisted of 1 ・ M oligomer [(5'-d(A)$_{10}$C(A)$_{10}$-3' and 5'-d(T)$_{10}$C(T)$_{10}$-3')], 2 μM of each metal ion in 10 mM Mops, and 100 mM NaNO$_3$ at pH 7.1. The thermally induced transitions of the duplexes in Figure S1 were monitored on a Beckman DU 7500 spectrophotometer with the T_m analysis accessory. The temperature was ramped at 0.5 ºC min^{-1}. Plots are shown for duplex solutions in the absence of metal (-○-), and in solutions containing 2 μM AgNO$_3$ (– - □ – -), 2 μM Hg(ClO$_4$)$_2$ (–■–), and 2 μM CuCl$_2$ (- -Δ- -).

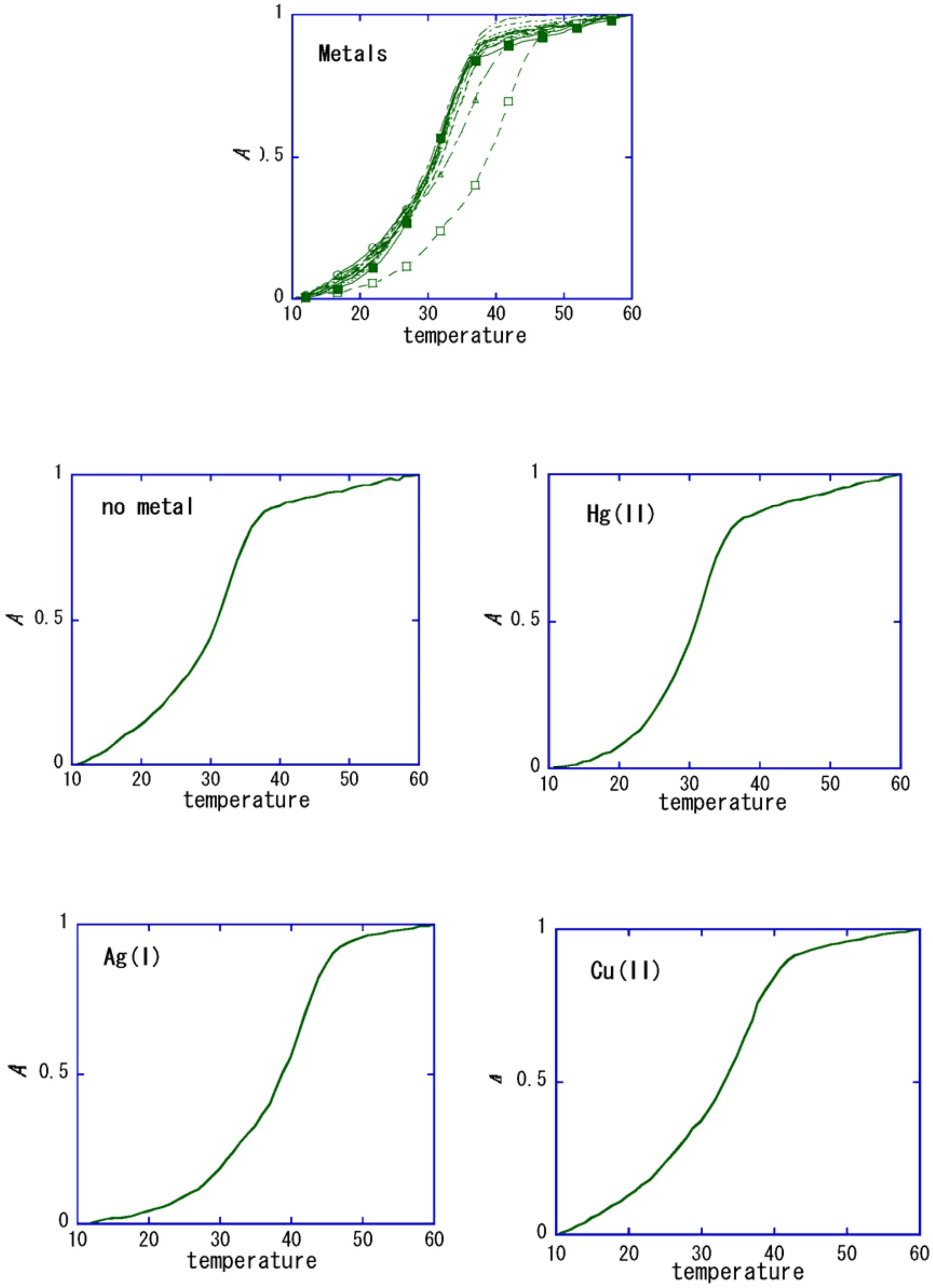

Metals
A
0.5
1
0
10
20
30
40
50
60
temperature
no metal
Hg(II)
Ag(I)
Cu(II)

Figure S3-1

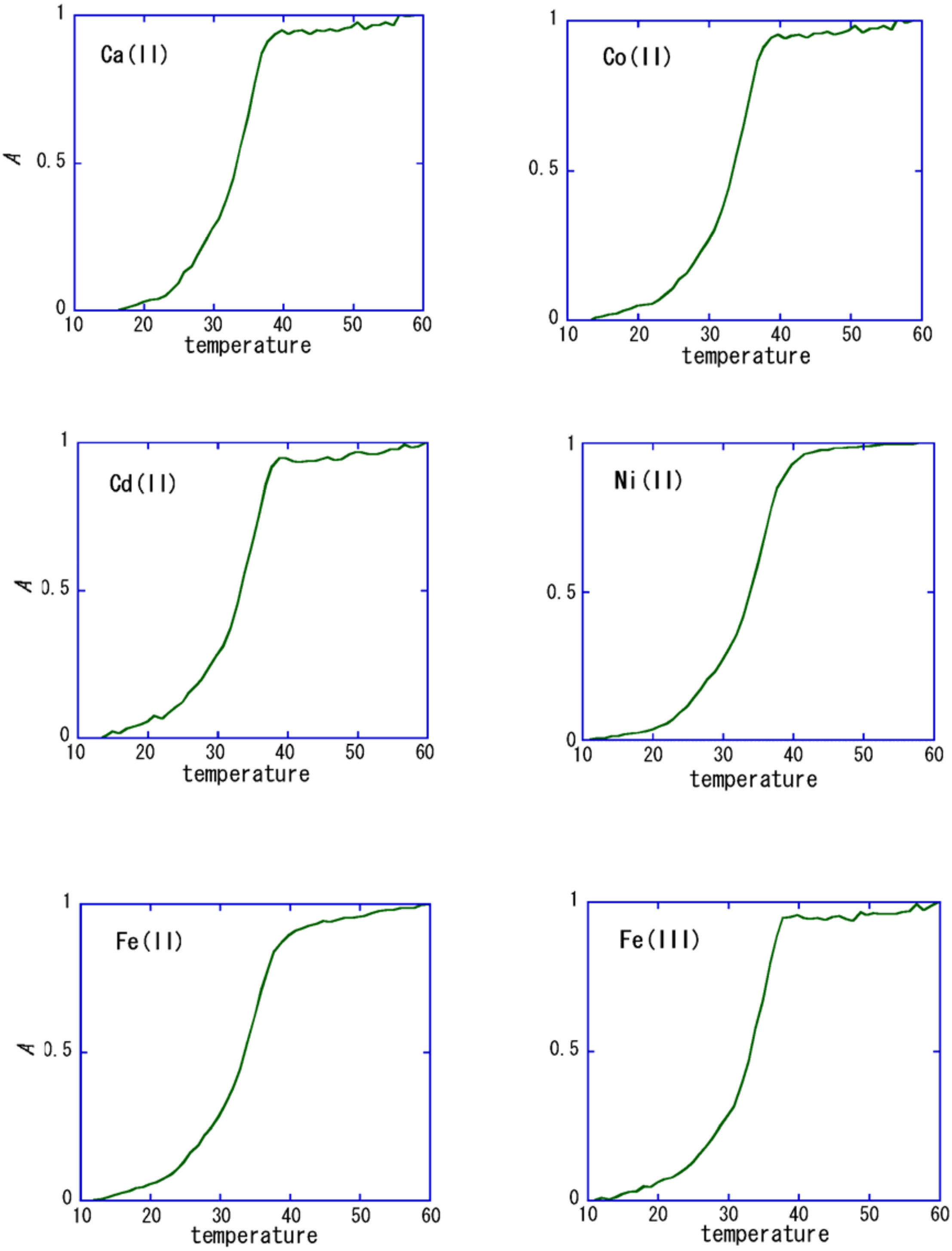

Ca(II)
Co(II)
Cd(II)
Ni(II)
Fe(II)
Fe(III)
A
0
0.5
1
10
20
30
40
50
60
temperature

Figure S3-2

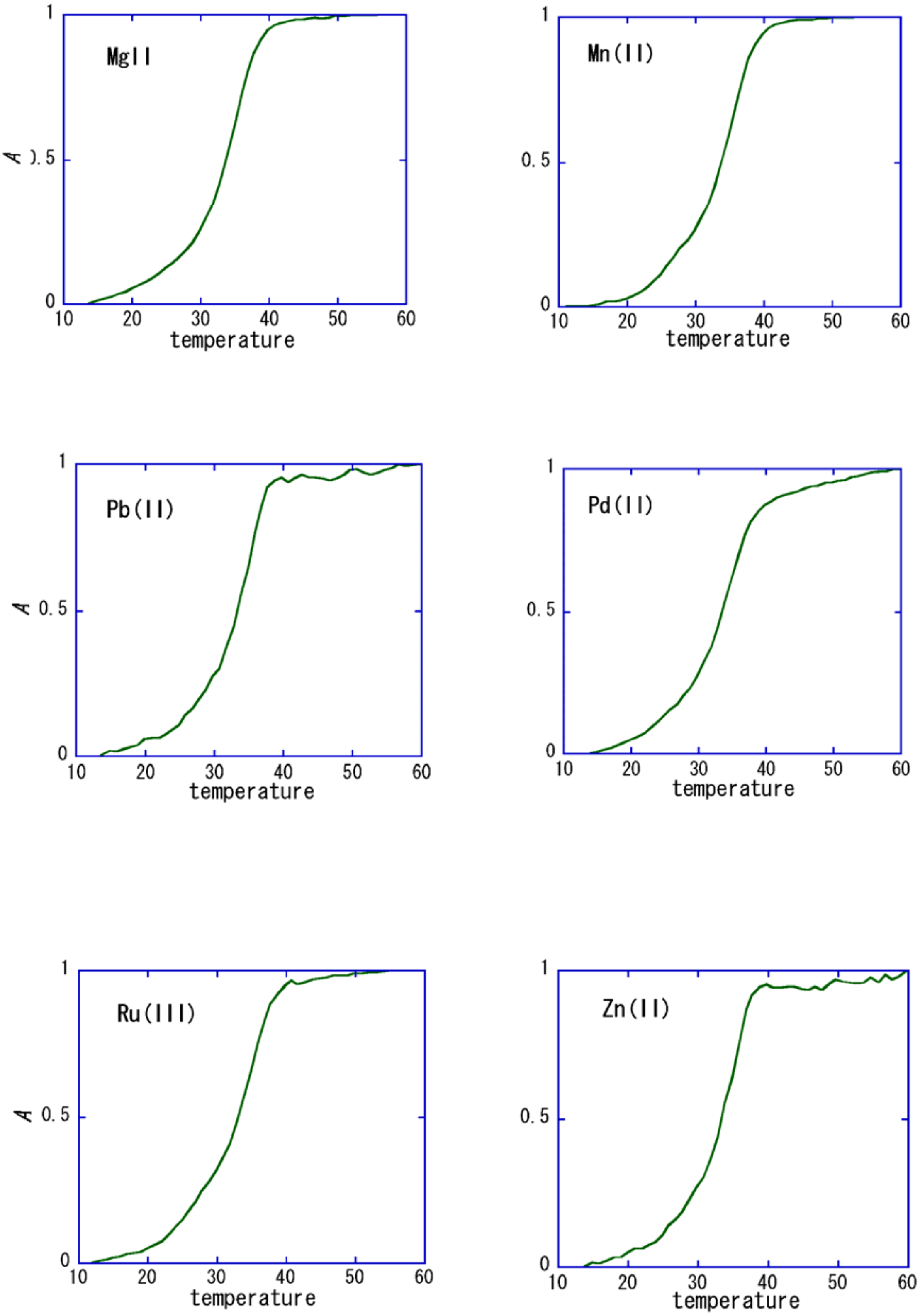

MgII
Mn(II)
Pb(II)
Pd(II)
Ru(III)
Zn(II)
A
0
0.5
1
10
20
30
40
50
60
temperature

Figure S3-3

Electrospray ionization mass spectroscopy

Figure S4-S8 shows an ESI mass spectrum of the DNA duplexes. ESI–MS measurements were performed on a time-of-flight mass spectrometer (JMS-T100; JEOL, Tokyo, Japan). The measurement conditions were as follows: needle voltage –1.5 kV; orifice voltage –50 V; desolvation temperature 80–100 °C; resolution (10% valley definition) 2000; and sample flow rate 20 µL min^{-1}. For sample preparation, each aqueous solution containing DNA and Ag(I) ions in 62.5 mM NH_4OAc (pH 6.9) was diluted with MeOH. The DNA concentration was 10 µM, the buffer (NH_4OAc) concentration was 50 mM, and the solvent was H_2O/MeOH (4:1).

Figure S4 (in page S8)
5′-d(GTGACCA**C**TGCAGTG)-3′
3′-d(CACTGGT**C**ACGTCAC)-5′

Figure S5 (in page S9)
5′-d(GTGACCA**C**TGCAGTG)-3′
3′-d(CACTGGT**C**ACGTCAC)-5′ in the presence of Ag(I) ions

Figure S6 (in page S10-11)
5′-d(GTGACCACTGCAGTG)-3′
3′-d(CACTGGTGACGTCAC)-5′

Figure S7 (in page S12-13)
5′-d(GTGACCACTGCAGTG)-3′
3′-d(CACTGGTGACGTCAC)-5′ in the presence of Ag(I) ions

In a spectrum for the duplex containing no miss pair in the presence of Ag(I) ions, small peaks which may arise from non-specific silver ion binding to double and single stranded DNA were observed (Fig. S7, in page S13). In contrast, in the spectrum for a duplex containing a C-C pair with Ag(I) ions, such small peaks due to non-specific silver binding were disappeared and only the peaks corresponding to the 1 : 1 duplex-silver ion complex were observed (Fig. S5, in page S9).

5'-d(GTGACCACTGCAGTG)-3' + 5'-d(CACTGCACTGGTCAC)-3'

$C_{290}H_{363}N_{112}O_{176}P_{28}$

Found, 1820.89; calculated for $[\text{duplex} - 5H]^{5-}$, 1820.18

$C_{290}H_{362}N_{112}O_{176}P_{28}$

Found, 1517.22; calculated for $[\text{duplex} - 6H]^{6-}$, 1516.65

$C_{146}H_{180}N_{58}O_{88}P_{14}$

Found, 1147.62; calculated for $[\text{5'-d(GTGACCACTGCAGTG)-3'} - 4H]^{4-}$, 1147.24

$C_{144}H_{180}N_{54}O_{88}P_{14}$

Found, 1127.51; calculated for $[\text{5'-d(CACTGCACTGGTCAC)-3'} - 4H]^{4-}$, 1127.23

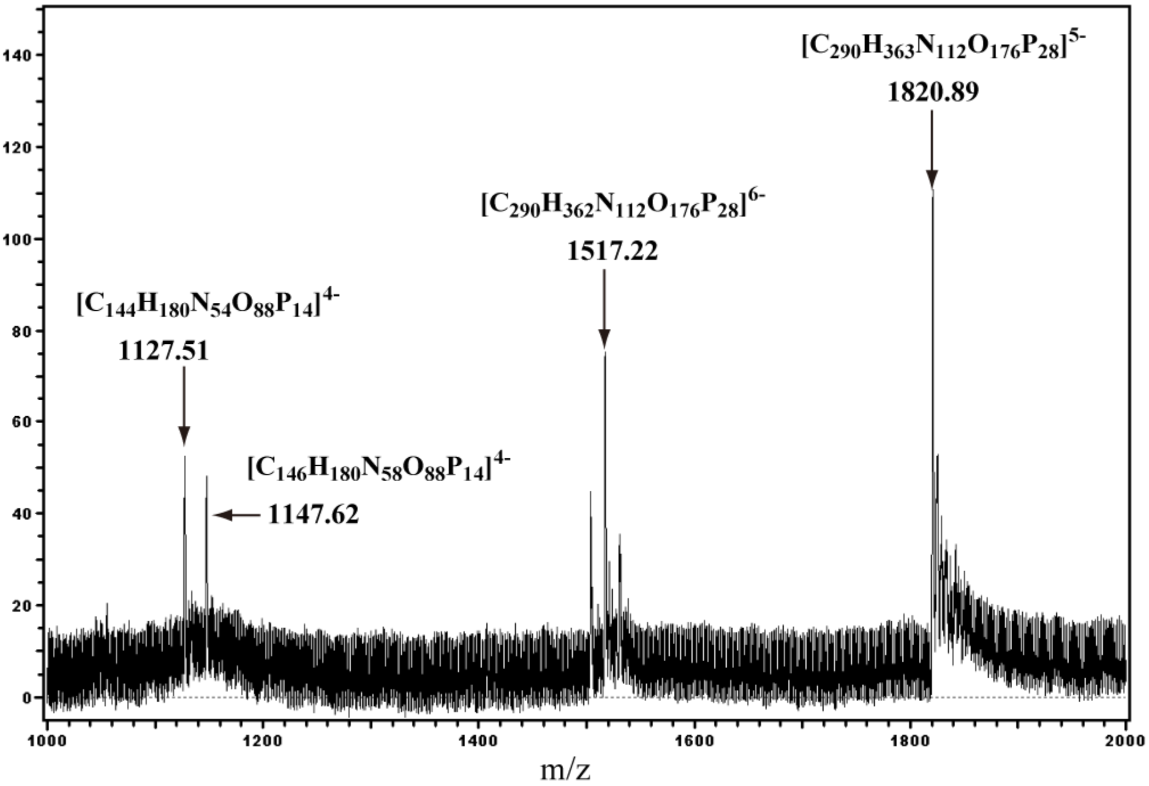


Figure S4

5'-d(GTGACCACTGCAGTG)-3' + 5'-d(CACTGCACTGGTCAC)-3' + Ag^{I}

$C_{290}H_{362}N_{112}O_{176}P_{28}Ag$

Found, 1842.17; calculated for $[(\text{duplex} + Ag^{I}) - 6H]^{5-}$, 1841.55

$C_{290}H_{361}N_{112}O_{176}P_{28}Ag$

Found, 1534.97; calculated for $[(\text{duplex} + Ag^{I}) - 7H]^{6-}$, 1534.46

$C_{146}H_{180}N_{58}O_{88}P_{14}$

Found, 1147.58; calculated for $[\text{5'-d(GTGACCACTGCAGTG)-3'} - 4H]^{4-}$, 1147.24

$C_{144}H_{180}N_{54}O_{88}P_{14}$

Found, 1127.55; calculated for $[\text{5'-d(CACTGCACTGGTCAC)-3'} - 4H]^{4-}$, 1127.23

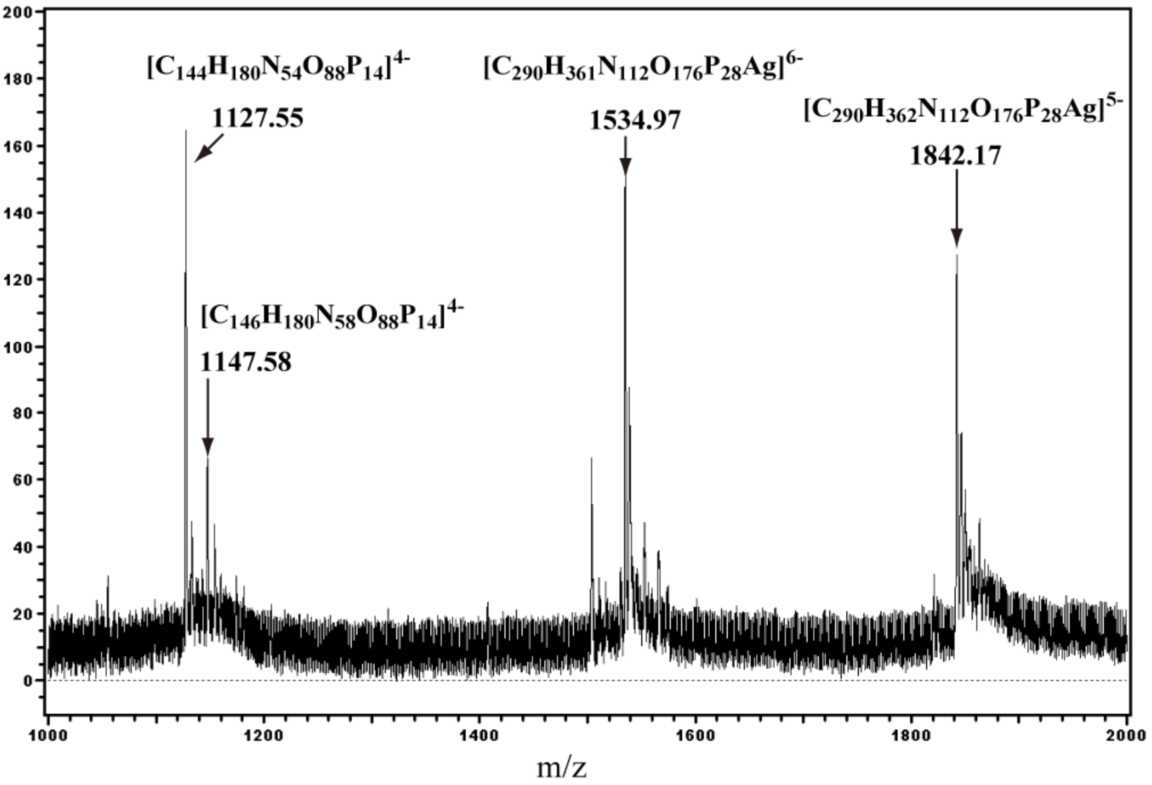


Figure S5

5'-d(GTGACCACTGCAGTG)-3' + 5'-d(CACTGCAGTGGTCAC)-3'

$C_{291}H_{363}N_{114}O_{176}P_{28}$

Found, 1828.71; calculated for $[\text{duplex} - 5H]^{5-}$, 1828.18

$C_{146}H_{181}N_{58}O_{88}P_{14}$

Found, 1530.35; calculated for [5'-d(GTGACCACTGCAGTG)-3' – 3H]$^{3-}$, 1534.63

$C_{145}H_{181}N_{56}O_{88}P_{14}$

Found, 1517.00; calculated for [5'-d(CACTGCAGTGGTCAC)-3' – 3H]$^{3-}$, 1516.65

$C_{146}H_{180}N_{58}O_{88}P_{14}$

Found, 1147.59; calculated for [5'-d(GTGACCACTGCAGTG)-3' – 4H]$^{4-}$, 1147.24

$C_{145}H_{180}N_{56}O_{88}P_{14}$

Found, 1137.46; calculated for [5'-d(CACTGCAGTGGTCAC)-3' – 4H]$^{4-}$, 1137.23

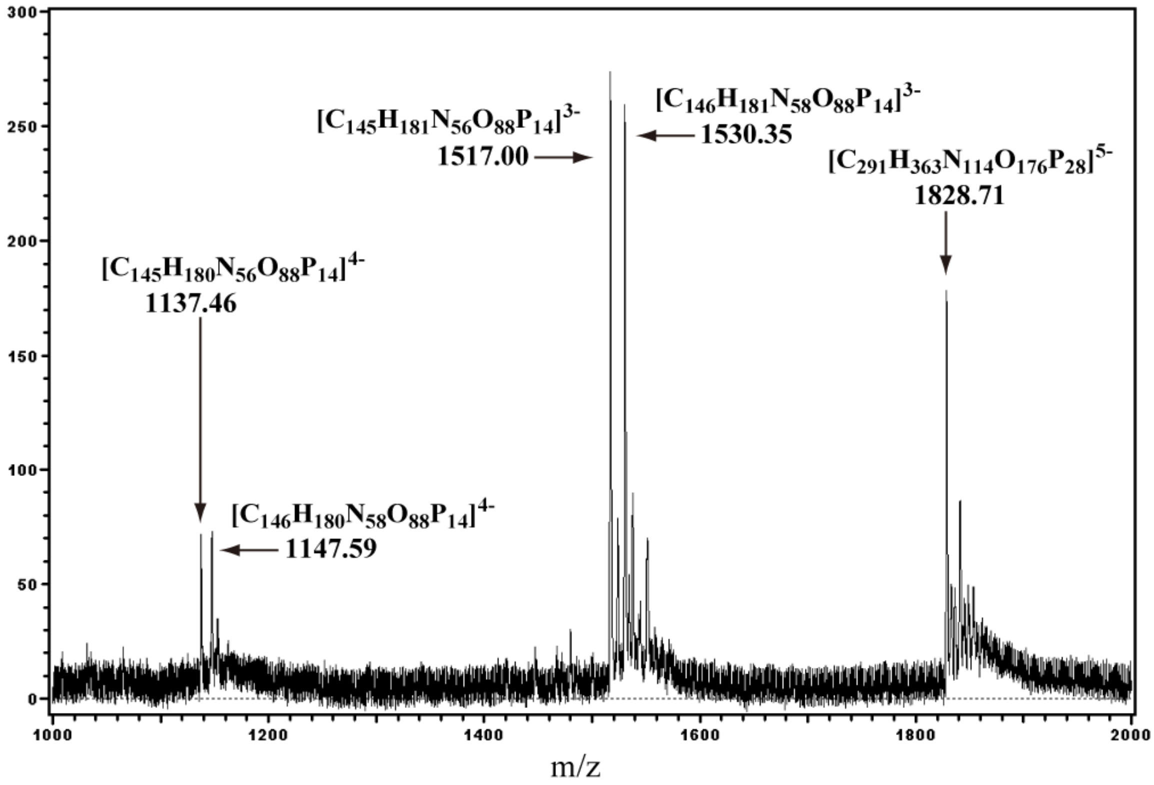

[$C_{145}H_{181}N_{56}O_{88}P_{14}$]$^{3-}$
1517.00
[$C_{146}H_{181}N_{58}O_{88}P_{14}$]$^{3-}$
1530.35
[$C_{291}H_{363}N_{114}O_{176}P_{28}$]$^{5-}$
1828.71
[$C_{145}H_{180}N_{56}O_{88}P_{14}$]$^{4-}$
1137.46
[$C_{146}H_{180}N_{58}O_{88}P_{14}$]$^{4-}$
1147.59
300
250
200
150
100
50
0
1000
1200
1400
1600
1800
2000
m/z

Figure S6

5'-d(GTGACCACTGCAGTG)-3' + 5'-d(CACTGCAGTGGTCAC)-3' + Ag^{I}

$C_{291}H_{362}N_{114}O_{176}P_{28}Ag$

Found, 1850.11; calculated for [(duplex + Ag^{I}]– 6H]$^{5–}$, 1849.56

$C_{291}H_{363}N_{114}O_{176}P_{28}$

Found, 1829.07; calculated for [duplex – 5H]$^{6–}$, 1828.18

$C_{291}H_{360}N_{114}O_{176}P_{28}Ag_2$

Found, 1559.46; calculated for [duplex + 2Ag^{I} – 8H]$^{6–}$, 1558.94

$C_{291}H_{361}N_{114}O_{176}P_{28}Ag$

Found, 1541.68; calculated for [duplex + Ag^{I} – 7H]$^{6–}$, 1541.13

$C_{291}H_{362}N_{114}O_{176}P_{28}Ag$

Found, 1523.89; calculated for [duplex – 6H]$^{6–}$, 1523.32

$C_{146}H_{178}N_{58}O_{88}P_{14}Ag_2$

Found, 1200.91; calculated for [5'-d(GTGACCACTGCAGTG)-3' + 2Ag^{I} – 6H]$^{4–}$, 1200.67

$C_{146}H_{179}N_{58}O_{88}P_{14}Ag$

Found, 1174.32; calculated for [5'-d(GTGACCACTGCAGTG)-3' + Ag^{I} – 5H]$^{4–}$, 1173.96

$C_{146}H_{180}N_{58}O_{88}P_{14}$

Found, 1147.54; calculated for [5'-d(GTGACCACTGCAGTG)-3' – 4H]$^{4–}$, 1147.24

$C_{145}H_{180}N_{56}O_{88}P_{14}$

Found, 1137.45; calculated for [5'-d(CACTGCAGTGGTCAC)-3' – 4H]$^{4-}$, 1137.23

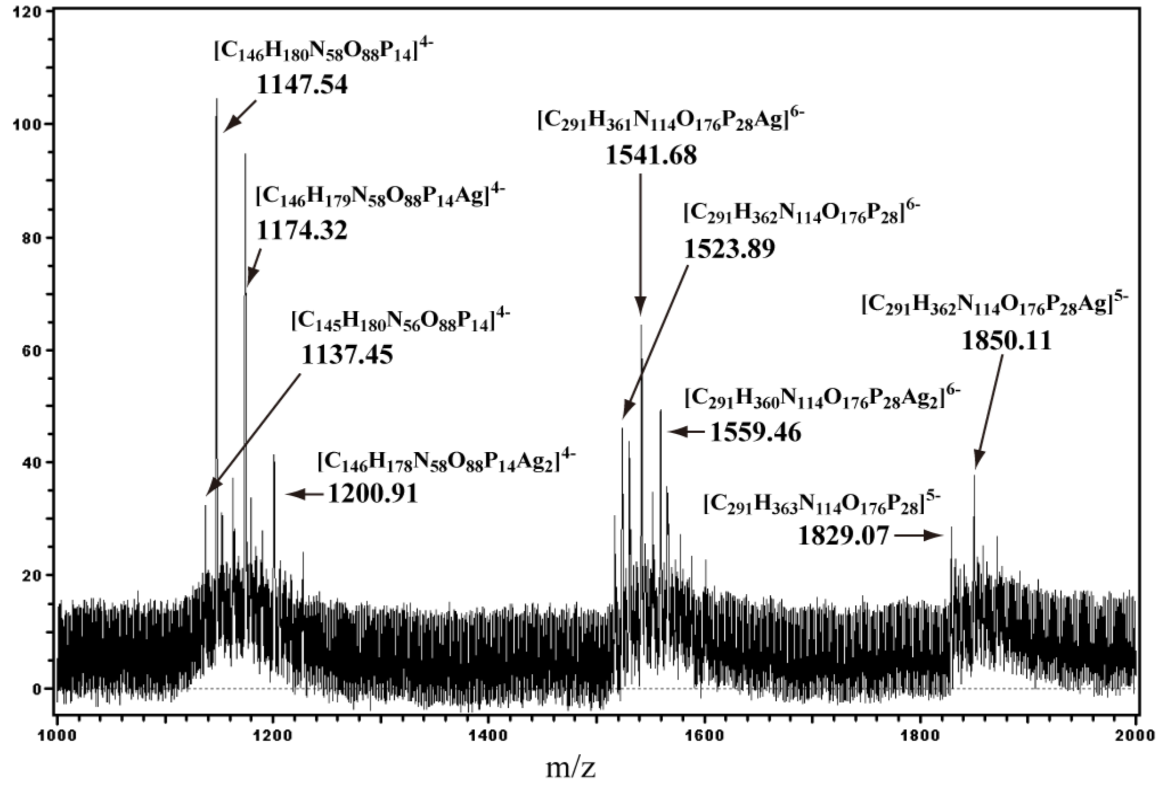


Figure S7

Fluorescence emission of D–ODN–F or anti-ODN solutions in the absence and presence of Ag(I) ions

When a double-stranded or hairpin structure was formed from two or one sensor molecules (**D**–**ODN**–**F**), respectively, with Ag(I) ions (Figure S8a), fluorescence resonance energy transfer (FRET) between the **F** and **D** residues was enhanced, which resulted in quenching of fluorescence emission. In the presence of excess **ODN**, however, the fluorescence emission was unchanged because FRET did not occur in the heteroduplex structures, as illustrated in Figure S8c. Conversely, if the hairpin structure was formed, the fluorescence emission intensity decreased dramatically, as depicted in Figure S8d.

D-ODN-F	**D-(CTCTCTTCTCTTCATTTTTCAACACAACACAC)-F**
ODN	**5'-d(CTCTCTTCTCTTCATTTTTCAACACAACACAC)-3'**
ODN-F	**(CTCTCTTCTCTTCATTTTTCAACACAACACAC)-F**

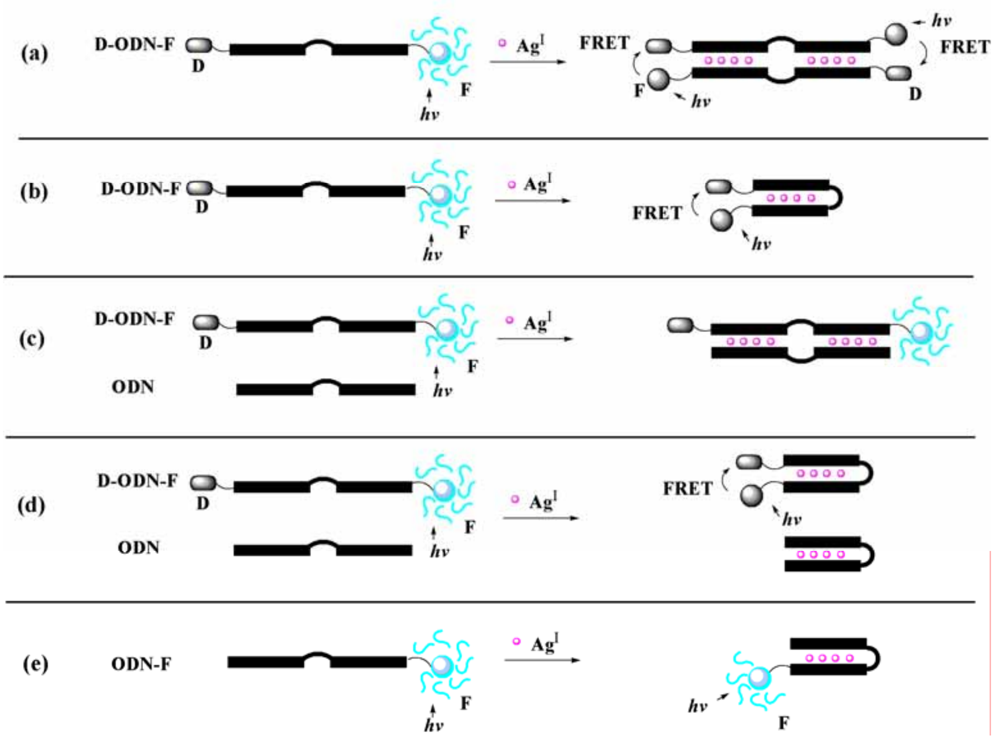


Figure S8. Schematic representation of the expected structures and related fluorescent properties.

As shown in Figure S9a, the fluorescence intensity of **D**–**ODN**–**F** was reduced by adding Ag(I) ions in the presence of excess **ODN**, which indicated the formation of hairpin structures in the presence of Ag(I) ions. Although the emission intensity of **ODN**–**F** decreased slightly upon the addition of Ag(I) ions (Figure S9b and –○– in S9c), this was not the major cause of the decrease in the emission intensity.

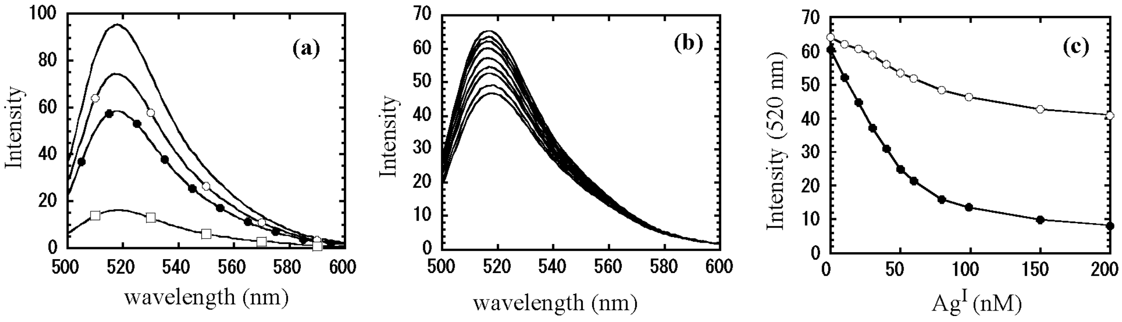


Figure S9. Fluorescence emission spectra. (a) — **D**–**ODN**–**F** (10 nM) + **ODN** (100 nM),–○– add 60 nM $AgNO_3$, –●– 120 nM $AgNO_3$, –□– 600 nM $AgNO_3$. (b) The fluorescence response of **ODN**–**F** (10 nM) to the addition of 0, 10, 20, 30, 40, 60, 80, 100, 150, and 200 nM $AgNO_3$. (c) The fluorescence emission intensity (520 nm) vs. the Ag^I concentration. –○– 10 nM **ODN**–**F**, –●–10 nM **D–ODN–F**. A buffer solution of 3-(*N*-morpholino)propanesulfonic acid (10 mM, pH 7.0) 50 mM $NaNO_3$ was used.