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A G-octamer scaffold *via* self-assembly of a guanosine-based Au(I) isonitrile complex for Au(I)–Au(I) interaction†

Xiangtai Meng,[a] Toshiyuki Moriuchi,*[a] Masatoshi Kawahata,[b] Kentaro Yamaguchi[b] and Toshikazu Hirao*[a]

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A guanosine-based Au(I) isonitrile complex was demonstrated to serve as the reliable scaffold *via* self-assembly, wherein the quartet and octamer were formed in the absence and presence of a potassium ion, respectively, exhibiting a switchable emission based on Au(I)–Au(I) interaction.

Recently, the research field of bioorganometallic chemistry, which is a hybrid area between organometallic chemistry and biochemistry, has drawn much attention.[1] Conjugation of organometallic compounds with biomolecules such as nucleobases, amino acids, and peptides is envisioned to provide novel systems depending on both properties.[1,2] Highly-ordered molecular assemblies are constructed in bio-systems to fulfill unique functions as observed in enzymes and receptors. Introduction of functional complexes into highly-ordered biomolecules is considered to be a convenient approach to the corresponding biomaterials and bio-inspired systems. Guanosine (G) and its derivatives have a high potential for self-assembly (Fig. 1).[3] These properties have been investigated in detail with the goal to synthesize new guanosine derivatives and to explore their electronic and optical properties. Moreover, functionalization of the guanosines at the C8 position or the sugar hydroxyl groups is allowed to construct functionalized assemblies in the presence of a cation. From this point of view, a variety of guanosine derivatives have been reported with porphyrin-G, pyrene-G, oligothiophene-G, and OPV-G.[4] On the other hand, the supramolecular architecture in gold(I) chemistry has attracted increasing attention, in particular with regard to the phenomenon of aurophilicity.[5] A number of di-, tri-, and polynuclear gold(I) complexes are known to exhibit specific luminescence properties based on Au(I)–Au(I) interaction.[6] Although numerous functionalized guanosine derivatives were developed, to the best of our knowledge, the utilization of self-assembly properties of guanosine derivatives to study the Au(I)–Au(I) interaction has not been reported so far. Herein, we report an Au(I) complex **1** possessing the guanosine moiety.

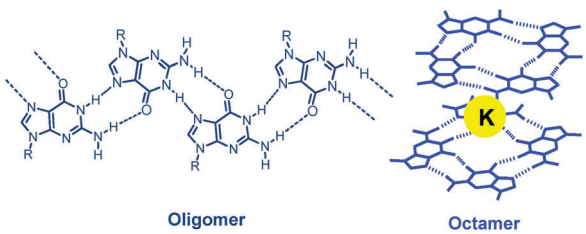
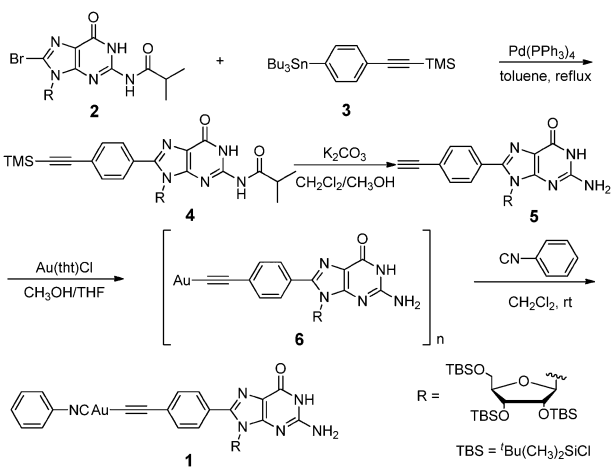


Fig. 1 Assembly types of guanosine derivatives.

The Au(I) complex **1** was obtained in a four-step synthesis from 8-bromoguanosine (Scheme 1). The Stille cross-coupling reaction of the 8-bromoguanosine **2** with the tin compound **3** afforded the protected guanosine **4**,[7] followed by deprotection with K_2CO_3 to give the 8-ethynylguanosine **5**.[8] Reaction of **5** with Au(tht)Cl (tht = tetrahydrothiophene) in the presence of NaOAc resulted in the neutral oligomer **6** as an orange solid in a high yield.[9] Upon addition of phenyl isocyanide to the CH_2Cl_2 suspension of **6**, the neutral Au(I) compound **1** was obtained. All new compounds were fully characterized by ^1H, ^{13}C NMR, IR, and HRMS techniques (see ESI†). A strong band due to $\nu(N\equiv C)$ was observed at 2209 cm^{-1} in the IR spectrum of **1**.



Scheme 1 Synthesis of **1**.

[a] *Department of Applied Chemistry, Graduate School of Engineering, Osaka University, Yamada-oka, Suita, Osaka 565-0871, Japan. E-mail: moriuchi@chem.eng.osaka-u.ac.jp,, hirao@chem.eng.osaka-u.ac.jp; Fax: +81-6-6879-7415; Tel: +81-6-6879-7413*
[b] *Pharmaceutical Sciences at Kagawa Campus Tokushima Bunri University, 1314-1 Shido, Sanuki, Kagawa 769-2193, Japan. E-mail: yamaguchi@kph.bunri-u.ac.jp; Fax: +81-87-894-0181; Tel: +81-87-894-511*

† Electronic supplementary information (ESI) available: Experimental procedures and characterization data for all new compounds, and excitation spectra of **1**. See DOI: 10.1039/c1cc10774g

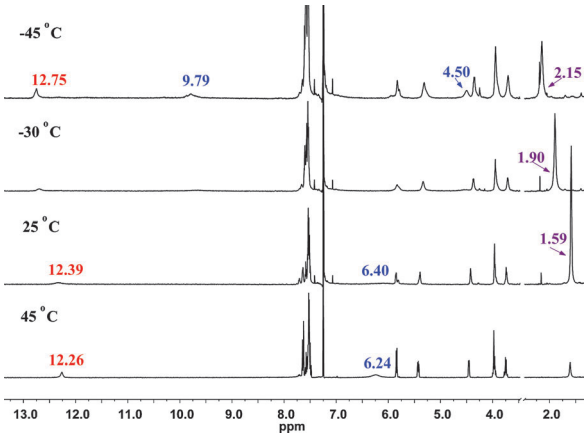


Fig. 2 ^{1}H NMR (600 MHz) spectra of **1** at various temperatures in the absence of KPF_6 in $CDCl_3$.

The Au(I) complex **1** is quite soluble in CH_2Cl_2, $CHCl_3$, THF and others. The ^{1}H NMR spectrum of **1** measured in $CDCl_3$ showed the equivalent amino protons (NH_2) as a broad singlet at 6.40 ppm while the amide proton (NH) resonates at 12.39 ppm at 25 °C (Fig. 2). These chemical shifts indicate that **1** self-associates in a mixture of oligomeric species in the absence of an alkaline cation. Warming the temperature to 45 °C, both the amino and amide protons upfield shifted and became slightly sharper. In contrast, lowering the temperature to −45 °C, the amino protons are split into two signals. The downfield-shifted signal at 9.79 ppm is assigned to the hydrogen-bonded proton and another signal around 4.50 ppm belongs to the 'free' amino proton. At the same time, the amide proton signal is downfield shifted to 12.75 ppm. These findings suggest that an empty G-quartet is formed even without the assistance of a cation template at the lower temperature.[7,10] Interestingly, the water signal downfield shifted from 1.59 ppm to 2.15 ppm during lowering the temperature. This shift suggests that water molecules are involved in stabilizing the empty G-quartet.[4e]

By adding 0.125 eq. of KPF_6 to a $CDCl_3$ solution of **1**, the ^{1}H NMR spectrum changed. As shown in Fig. 3, the amino proton signal disappeared and the amide proton signal became sharper at 25 °C. Lowering the temperature to −30 °C, the amide proton signal became rather sharp and a new signal appeared at about 10.12 ppm. The latter is considered to be attributable to the hydrogen-bonded amino protons. Moreover, only one set of signals appears in the ^{1}H NMR spectrum. With reference to previous studies on the assembly properties of guanosine derivatives,[11] a D_4-octamer (all of the sugar moieties of guanosine are *syn*) appeared to be formed.[12] The amino and amide signals are broad at 25 °C, but become sharper at low temperatures probably because the octamer structure becomes more rigid. Furthermore, at a low temperature, the chemical shifts of the hydrogen-bonded amide (12.75 and 12.32 ppm) and amino (9.79 and 10.12 ppm) proton signals are different in the absence and presence of a potassium ion, respectively, indicating that the two aggregates are different: one is an 'empty' quartet and another is a cation assisted octamer.

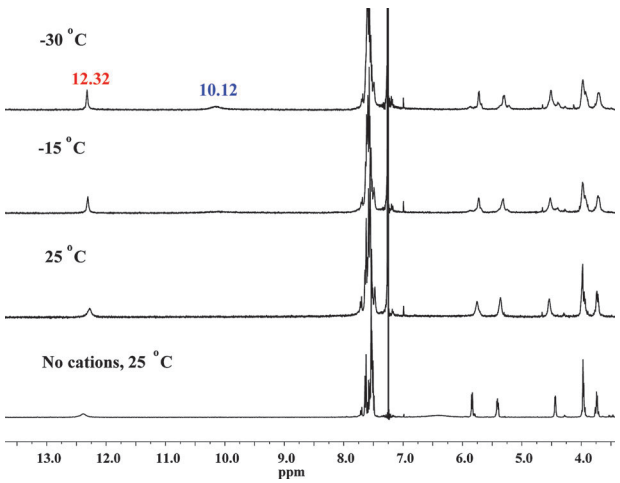


Fig. 3 ^{1}H NMR (400 MHz) spectra of **1** at various temperatures in the presence of KPF_6 (0.125 eq.) in $CDCl_3$.

Circular dichroism (CD) spectroscopy provides insight into the chirality of this assembly in solution.[13] As shown in Fig. 4, the CD spectrum of **1** in $CHCl_3$ in the absence of KPF_6 at 25 °C showed a random coil conformation due to the formation of the oligomeric species. In sharp contrast, in the presence of 0.125 eq. of KPF_6, a significant change was shown in the CD spectrum: a positive band at 262 nm and a very strong positive band at 334 nm were observed, being accompanied by a negative band centered at 288 nm and a very strong negative band at 228 nm. Although no detailed information on the electronic transitions is available so far for this Au(I) complex, this difference indicates a change in the conformation and/or secondary structure of **1** after addition of KPF_6. This finding might closely resemble those reported for other unmodified lipophilic guanosines.[3a,b]

In the electronic spectrum of **1** in $CHCl_3$ shown in Fig. 5, a high-energy band at 250–300 nm and a more intense low-energy absorption band at 320–340 nm were observed. Upon addition of KPF_6, a drop in intensity was observed with the absorption band at about 330 nm, together with the concomitant growth of a new low-energy shoulder in the region of approximately 380–430 nm. These observations indicate that the self-associate of the guanosine **1** and aurophilicity is likely to bring the gold atoms into close proximity, in which Au(I)–Au(I) interaction is allowed to be present.

Since Au(I) compounds are known to show rich luminescence properties, the luminescence response of **1** towards KPF_6 was investigated. In the absence of the potassium ion, **1** exhibited an intense emission band around 400–600 nm (Fig. 6a, λ_{ex} = 380 nm). Upon addition of KPF_6 to a $CHCl_3$ solution of **1**, a new low-energy emission band at *ca.* 510 nm appeared (Fig. 6b, λ_{ex} = 440 nm). The excitation spectra of **1**

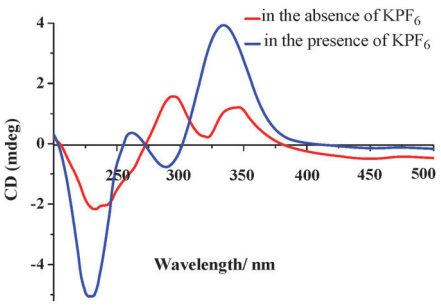


Fig. 4 CD spectra of **1** in the absence (red line) and presence (blue line) of KPF_6 (0.125 eq.) in $CHCl_3$.

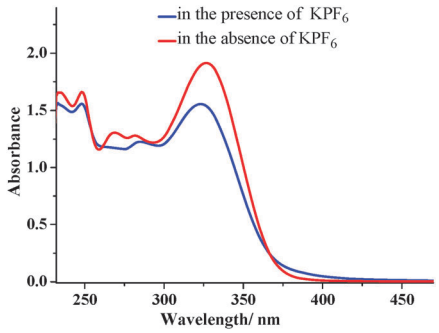


Fig. 5 UV-vis spectra of **1** in the absence (red line) and presence (blue line) of KPF_6 (0.125 eq.) in $CHCl_3$.

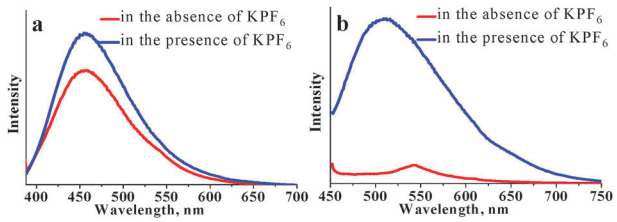


Fig. 6 Emission spectra of **1** in the absence (red line) and presence (blue line) of KPF_6 (0.125 eq.) in $CHCl_3$ ((a) λ_{ex} = 380 nm; (b) λ_{ex} = 440 nm).

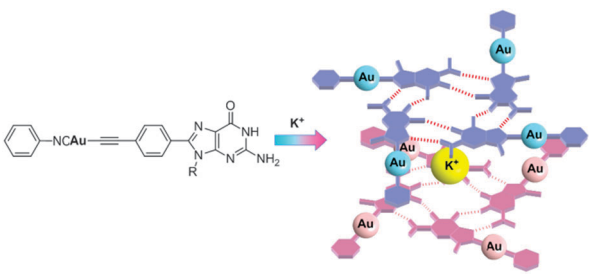


Fig. 7 A possible diagram showing the formation of Au(I)–Au(I) interaction upon addition of KPF_6.

in the presence and in the absence of KPF_6 revealed that the low-energy and the high-energy bands are derived from different excited state origins (Fig. S1, ESI†). The excitation spectrum showed a weak low-energy shoulder at 440 nm in the presence of KPF_6 (Fig. S1, ESI†), which coincides with the new absorption band at about 400–450 nm in the UV-vis spectrum resulting from the Au(I)–Au(I) interaction. Upon addition of KPF_6, the sandwich-like octamer was formed, thereby bringing the two quartets containing Au(I) centers into close proximity (Fig. 7). On the basis of related literature, the distance between the two quartets might be about 3.3 Å,[3] which is suitable for the overlap of the orbital on each Au(I) atom. Therefore, the low energy emission band at 510 nm is considered to be attributed to the Au(I)–Au(I) interaction.[6]

In conclusion, a bioorganometallic Au(I) complex possessing the guanosine moiety was designed and synthesized. The designed guanosine-based Au(I) isonitrile complex was demonstrated to form the quartet and octamer in the absence and presence of a potassium ion, respectively, exhibiting a switchable emission based on Au(I)–Au(I) interaction, wherein the G-octamer *via* self-assembly serves as a reliable scaffold for the arrangement of the Au(I) isonitrile moieties. Studies on the application of the G-octamer induced metal ion aggregates including functional materials and catalysts are now in progress.

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