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Towards understanding of poly-guanine activated fluorescent silver nanoclusters

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Abstract

It has been recently reported that the fluorescence of some DNA-templated silver nanoclusters (AgNCs) can be significantly enhanced upon by hybridizing with a partially complementary DNA containing a G-rich overhang near the AgNCs. This discovery has found a number of analytical applications but many fundamental questions remain to be answered. In this work, the photostability of these activated AgNCs is reported. After adding the G-rich DNA activator, the fluorescence intensity peaks in ~ 1 h and then starts to decay, where the decaying rate is much faster with light exposure. The lost fluorescence is recovered by adding NaBH_4 , suggesting that the bleaching is an oxidative process. Once activated, the G-rich activator can be removed while the AgNCs still maintain most of their fluorescence intensity. UV-vis spectroscopy suggests that new AgNC species are generated upon hybridization with the activator. The base sequence and length of the template DNA have also been varied, leading to different emission colors and color change after hybridization. G-rich aptamers can also serve as activators. Our results indicate that activation of the fluorescence by G-rich DNA could be a convenient method for biosensor development since the unstable NaBH_4 is not required for the activation step.

Keywords: DNA, fluorescence, silver, biosensor, nanoclusters

 Online supplementary data available from stacks.iop.org/Nano/25/155501/mmedia

(Some figures may appear in colour only in the online journal)

1. Introduction

In recent years, DNA-templated fluorescent silver nanoclusters (AgNCs) have attracted extensive interest in biosensor development since they are highly fluorescent, cost-effective to produce, and less toxic compared to semiconductor quantum dots. In addition, different DNA sequences produce various emission colors [1–6], allowing multiplexed detection. The emission color is likely to relate to the arrangement of silver species and their interaction with the surrounding nucleotides [6]. Their fluorescence property is also sensitive to heavy metal ions, change of pH, light, and nearby nucleotide composition [7–15]. Since DNA is an intrinsic component of such AgNCs, it is quite convenient to harness the molecular recognition property of DNA. Beyond sensing complementary DNA (cDNA), aptamers can recognize a broad range of

analytes. A number of aptamer and AgNC based sensors have already been reported [16–20].

A few strategies have been developed to design biosensors using AgNCs. (1) Most AgNCs are sensitive to high redox potential metal ions such as Hg^{2+} and Cu^{2+} , which strongly quench the fluorescence of both Au and AgNCs [21–25]. A few mechanisms have been proposed to explain fluorescence quenching and we recently showed that oxidation might be an important one [26]. (2) The production of AgNCs is usually facilitated by a loop of cytosine-rich DNA. Generation of such loops in the presence of target analytes has been utilized for sensing [27–31]. However, Ag^+ reduction by an unstable chemical (NaBH_4) is a required step in the detection process, which is a challenge for field applications. (3) AgNCs have been used as a simple fluorophore label that can be quenched

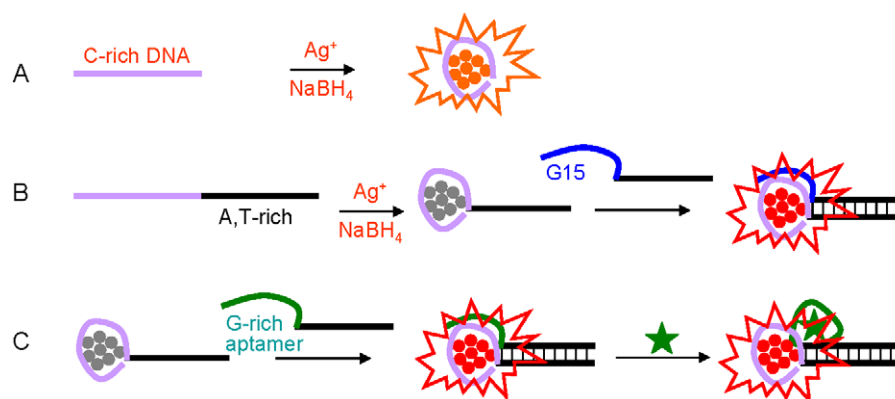


Figure 1. Schemes of DNA-templated AgNC synthesis and fluorescence generation. (A) Producing AgNCs with a C-rich DNA template and NaBH_4 as the reducing agent. (B) The extended DNA produces non-fluorescent AgNCs, which become fluorescent upon hybridizing with a DNA containing a G-rich overhang. (C) Some G-rich aptamers can also activate the fluorescence, but aptamer binding to its target has little influence on fluorescence intensity.

by external dark quenchers [32–35]. (4) Werner, Martinez and co-workers reported that a G-rich DNA could enhance the fluorescence of a DNA-templated AgNC by over 500-fold (see figure 1(B)) [36]. A few biosensors have been designed by manipulating the distance between the G-rich DNA and AgNCs [36–40].

A problem limiting practical applications of AgNCs is photostability; most DNA-templated AgNCs are easily bleached upon light exposure [26, 41]. We reason that G-rich DNA activated AgNCs might provide a solution for the photostability problem. G-rich DNA is highly stable and easy to handle, making it possible to activate the fluorescence on-demand without using the unstable NaBH_4 . In this work, we systematically test the stability of such AgNCs. In addition, we study a number of different templating and activating DNA sequences to have a more complete understanding on this system.

2. Materials and methods

2.1. Chemicals

All of the DNA samples were purchased from Integrated DNA Technologies (IDT, Coralville, IA) and purified by standard desalting. The DNA sequences are shown in table 1. AgNO_3 and NaBH_4 were from Sigma-Aldrich. 4-(2-hydroxyethyl)-1-piperazineethanesulfonic acid (HEPES), its sodium salt, NaH_2PO_4 , NaNO_3 , and adenosine and other ribonucleosides were purchased from Mandel Scientific (Guelph, ON). Milli-Q water was used for making buffers and dilutions.

2.2. Preparation of AgNCs

DNA/Ag NCs preparation procedure was based on the literature [36]. Concentrations of starting solutions were 100 μM for DNA, 1 mM for AgNO_3 , 1 mM for NaBH_4 , 500 mM for sodium phosphate buffer (pH 6.6). AgNCs were formed by firstly preparing the mixture solution containing final concentrations of 15 μM DNA, 90 μM AgNO_3 , 90 μM NaBH_4 and 20 mM for sodium phosphate buffer, where freshly prepared NaBH_4 was added at the last step. The NaBH_4 solution was

prepared by dissolving the powder in water and the required volume was added to the DNA/ Ag^+ mixture within 30 s followed by vigorous shaking for 5 s. The reaction was kept in dark at room temperature for 24 h before hybridization. In case of DNA7a, NaBH_4 concentration was 120 μM and the incubation time after adding NaBH_4 was 2 h.

2.3. Hybridization with G-rich sequences

After adding NaBH_4 for 24 h, DNA_G15 (11.5 μl of 100 μM solution) was added to the samples (50 μl of reaction solution). The ratio DNA_G15/DNA1–7 was approximately 1.5:1. The final concentrations of DNA1 (or other template DNA) and DNA_G15 were 12.2 μM and 18.7 μM , respectively. This was followed by 1 h incubation in dark at room temperature before fluorescence spectra were measured.

2.4. Fluorescence measurements

Fluorescence was measured using a Varian Cary Eclipse Fluorescence Spectrophotometer. The samples (50 μl of DNA-Xa or DNA-X samples and 61.5 μl of DNA-X + DNA_G15 samples, $X = 1-7$) were diluted with water so that the final volume was 600 μl and final concentration of ssDNA (DNA-X and DNA-Xa) or dsDNA (DNA-X + DNA_G15) was 1.25 μM . Also, excitation wavelength was dependent on each sample and respective excitation wavelengths are in the legend describing the spectra plots. Just before spectra measurement a photograph of each sample exposed to a handheld UV lamp was taken using a Canon SD1200 IS camera.

2.5. Photobleaching

The prepared DNA1-AgNC/DNA_G15 samples were either stored in dark for 72 h or exposed to the light for 1 h. In both cases, this was followed by adding an additional portion of NaBH_4 solution (9 μl of 1 mM NaBH_4 to 122.5 μl of the bleached sample) and incubating at room temperature in dark for 3 h before spectral measurements.

Table 1. DNA sequences used in this work.

Names	Sequences (from 5' to 3')
DNA1a	CCCTTAATCCCC
DNA1	CCCTTAATCCCCTATAATAAATTTTAAATATTATTTATTAAT
DNA2a	CCCTCCCTCCCC
DNA2	CCCTCCCTCCCCTATAATAAATTTTAAATATTATTTATTAAT
DNA3a	CCCCCCCCCCCC
DNA3	CCCCCCCCCCCCCTATAATAAATTTTAAATATTATTTATTAAT
DNA4a	CCCTAACTCCCC
DNA4	CCCTAACTCCCCTATAATAAATTTTAAATATTATTTATTAAT
DNA5a	CCCAACCTTCCAACCC
DNA5	CCCAACCTTCCAACCCCTATAATAAATTTTAAATATTATTTATTAAT
DNA6a	CCCTTCCTTCCAACCC
DNA6	CCCTTCCTTCCAACCC TAT AAT AAA TTT TAA ATA TTA TTT ATT AAT
DNA7a	CCCCCCCCCCCCCCCCGCCCGCC
DNA7	CCCCCCCCCCCCCCCCGCCCGCCTATAATAAATTTTAAATATTATTTATTAAT
DNA_G15	ATTAATAAATAATATTTTAAAATTTATTATAGGGTGGGGTGGGGTGGGG
DNA_A/T	ATTAATAAATAATATTTTAAAATTTATTATA
Ade_apt	ATTAATAAATAATATTTTAAAATTTATTATAACCTGGGGGAGTATTGCG GAGGAAGGT
cAde_apt	ACCTTCCTCCGCAATACTCCCCAGGTTATAATAAATTTTAAATATTATTT ATTAAT
Pb ²⁺ _apt	ATTAATAAATAATATTTTAAAATTTATTATAGGGTTAGGGTTAGGGTTAGGG

2.6. UV-vis spectroscopy

The procedure of DNA1/AgNCs preparation is the same as described above. UV-vis spectra were measured using an Agilent 8453A spectrometer. Firstly, spectrum for 100 μ l of DNA-*X*/AgNCs (*X* = 1–7) sample was measured and then 22.5 μ l of 100 μ M DNA_G15 or DNA_A/T was added and spectra measured after different times.

2.7. Aptamer binding

The procedure for AgNC synthesis was the same but a different DNA sequence was used. The aptamer activated AgNCs were diluted with buffer so that the final concentrations of DNA1 and Mg²⁺ ions were 1.25 μ M and 2 mM, respectively. Then, adenosine, thymidine or cytidine was added and the maximum intensity at 630 with 570 nm excitation was measured. The experiment was repeated three times.

3. Results and discussion

3.1. Stability of fluorescence signal

For sensing applications, it is important to have stable fluorescence signal. We recently reported that UV light bleaches DNA-templated AgNCs, which was attributed to oxidation [26]. Since hybridization with G-rich DNA appears to be a novel way of signal generation and the presence of nearby guanines might result in different properties, we herein studied their stability. AgNCs were prepared using DNA1 (see table 1 for DNA sequences) as the template, which is the published sequence and has been used by most researchers for this purpose [36]. As expected, no fluorescence was observed for this sample (figure 2(A), zero time point). After adding the G-rich DNA (DNA_G15), red fluorescence rapidly increased,

reaching ~80% of its maximal intensity in the first 15 min. The fluorescence then started to decrease after 1 h even when the sample was stored in dark, turning into faint yellow after 24 h. The fluorescence emission spectra of these samples were measured and a peak at 640 nm was observed at each time point (figure 2(B)). This peak decayed almost linearly from 1 to 6 h (figure 2(C), red dots). A second emission peak at 550 nm was also observed. At 1 h, the intensity of the 640 nm peak was more than 20-fold stronger than that of the 550 nm peak, producing red fluorescence. At 24 h, their intensities were comparable due to the growth of the 550 nm peak (figure 2(D)) and the drop of the 640 nm one (figure 2(B)), which explained the yellow fluorescence (figure 2(A)). This conversion of red to green emission has been observed by a few groups for different DNA sequences [26, 42–44], and this is attributed to oxidation of the AgNCs. The reduced AgNCs emit red light, and the oxidized AgNCs emit green. Therefore, such G-rich DNA activated AgNCs also suffer from decay of fluorescence signal, potentially because of oxidation, similar to most AgNCs that do not require this activation step. Having a G-rich DNA nearby the AgNC does not directly increase photostability.

To test whether the time-dependent fluorescence decay in figure 2(B) is related to oxidation of AgNCs, a reducing agent (NaBH₄) was added to an aged sample. Indeed, fluorescence recovery was achieved and the emission peak remained at the same position (figure 3(A)). During this aging process, the above samples were stored in dark to minimize photobleaching. Next we tested whether light exposure could accelerate fluorescence bleaching. A highly fluorescent sample after hybridization with DNA_G15 was exposed to a fluorescent tube light for 1 h, dropping the fluorescence to the background level (figure 3(B), red spectrum). Note that it takes more than 24 h to drop fluorescence to a similar value when the sample

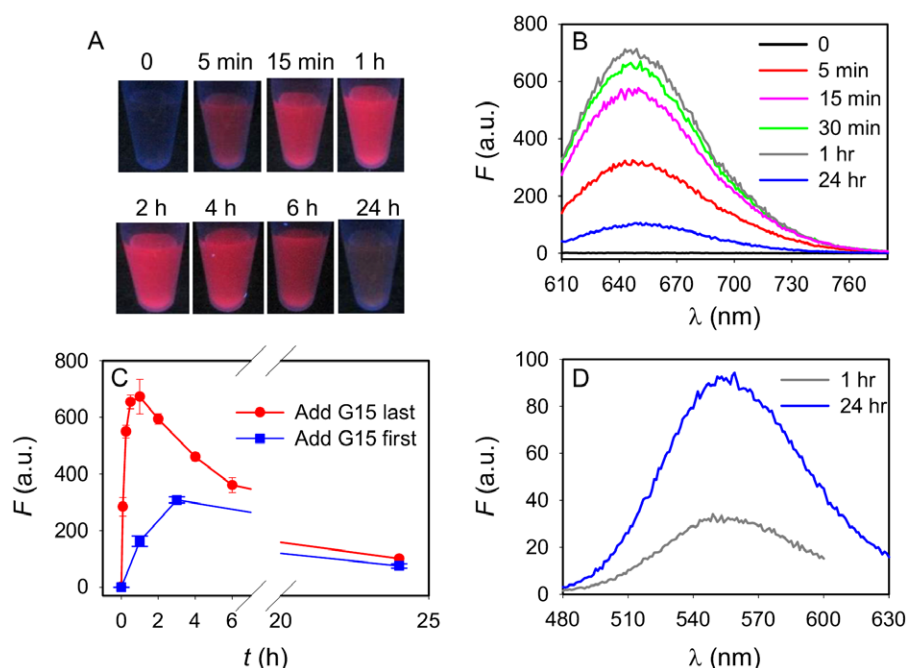


Figure 2. (A) Photographs of DNA1-templated AgNCs at various time points after adding DNA_G15. The scheme of fluorescence activation is shown in figure 1(B). The final mixture contained 15 μM DNA, 90 μM AgNO₃, 90 μM NaBH₄ and 20 mM phosphate buffer (pH 6.6). NaBH₄ was freshly prepared. (B) Fluorescence spectra of the samples in (A) by exciting at 596 nm. (C) Intensity of the 640 nm emission peak as a function of time for samples in (B) (red dots). In addition, DNA_G15 was hybridized to DNA1 before adding NaBH₄ and the fluorescence intensity was recorded after adding NaBH₄ as a function of time (blue dots). (D) Fluorescence spectra of the 1 and 24 h samples in (A) by exciting the green emitter at 458 nm.

is stored in dark. Addition of NaBH₄ to this bleached sample also recovered the fluorescence. However, the sample only reached $\sim 80\%$ of the initial intensity after recovery, which is attributed to the loss of some silver species by forming large non-fluorescent silver nanoparticles (AgNPs). There is always a competition between forming AgNCs and AgNPs. Nevertheless, similar to the normal DNA-templated AgNCs [26], samples activated by DNA_G15 can also be bleached by UV light and recovered with NaBH₄. Photobleaching needs to be considered for biosensing or imaging applications.

In the previous samples, DNA_G15 was added at the final step to activate fluorescence. Next, we hybridized DNA_G15 with DNA1 first, followed by adding AgNO₃ and NaBH₄. Similarly, red fluorescence was observed (figure 3(C)), although the intensity was not as strong as the sample with DNA_G15 added at the last step (e.g. compare the blue and red dots in figure 2(C)). The weaker fluorescence was attributed to the presence of more DNA during AgNC synthesis and thus some Ag⁺ might be associated with the activator. In addition, the template and activator may partially hybridize (one is C-rich and one is G-rich), weakening Ag⁺ binding. Therefore, it is better to form AgNCs with the template DNA alone first. For such samples, the fluorescence still decayed over time (figure 2(C)), blue line.

Such time-dependent fluorescence decay poses a challenge for analytical applications. Even though fluorescence can be recovered by adding NaBH₄, NaBH₄ is an unstable chemical and needs to be freshly prepared, making it undesirable for field applications. This problem might be partially solved

by this DNA_G15 activation reaction. To test this, we studied whether DNA1-templated AgNCs are stable before hybridizing with DNA_G15. We waited for various time after adding NaBH₄, but before DNA_G15 was added. As shown in figures 3(D) and (E), the final fluorescence intensity was very stable as long as the previous incubation step (addition of NaBH₄) was more than 5 h. No decay was observed even after 48 h. Therefore, the AgNCs are in a stable (but non-fluorescent) state before adding DNA_G15. Once activated by DNA_G15, however, the time window for operation is only a few hours. UV-vis spectroscopy results also confirmed the stability of such AgNCs over two days (figure 3(F)). This observation might partially solve the fluorescence stability problem of AgNCs, allowing assembly of sensors without using unstable NaBH₄. Although the time window of experiment is only ~ 2 h, using a DNA for activation is more convenient than using NaBH₄.

3.2. Changing the template DNA sequence

It is well-established that there is a correlation between DNA sequence and the resulting fluorescence property of AgNCs [1–6], although the underlying chemical principle remains unclear. For the current system, there are two DNA components: a template DNA for making AgNCs and an activator DNA. Different emission colors can be obtained by simply changing the overhang sequence in the activator DNA, where poly-G DNA gives red emission and poly-T DNA gives green emission [36, 45]. However, the effect of the template DNA has not been systematically explored. To study this, we changed the sequence and length of the C-rich DNA templates

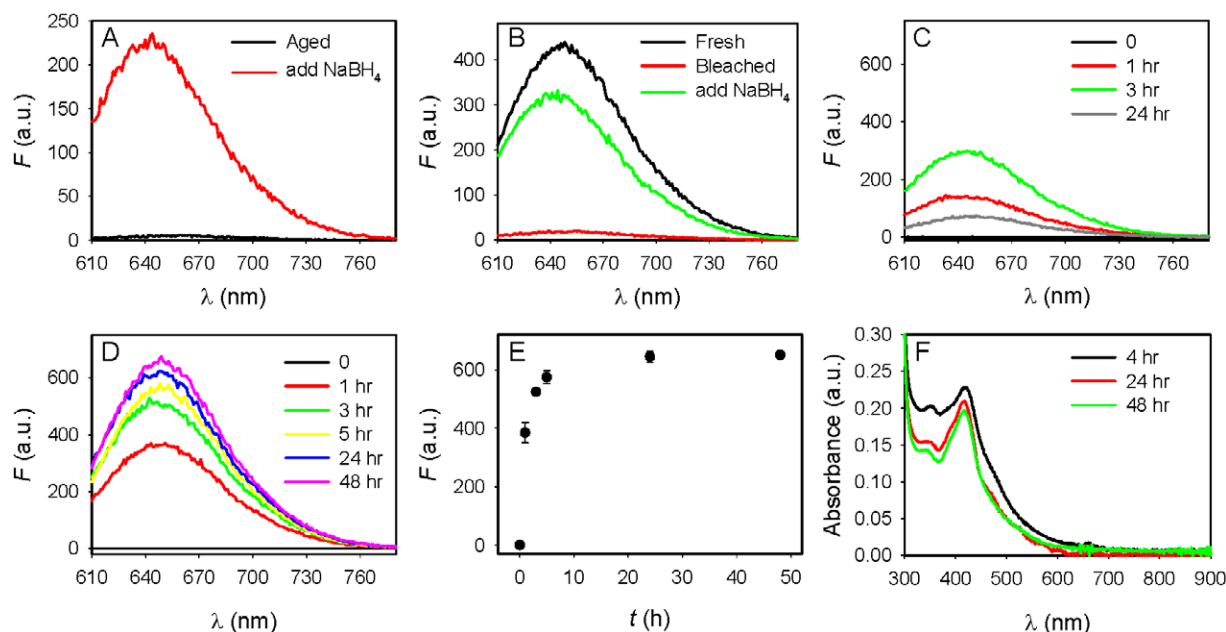


Figure 3. (A) Fluorescence spectra of DNA1-templated AgNCs after hybridizing with DNA_G15 and stored in dark for 3 days (black spectrum) and 1.5 h after adding NaBH_4 to this aged sample (red spectrum). (B) The freshly prepared AgNC spectrum (black), fluorescence after exposure to a fluorescent tube light for 1 h (red) and recovered for 3 h after adding NaBH_4 (green). (C) AgNC fluorescence spectra of samples prepared by hybridizing DNA_G15 with DNA1 first before adding NaBH_4 . Spectra were collected at different time after adding NaBH_4 . (D) Fluorescence spectra and (E) peak intensity quantification for AgNCs aged for different time after adding NaBH_4 . (F) UV-vis spectra of DNA1-templated AgNCs at different time points after adding NaBH_4 (DNA_G15 was not added).

and studied six more sequences (DNA2–7). The experiment was conducted by comparing the fluorescence of the C-rich DNA template alone without extension (DNA1a–7a), the C-rich DNA with the A/T-rich DNA extension (DNA1–7), and after hybridizing with DNA_G15. Note that DNA1a–7a have been reported previously to template AgNCs with different emission properties [1, 46]. For each sequence, the emission spectrum was measured at the excitation maximum in the visible region (figure 4). Both the fluorescence spectra and the photographs under UV excitation are presented.

A few interesting observations were observed. (1) By comparing the first two tubes in each panel, the AgNC fluorescence is often reduced when the DNA contains the A/T tail. Therefore, the A/T tail might have fluorescence quenching property or have affected the formation of AgNCs. (2) By comparing the last two tubes, a large increase in fluorescence intensity is often observed, and sometimes even a change in emission color, suggesting this poly-G activated fluorescence works for many DNA sequences. (3) DNA1–4 contained 12-mer C-rich DNA and they all produced red emitters. DNA1 has thus far been the best candidate for signaling since it has high fluorescence enhancement and also strong final fluorescence. DNA4 also has large enhancement but the final fluorescence is ~ 3 -fold lower than that from DNA1. DNA2 and DNA3 are poor choices since the background fluorescence before adding DNA_G15 is quite high. On the other hand, the three longer C-rich DNA (DNA5–7) all produced emission color changes. This is due to the presence of dual emitters either before or after hybridizing with DNA_G15 (or both), which can be observed from the different emission spectra. In figures 4(E)–(G), the spectra in the same color are from AgNCs

templated by the same DNA but with different excitation wavelengths.

We previously studied DNA7, which produces both green and red emitters [26, 46]. The switching from red to green emission normally takes a day in dark and is related to an oxidation reaction. When DNA_G15 was used, this conversion occurred within 1 h in dark. This suggests that DNA_G15 has facilitated oxidation of the red emitter and accelerated the conversion to green emission.

3.3. UV-vis spectroscopy

To further understand G-rich DNA activated fluorescence, UV-vis spectroscopy was used to follow the samples after adding DNA_G15. In figure 5(A), DNA1-templated AgNCs initially absorbed at ~ 420 nm. While this is close to the surface plasmon band of AgNPs, the surface plasmon peak is usually much sharper. Therefore, at least a fraction of it should be from AgNCs. A new peak grew at 575 nm after adding DNA_G15, accompanying a decrease in the 420 nm peak. Such an absorption peak shift indicates the formation of new AgNC species and it occurred at a timescale comparable to its fluorescence signal generation (figure 5(B)). Therefore, DNA_G15 DNA is likely to cause re-organization of AgNCs in such a way that the new AgNCs have stronger fluorescence. In other words, the activation step is not a simple providing of a G-rich environment but is related to the formation of new emitters. As a control experiment, if we use only the A/T rich DNA without the G-rich part (DNA_A/T in table 1), no such shift was observed (figure 5(C)). In addition, this UV-vis spectral shifting is general and occurs with all the tested DNAs. Another example of such is presented in figure 5(D) for DNA7.

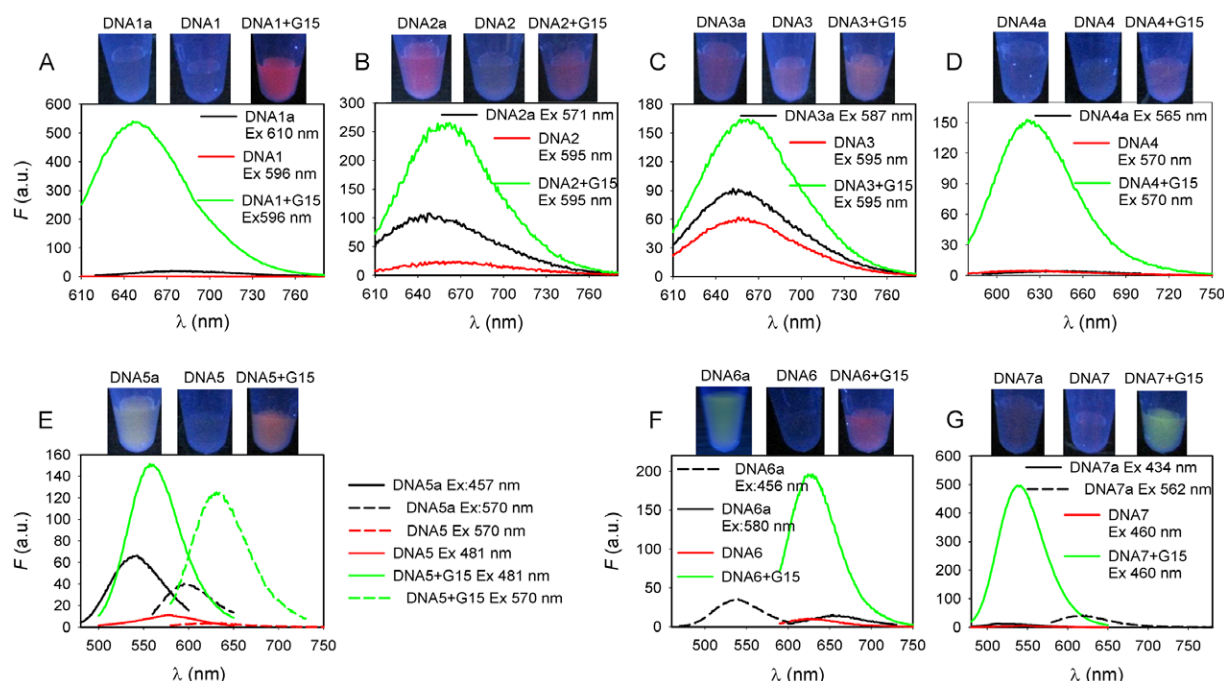


Figure 4. (A)–(G). Fluorescence spectra and photographs of the DNA1a–7a, DNA1–7 and after hybridizing DNA_G15 with DNA1–7. For ((E)–(G)), some samples showed dual emission peaks, which are denoted by spectra of the same color but with either continuous or dashed lines. The conditions are the same as that described in figure 2.

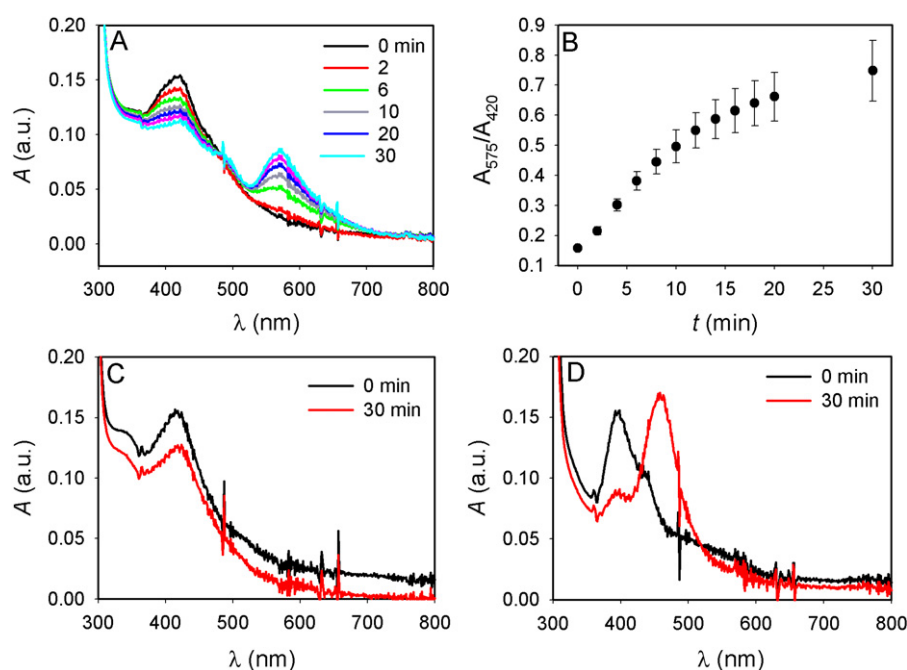


Figure 5. (A) Time-dependent UV-vis spectra of DNA1-templated AgNCs after adding DNA_G15. (B) Kinetic of the change of the peak ratio for the spectra in (A). (C) Spectra collected after adding DNA_A/T lacking the G-rich sequence. (D) Spectra collected using DNA7 and after adding DNA_G15. The samples were measured directly after synthesis without dilution.

3.4. Removal of the activator

An interesting and unresolved question is whether fluorescence is again quenched if the G-rich activator DNA is removed after the activation step. To investigate this, we employed structure switching aptamers (figure 1(C)). Many aptamers are rich

in guanine and may also serve as an activator. Indeed, both the Pb^{2+} aptamer (figure 6(A)) and the adenosine aptamer (figure 6(B)) produced strong fluorescence enhancement. The enhancement with the adenosine aptamer was compared to that with DNA_G15 (figure 6(C)), while the Pb^{2+} aptamer only achieved ~ 50 -fold enhancement. It is interesting to

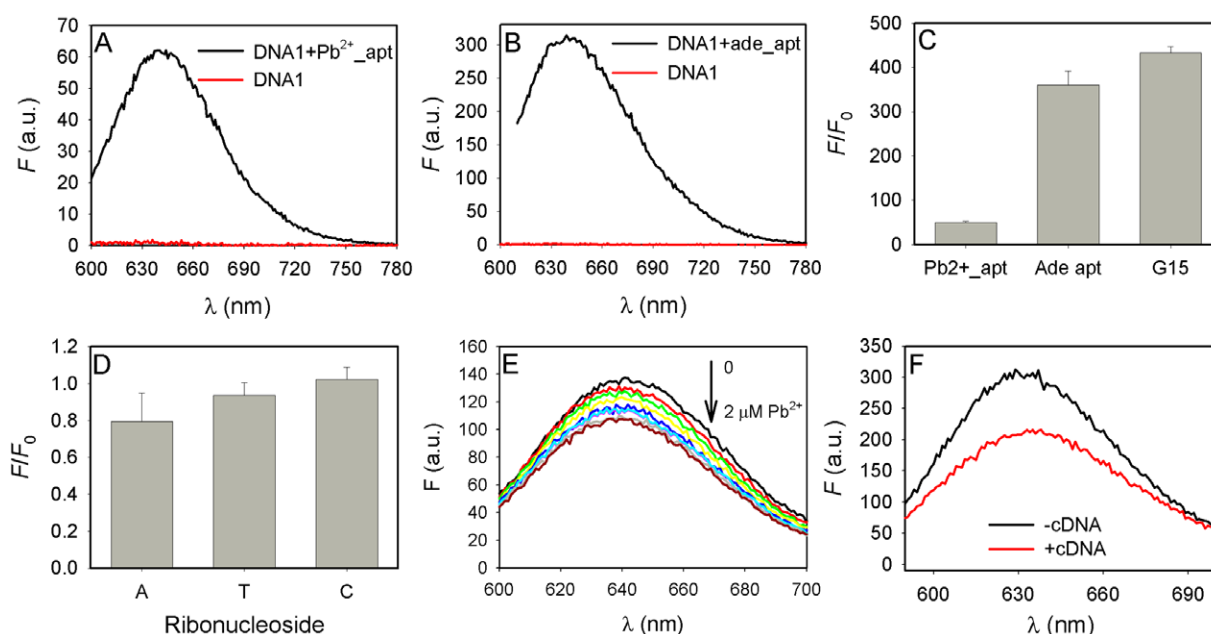


Figure 6. Fluorescence spectra of AgNCs templated by DNA1 and after hybridizing with DNA containing a Pb²⁺ aptamer overhang (A) or an adenosine aptamer overhang (B). (C) Fluorescence enhancement after hybridizing DNA1 with various G-rich DNA. (D) Decrease of AgNC fluorescence upon addition of 1 mM of adenosine, thymidine or cytidine. The buffer also contained 2 mM Mg²⁺. (E) Titrating Pb²⁺ to the Pb²⁺ aptamer sample. (F) Change of fluorescence after adding the cDNA of the adenosine aptamer to remove it from the AgNC. The cDNA concentration (2.5 μ M) was twice of that for the adenosine aptamer to ensure complete removal.

note that the number of guanine bases in DNA_G15 (15 guanines), adenosine aptamer (13 guanines) and Pb²⁺ aptamer (12 guanines) is quite similar. However, the enhancement with the Pb²⁺ aptamer was significantly lower, indicating that the distribution of the guanine bases in the DNA is also important. Aptamers that are not rich in guanine do not enhance the fluorescence (figure S1 available at stacks.iop.org/Nano/25/155501/mmedia).

It is well-established that the aptamer folds when adenosine is added as shown in figure 1(C) [47, 48]. However, with 1 mM adenosine, the fluorescence quenching was just ~20% (figure 6(D)), although control experiment with cytidine and thymidine showed slightly less fluorescence quenching. This suggests that the influence of aptamer binding to its target on fluorescence is quite moderate. Similarly, we observed very little fluorescence change when Pb²⁺ was added to the Pb²⁺ aptamer sample (figure 6(E)), where Pb²⁺ is known to fold the DNA into a G-quadruplex. To further confirm it, we added the cDNA of the adenosine aptamer (cAde-apt) to completely remove it from the AgNC and the fluorescence drop was still only ~30% (figure 6(F)). Therefore, once activated, removal of the G-rich DNA has minimal effect on the fluorescence. In other words, the activated AgNCs do not need the G-rich DNA environment to maintain its fluorescence. Since guanine is easily oxidized, the G-rich overhang may serve as a reducing agent to reduce the nearby AgNCs [36]. After the reaction, the G-rich DNA is no longer needed.

4. Conclusions

In summary, we have performed a comprehensive study on G-rich DNA activated AgNCs in terms of fluorescence

stability, fluorescence generation kinetics, effect of DNA sequence, photobleaching and recovery of fluorescence. Using G-rich DNA to activate AgNC fluorescence might partially solve the photostability problem of AgNCs since fluorescence activation can be achieved using the stable G-rich DNA alone without the need of unstable NaBH₄; NaBH₄ is needed only in the initial synthesis step. We demonstrated that the emission color can be controlled by tuning the C-rich DNA template, which complements to the previous report using different overhang sequences to achieve the same goal [45]. In addition, UV-vis spectroscopy suggested a change in the structure of AgNCs after adding the G-rich DNA. Many aptamer sequences are rich in guanine; we showed that these aptamers can also be used for fluorescence activation. After the activation step, the G-rich DNA is no longer needed for maintaining the fluorescence. It is quite likely that the AgNCs we produced are a mixture of various species. Ideally, single species are more valuable for mechanistic studies. This might be achieved by purifying with HPLC, but that requires that the DNA/AgNC complex to be stable and does not dissociate when free Ag⁺ is removed. Follow up work to improve stability of AgNCs is a future direction to be investigated.

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