

# Silver cation-mediated dual-emissive Au–Ag bimetallic nanoclusters for pH ratiometric sensing

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**Abstract:** Metal nanoclusters (NCs) with intrinsic dual-emission are not only significant for fundamental research but also for accurate ratiometric sensing and imaging. Using 1-dodecanethiol (DT) as protected-cum-reduced ligand, the core-shell structured Au-Ag bimetallic NCs with well-resolved dual-emission bands centered at 440 nm and at 630 nm were successfully synthesized by a facile one-pot approach. A combined characterizations of X-ray photoelectron spectroscopy (XPS), transmission electron microscope (TEM) and optical spectrum revealed that the Au-Ag bimetallic NCs had a core-shell structure with a metallic Au(0) core coated by a shell of Au(I)- and Ag(I)-thiolate motifs. Very interestingly, the dual-emissive Au-Ag NCs exhibited unique ratiometric pH-dependent emissions, which could be used as an ideal pH ratiometric nanosensors. Most importantly, our observed Ag<sup>+</sup> mediated pH-dependent dual-emissive behavior suggests that the metal NCs core is not real emitter center, while structural water molecules (SWs) confined at the nanoscale interface of metal core are true luminous centers, which answers that the optical properties of metal NCs are very sensitive to the delicate change of surrounding microenvironment of metal NCs, including the dosing of Ag<sup>+</sup>, pH and packing mode of surface ligands. Our discovery not only opens up new possibilities for the design of ultra-small ratiometric pH nanoindicators, but also provides new insights on the origin of photoluminescent (PL) emission of metal NCs.

## Introduction

Quantum sized metal nanoclusters, that bridging the gap between organometallics and nanocrystals, exhibit dramatically unique electronic and optical properties, such as molecule-like energy gaps<sup>[1-8]</sup>, intense photoluminescence<sup>[9-13]</sup> and catalytic properties<sup>[14-20]</sup>. Luminescent thiolated-protected Au and Ag NCs in particular have attracted tremendous interest due to their wide applications in bio-imaging, bio-medicine, sensing and catalysis, etc<sup>[21-29]</sup>. Various strategies, such as heteroatom doping<sup>[30]</sup>, aggregation-induced-emission (AIE)<sup>[12]</sup>, assembly induced emission enhancement<sup>[31]</sup>, *etc.* have been developed to prepare highly luminescent Au and Ag NCs. Since the crystal structure of ligand-protected Au NCs, which usually comprised by metallic core and peripheral gold(I)-thiolate staple motifs, have been revealed at atomic resolution<sup>[32]</sup>, heteroatom substitution of specific native sites could give an in-depth sight to understand the structure/composition-correlated properties and provided an efficient way to diversify and tailor

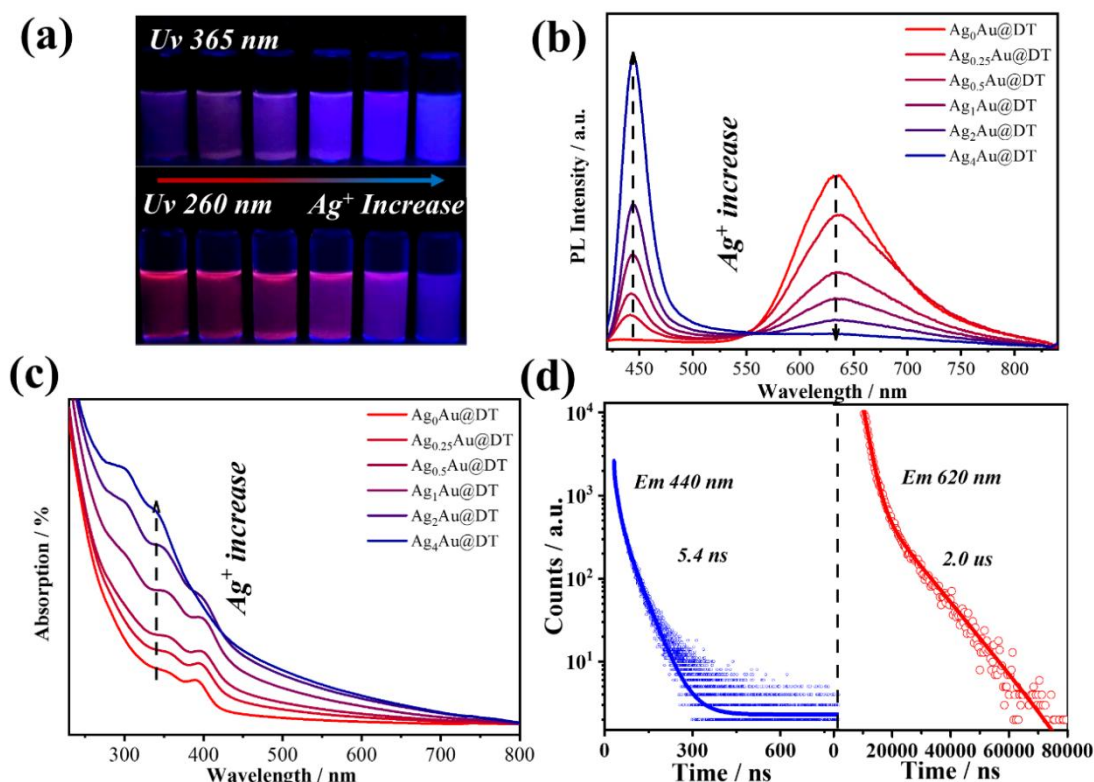
the physicochemical properties of metal NCs<sup>[33, 34]</sup>. Several strategies have been developed to the synthesis of bimetallic Ag-Au NCs, such as one-pot co-reduction method<sup>[35-37]</sup> (spontaneous reduction of as-mixed Ag and Au precursors through balancing the redox potentials of metal pairs by thiol ligand<sup>[38, 39]</sup>), classical galvanic replacement reaction approach<sup>[40]</sup> (involves the spontaneous reduction of a noble-metal cationic by a less noble metal in solution driven by the difference in redox potentials), abnormal anti-galvanic replacement reaction approach<sup>[41, 42]</sup> (inverse process for galvanic replacement reaction recently observed for the synthesis of thiolate-protected Ag-Au NCs) and addition reaction<sup>[43-45]</sup> (a hydride-mediated controlled growth process), etc. And intriguingly, as-formed heteroatom doped metal NCs generally exhibited dramatically enhancement of luminescent and catalytic performance<sup>[30, 46-52]</sup>, which are expected to have synergistic effects in their physicochemical properties compared with their mono-metallic analogues<sup>[53]</sup>. Nevertheless, the origin of PL or the nature of emitter of heteroatom doped metal NCs remain unclear and even controversial, which limits the rational design of metal nanoclusters with improved and tailored optical and catalytic properties.

Luminescent metal NCs with dual-wavelength emission have been exploited as ratiometric nanoprobe for sensing and imaging<sup>[54]</sup>, rather than absolute intensity-dependent signal readout of single-emissive metal NCs, ratiometric measurements provide built-in self-calibration for signal correction, enabling more sensitive and reliable detection, which imposed the metal NCs possess two target-responsive reversible signal changes or one of the signal is target-insensitive as reference<sup>[55, 56]</sup>. However, in most cases, well-resolved dual-wavelength emission of metal NCs was rarely observed simultaneously. Herein, we demonstrated that, using 1-dodecanethiol (DT) as a protected ligand, Au-Ag bimetallic NCs can be readily synthesized by a facile one-pot approach, exhibiting an interesting silver cation-mediated dual-emission behavior at 440 nm and 630 nm. Very interestingly, the dual-emissive Au-Ag bimetallic NCs display a unique reversible environment-pH-responsive emission behavior, which makes them ideal as potential pH ratiometric sensors: at acid conditions, the long-wavelength emission at 630 nm is dominated, while at basic conditions, the short-wavelength emission at 440 nm is prevailed. The combined characterizations of absorption, excitation and emission spectrum evidenced that the dual-emissions come from the same luminous center, *i.e.*, structural water molecules (SWs) dynamically confined on the metal NCs core, but with varied binding strength with surface Au(I)- and Ag(I)-thiolate motif, corresponding to the emission at 630 nm and 440 nm, respectively. The assignment of SWs as emitters is consistent our previously reported results,<sup>[57, 58]</sup> which also answers that the efficiency of dual-emissions is very sensitive to the delicate change of surrounding microenvironment of metal NCs, including the dosing of Ag<sup>+</sup>, pH and packing mode of surface ligands since the surface states formed by space overlapping of p orbitals of O atoms in the SWs {H<sub>2</sub>O·OH<sup>-</sup>} as dynamic feature with  $\pi$  bonding nature.

## Results and discussion

The synthesis protocol of Au-Ag@DT NCs using DT as protected-cum-reduced ligand was modified from the previously reported method<sup>[49]</sup>. Ag(I)-complexes was firstly formed by mixing DT alcoholic solution and AgNO<sub>3</sub> under vigorous stirring for 10 min. HAuCl<sub>4</sub> solution was then added into the mixed solution and the mixtures were further stirred 12 h and incubated overnight at room temperature, the obtained samples denoted as Ag<sub>x</sub>Au@DT NCs, which the x represented the feeding ratio of Ag to Au (synthesis details in the ESI). The incorporation of silver and gold to form Ag<sub>x</sub>Au@DT NCs was evidenced through the thermogravimetric analysis

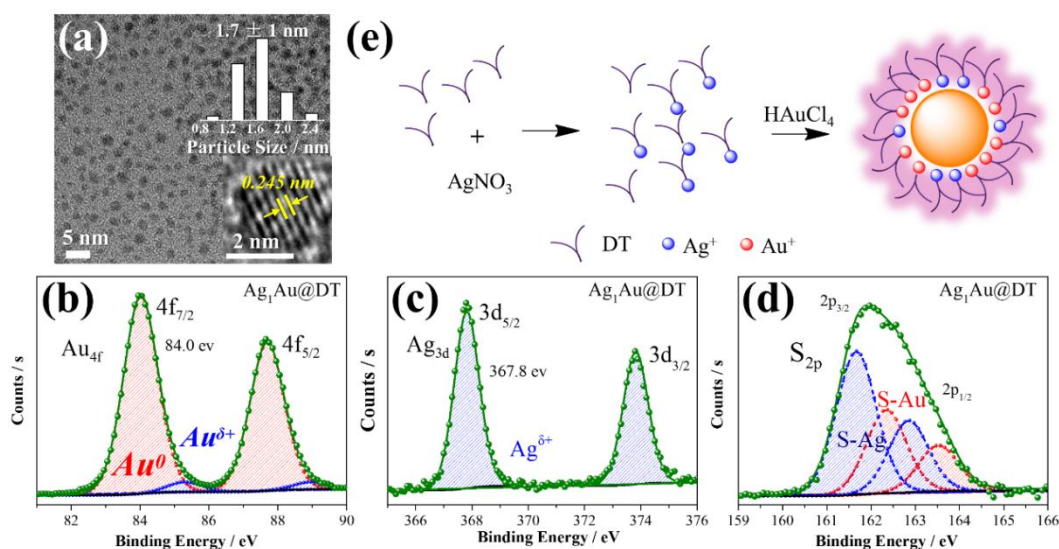
(TGA) and inductively coupled plasma (ICP) atomic emission spectroscopy (Fig. S1 and Tab. S1), with increasing the feeding ratio of Ag-Au from 0.25, 0.5, 1, 2 and 4, the actual ratio of Ag to Au in the obtained NCs analyzed through ICP was determined as 0.11, 0.23, 0.47, 1.02 and 1.25, respectively, and the ligand weight loss (Fig. S1) was also gradually increased from 47.57% to 61.80%, stoichiometric formula of obtained  $\text{Ag}_x\text{Au}@DT$  NCs can be estimated as  $\text{Ag}_{0.11}\text{Au}@DT$ ,  $\text{Ag}_{0.23}\text{Au}@DT$ ,  $\text{Ag}_{0.47}\text{Au}@DT$ ,  $\text{Ag}_{1.02}\text{Au}@DT$  and  $\text{Ag}_{1.25}\text{Au}@DT$  respectively (Tab. S1), As show in Fig. 1a and b, with increasing the feeding ratio of Ag to Au, a new narrow blue emission band centered at 440 nm of  $\text{Ag}_x\text{Au}@DT$  NCs was generated and then boosted, and the inherent red emission band centered at 630 nm of Au NCs was concomitantly declined, showing a relation of ‘as one falls, another rises’ (Fig. 1b). In a range of Ag/Au molar ratio from 0.25 to 2.0, because of the color mixing of dual-emissions, the as-synthesized Au-Ag bimetallic NCs exhibited the bright purple photoluminescence under UV irradiation of both 260 nm and 365 nm (Fig. 1a). However, if further  $\text{Ag}^+$  doping with Ag/Au molar ratio of 4.0, the single emission at 630 nm of monometallic Au NCs was almost completely disappeared, only a sharp and strong emission band center at 440 nm was observed for  $\text{Ag}_4\text{Au}@DT$  NCs (Fig. 1b). Time-resolved PL spectroscopy showed that the radiation decay of blue and red emission channels had distinguished lifetimes of 5.4 nanoseconds (ns) and 2.0 microseconds ( $\mu\text{s}$ ), respectively (Fig. 1d). It is importantly noted that, if according to conventional quantum size confinement mechanics of metal NCs, the inherent long-wavelength emission at 630 nm from Au core could not be disappeared since the Au NCs core remains intact with the increase of  $\text{Ag}^+$  loading (Fig. S2), suggesting the irrationality of Au NCs as emitters.



**Figure 1.** (a) Luminescent photographs of  $\text{Ag}_x\text{Au}@DT$  NCs under UV 365 nm (top) and 260 nm (bottom) irradiations. Photoluminescence emission spectra (b) and absorption spectra (c) of  $\text{Ag}_x\text{Au}@DT$  NCs. (d) Time-resolved luminescence decay profiles of  $\text{Ag}_1\text{Au}@DT$  NCs measured at 440 nm (left panel) and 630 nm (right panel), respectively.

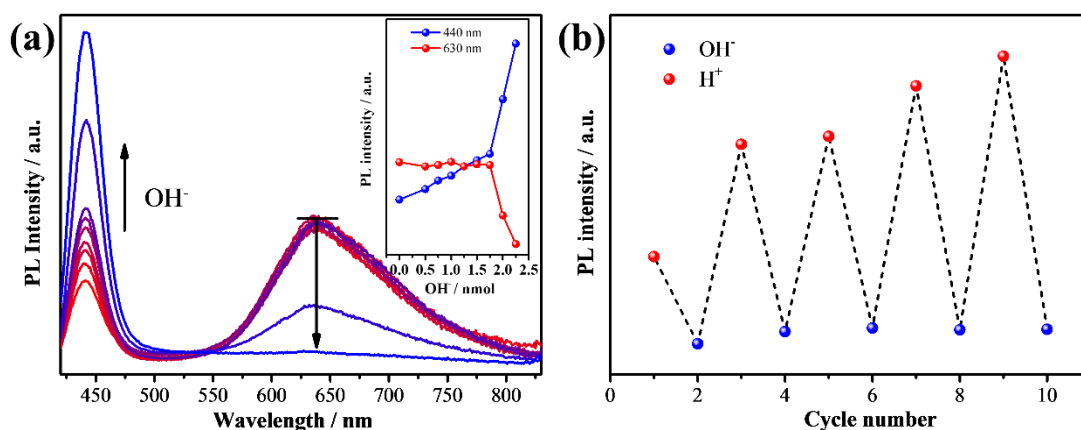
The UV-visible absorption spectrum of  $\text{Au}_x\text{Ag}@DT$  was collected in Fig 1c. Without the doping of silver, the Au NCs showed three remarkable absorption peaks located at 285 nm, 350 nm and 390 nm, respectively, which has been previously assigned to Au 6sp intraband and interband transitions of Au NCs with 10~12 atoms<sup>[3]</sup>. The absence of localized surface plasmon resonance bands at 420 nm in the absorption spectrum implies that the particle size of Au-Ag bimetal is in the range of metal nanoclusters, consistent with the results of TEM (Fig. 2a and Fig. S2). Interestingly, with the increasing feeding ratio of Ag to Au, the intensity of absorption bands at 350 and 390 nm is not changed, while the absorption at 285 nm is gradually intensified. Thus we assigned the absorptions at 350 nm and 390 nm to the Au 6sp intraband and interband transitions of Au NCs without the size change of Au NCs core, while the intensified adsorption at 285 nm is attributed to the ligand (thiol) to metal ( $\text{Au}^+$  or  $\text{Ag}^+$ ) charge transfer (LMCT), consistent with an ascending trend of molar ratio of DT/Ag in Au-Ag bimetal NCs (Fig. S1 and Tab. S2) with more dosing of  $\text{Ag}^+$ . Thus, we supposed that the Au-Ag bimetal NCs had a core-shell structure with Au NCs core coated by Au- and / or Ag-thiolate motifs. But, we cannot confirm the valence charge states of metals.

High-resolution transmission electron microscopy (HRTEM) and X-ray photoelectron spectra (XPS) characterizations supported this hypothesis. HRTEM images (Fig. 2a) corroborated the size of as-formed  $\text{Ag}_1\text{Au}@DT$  NCs of *ca.* 1.7 nm and no variation with the doping of silver (Fig. S2). The measured inter-planar distance from fringes in HRTEM images (0.24 nm, Fig. 2a insert) corresponds to the (111) plane of the cubic phase structure of Au (JCPDS ID 04-0784). The XPS was used to analyze the valence charge state of metal and composition of Au-Ag bimetal NCs (Fig. 2 b-d). As shown in the Ag 3d spectra (Fig. 2b), the oxidation state of silver was all Ag(I) components with binding energy of 367.8 eV, suggesting the single Ag(I)-thiolate species in the  $\text{Ag}_1\text{Au}@DT$  NCs<sup>[46]</sup>, and the Au 4f spectra (Fig 2c) were deconvoluted into Au(I) and Au(0) components with binding energies of 84.0 and 85.2 eV, respectively, and the content of Au(I) determined as such only account small fraction (~5%) of all Au atoms in the  $\text{Ag}_1\text{Au}@DT$  NCs. As reference to conventional Au-thiolate NCs<sup>[12, 59]</sup>, this value is significantly lower and is the consequence of the substitution of Au(I)-thiolate staple motifs by incoming Ag(I)-thiolate.



**Figure 2.** (a) Scheme for the synthesis process of  $\text{Ag}_1\text{Au}@DT$  NCs. TEM (b) and XPS spectrum of Au 4f (c), Ag 3d (d) and S 2p (e) for  $\text{Ag}_1\text{Au}@DT$  NCs.

More prominent results were demonstrated by the deconvolution of S 2p spectra (Fig. 2d), two distinct components with binding energies of 161.7 eV and 162.3 eV were assigned to the Au(I)-thiolate and Ag(I)-thiolate, respectively. The content of the later one was increased with the increasing feed ratio of Ag to Au (Fig. S3 and Tab. S2), which is consistent to the ICP and TGA results. The detailed fitting result is summarized in Table S2. Therefore, a scheme was illustrated for the formation process of core-shell structured  $\text{Ag}_1\text{Au@DT}$  NCs. Initially, Ag(I)-thiolate complexes were formed after the mix of DT and  $\text{AgNO}_3$ , due to the lower redox potential of  $\text{Ag}^+/\text{Ag}$  (0.8 eV) than  $\text{AuCl}_4^-/\text{Au}$  (1.0 eV) and the fast etching kinetics of Ag(I)-thiolate<sup>[60]</sup>, Ag(I)-thiolate was not reduced in this synthetic protocols, the subsequently added  $\text{HAuCl}_4$  was reduced and protected by DT to form the metallic Au(0) core which stapled Ag(I)-thiolate and Au(I)-thiolate motifs together. Obviously, according to well-accepted quantum size confinement effect of metal NCs with zero charge state, the surface thiolate- $\text{Ag}^+$  motif could not be the emitter center of short-wavelength at 440 nm. Overall, our results of dual-emission of Au-Ag bimetal NCs mediated by  $\text{Ag}^+$  doping cannot support the quantum size confinement mechanics for the elucidation of origin of PL of metal NCs.

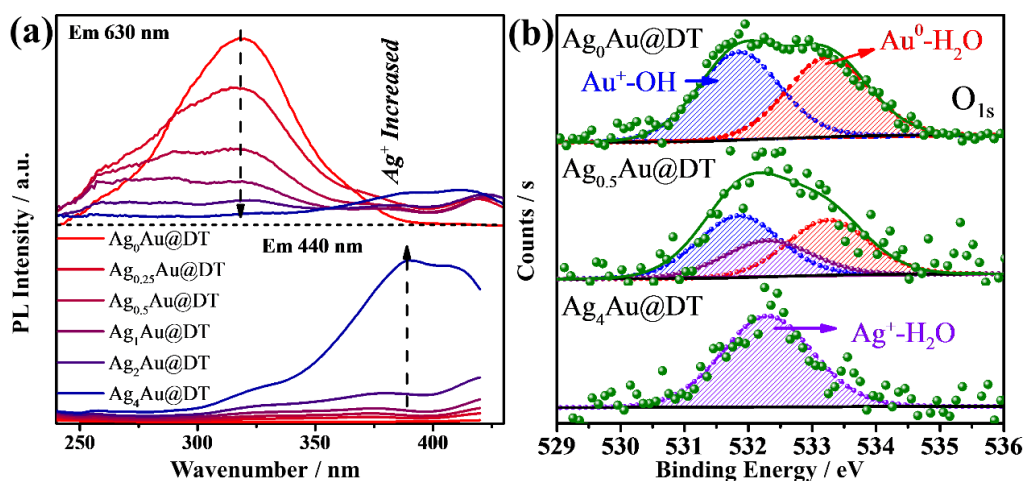


**Figure 3.** Photoluminescence spectra of as-synthesized  $\text{Ag}_1\text{Au@DT}$  NCs after adding increasing amount of 50 mM NaOH aqueous solution, Fluorescence spectra were measured at  $\lambda_{\text{ex}} = 320$  nm. The inset displays the relationship between photoluminescence (440 nm and 630 nm) intensity and the added mole amount of NaOH. (b) PL intensity of  $\text{Ag}_1\text{Au@DT}$  NCs upon cyclic switching of the pH by adding 50  $\mu\text{l}$  50 mM NaOH and 50  $\mu\text{l}$  50 mM HCl aqueous solution.

Not only the dosing of  $\text{Ag}^+$ , the environmental pH of  $\text{Ag}_1\text{Au@DT}$  NCs also shows a prominent impact to the photoluminescence emission. Based on the reduction of  $\text{HAuCl}_4$  precursors and complex interaction of Au(I)/Ag(I) with thiol groups ( $-\text{SH}$ ) during the synthesis of metal NCs, the amount of  $\text{H}^+$  in the stock solution can be precisely calculated to be 1.875 nmol (Equation 1 and 2, SI), so the solution of as made Au-Ag bimetallic NCs is acidic. Very interestingly, when varied amount of NaOH solution (0, 0.5, 0.75, 1.0, 1.25, 1.5, 1.75, 2.0 and 2.25 nmol) was added, the dual-emissive Au-Ag NCs exhibited unique ratiometric pH-dependent emissions (Fig. 3). As shown in Fig. 3a, if the added amount of  $\text{OH}^-$  (0~1.75 nmol) is less than the calculated value (1.875 nmol), the red emission at 630 nm is almost unchanged, whereas the blue one (440 nm) was slightly but linearly increased with the increasing amount  $\text{OH}^-$ . Once more NaOH solution was added ( $>1.875$  nmol), *i.e.*, solution is basic, the dual emissions of Au-Ag NCs exhibited the opposite trend: the red emission dramatically reduced and almost quenched, while the blue emission precisely increased by two times, suggesting that the original red-emissive Au emitters

due to the strong coordination interaction of  $\text{HO}^-$  with Au induce the formation of the blue emitters because of Au/Ag molar ratio of 1:1 (Fig. 3a and inset). Besides, we observed that the blue and red emission can be reversibly recovered and quenched by a cycling titration of acid and base solution (Fig. 3b), respectively, indicating the meta-stability of luminous centers. Thus, as-synthesized  $\text{Ag}_1\text{Au@DT}$  NCs could serve as potential ratiometric nanoprobe for pH sensing.

Nevertheless, the origin of dual-emission band for  $\text{Ag}_1\text{Au@DT}$  NCs and its pH-dependent PL emission remains elusive. In most of case, the pH-dependent fluorescence properties was generally observed for ligand-protected metal NCs with AIE characteristic<sup>[61-63]</sup>, in which the pH value was deemed to alter the charge state of the protected ligand and inhibited the aggregation of the Au(I)-thiolate staple due to the electrostatic repulsion. In our case, the pH variation cannot be a trigger of AIE for  $\text{Ag}_1\text{Au@DT}$  NCs because of the nonionic nature of alkylthiol (DT) protective ligands on the metal core surface. In the previous discussion, we precluded the possibility of PL emission due to the quantum size confinement effect of metal NCs, since the  $\text{Ag}^+$  doping and pH variation did not change the structure of Au NCs core based on the characterizations of TEM and XPS (Fig. S2 and S3). Excitation spectrum of Au-Ag bimetal NCs gives more information on the nature of excited states of dual emissions (Fig. 4a). Unexpectedly, the long-wavelength red emission at 630 nm shows a broad excitation band centered at *ca.* 320 nm, and with an increase of  $\text{Ag}^+$  dosing, its excitation intensity is gradually decreased and finally completely disappears, consistent with the evolution of PL emission (Fig. 1b); while the short-wavelength blue emission at 440 nm exhibits a long-wavelength excitation centered at 390 nm. Similar excited state energy levels with just 0.70 eV energetic gap answers the strong energy transfer between two emission centers of Au-Ag bimetal NCs (Fig. 1a), which also precludes the LMCT and/or LMMCT model of ligand to metal (or metal NCs) charge transfer for the contribution of PL emission with much higher theoretical energy levels.<sup>[64]</sup>



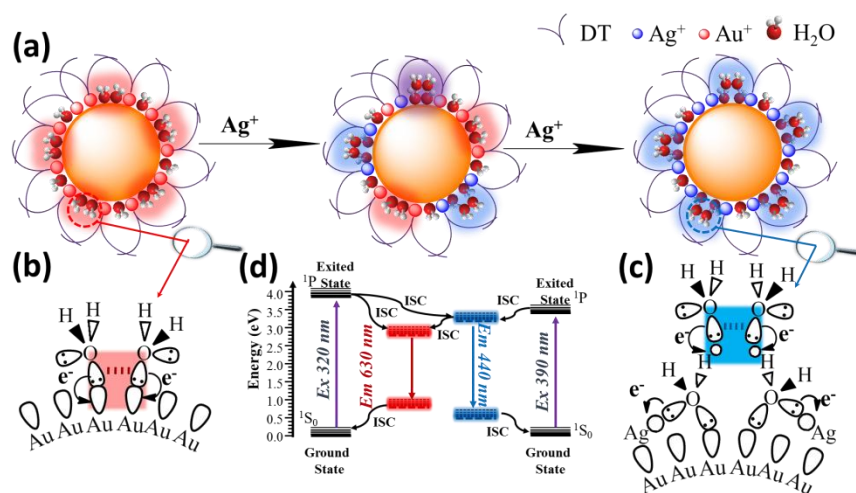
**Figure 4.** Excitation spectra (a) of  $\text{Ag}_x\text{Au@DT}$  NCs and XPS spectrum (b) of O 1s for  $\text{Ag}_0\text{Au@DT}$  and  $\text{Ag}_{0.5}\text{Au@DT}$  and  $\text{Ag}_4\text{Au@DT}$  NCs.

Very recently, after long-term and systematic investigation, using a combined experimental and computational approach, in particular with the help of steady and ultra-fast absorption and emission spectra, we unambiguously confirmed the existence of new interface states due to the spatial overlapping of p orbitals of oxygen atoms of structural water molecules (SWs) at the confined nanointerface of soft and hard nanocavity.<sup>[57, 58, 64-71]</sup> It is called the p band intermediate state (PBIS) with  $\pi$  bonding features, which not only provides an ensemble of intermediate states



for bright photoluminescence (PL) emission, but also acts as an alternative reaction channel for static electron transfer.<sup>[69-71]</sup> Considering the ubiquitous properties of structural water molecules (SWs) at heterogeneous interface and the universality of our PBIS model, we performed the XPS measurement of O<sub>1s</sub> to test the presence of species of SWs for three typical metal NCs of Ag<sub>0</sub>Au@DT and Ag<sub>0.5</sub>Au@DT and Ag<sub>4</sub>Au@DT NCs (Fig. 4b). As expected, mono-metal Ag<sub>0</sub>Au@DT NCs show two distinct binding energies at 531.8 eV and 533.2 eV with molar ratio close to 1:1 (Fig. 4b, top and Tab. S3), which was assigned to hydroxide and water molecules chemically adsorbed on the Au(I) ion and Au atoms, respectively, indicating the presence of SWs {OH<sup>-</sup>·H<sub>2</sub>O} at the metal core surface (Fig. 5b). With the increase of Ag<sup>+</sup> dosing in the synthesis, the content of SWs interacted with Au atoms was significantly decreased, while a new chemically adsorbed specie containing O atoms of Ag<sub>0.5</sub>Au@DT was produced at 532.3 eV, which was assigned to water coordinated with Ag<sup>+</sup> (Fig. 4b, middle). If the Au core was completely covered by a thiolate-Ag<sup>+</sup> motif shell, only Ag<sup>+</sup>-H<sub>2</sub>O complexes were observed at 532.3 eV (Fig. 4b, bottom and Fig. 5c).

Importantly, it is worth noting that, after the vacuum evacuation or ice-drying, due to the removing of SWs with weak interactions (Fig. 5c), the blue emission at 440 nm of Ag<sub>4</sub>Au@DT NCs was quenched. If trace amount of water was re-added, the blue emission could be recovered (not shown here). This probably answers that, Ag<sub>4</sub>Au@DT NCs only captured one signal of chemically adsorbed water molecules with Ag<sup>+</sup> at 532.3 eV owing to high vacuum treatment during the XPS measurement, indicating the blue emissive SWs are weakly bonded on the fully core-shell structured Au-Ag bimetal Au NCs though water bridge which strongly coordinated with Ag<sup>+</sup> (Fig. 5c). Thus, PL properties strongly depend on the binding mode of SWs. Only the SWs with medium binding strength to metal emit the long-wavelength emission, while the SWs strongly coordinated with metals do not emit the color due to the limitation of spatial configuration of p orbitals of O atoms in the SWs, eg., {Ag<sup>+</sup>·H<sub>2</sub>O} dimers, but weakly bound SWs by hydrogen-Bonding on the {Ag<sup>+</sup>·H<sub>2</sub>O} dimers could emit the short-wavelength blue emission (Fig. 5c). This also answers the origin of unique ratiometric pH-dependent dual-emissions (Fig. 3). At acid conditions, the hydroxide adsorbed on the Au-Ag bimetal NCs was neutralized, only red-emission was observed. At basic conditions, the first layer of SWs weakly interacted with Au(I) and Au(0) were replaced by hydroxide groups with stronger coordination ability to metals, which can be used as new immobilized sites for hosting SWs with weak interaction by H-bonding interaction (the blue emissive SWs with less stability), consequently the blue emission was intensified (Fig. 3a). obviously, the overlapping degree of two O atoms in the varied SWs, *ie.*, the stability of two type of SWs as emitters, determines the abnormal relation of long-wavelength emission with short-wavelength excitation (Fig. 4a and Fig. 5) and their varied lifetimes of dual-emissions (Fig. 1d). The presence of SWs with the varied stability and multiple intermediate states at nanoscale interface probably answers the promoting role of alkali metal ion in both electro-catalytic reaction of HER and ORR and water-gas shift reaction (WGSR) by providing the alternative channels for concerted proton and electron transfer.<sup>[69-71]</sup>



**Figure 5.** Schematic illustration of structural water molecules (SWs) confined at nanoscale interface of Au-Ag bimetal NCs packed by protective ligands emit bright dual-photoluminescence (a), the red emissive SWs strongly binding on the single metal Au NCs (b), the blue emissive SWs weakly binding on the fully core-shell structured Au-Ag bimetal Au NCs though water bridge which strongly coordinated with  $\text{Ag}^+$  (c), and energy diagram of dual emissions of Au-Ag bimetal NCs.

The diagnostic experiments through dosing with  $\text{S}^{2-}$  anions (Fig. S4), the blue emission of  $\text{Ag}_1\text{Au@DT}$  NCs was gradually quenched with the increasing dosing amount  $\text{S}^{2-}$  due to its strong capacity to precipitate  $\text{Ag}^+$ . Obviously, the removal of surface  $\text{Ag}^+$  induce the losing of SWs confined on the thiolate- $\text{Ag}^+$  motifs, resulting in the quenching of blue emissions. Even though the red-emission was also reduced, its emission also could be easily distinguished due to relative strong affinity of SWs with  $\text{Au(I)}$  and  $\text{Au(0)}$  (Fig. S4 and inset). The weakening of red-emission probably is attributed to the covering of emitters due to the deposition of  $\text{AgS}$  precipitates. Indeed, the surface thiol ligand plays a role to create the nano-microenvironment with hydrophobicity for hosting the SWs. This was verified by changing the DT concentration during synthesis to influence the dual-emissions (Fig. S5). At low concentration of DT ligands (less than 2.0 equivalent to metal), the dual-emissions were hardly distinguished (Fig. S6, inset). Only above this critical value, the dual-emissions of  $\text{Ag-Ag}$  bimetal NCs were boosted with more feeding of DT molecules since the dense packing of DT on the metal core creates more hydrophobic environment, which strengthen the stability of SWs (or stronger overlapping of p orbitals of O atoms by space interactions). Thus, we clearly addressed that, the emitter of dual-emissive Au-Ag bimetal NCs are coming from the SWs with varied stability (Fig. 5b and 5c), instead of metal NCs or AIE of surface protective ligands<sup>[46, 72]</sup>.

If we consider SWs confined at nanoscale interface as emitters, the reported abnormal PL properties of metal NCs could be easily elucidated, including solvent effect, pH-dependent behavior, surface ligand effect, multiple emitter centers, large-Stoke's shift, [12, 57, 66, 67, 73-83]. Herein, using our theory, taken an example of abnormal anti-galvanic replacement reaction approach for the synthesis of thiolate-protected  $\text{Ag-Au}$  NCs could be easily explained.<sup>[41, 42]</sup> Classical galvanic replacement reaction involves the spontaneous reduction of a noble-metal cationic by a less noble metal in solution driven by the difference in redox potentials ( $\text{Ag} + \text{Au}^+ \rightarrow \text{Ag}^+ + \text{Au}$ ),<sup>[40, 45]</sup> while the anti-galvanic replacement reaction means an inverse process ( $\text{Ag}^+ + \text{Au} \rightarrow \text{Ag} + \text{Au}^+$ ), which really subverted our traditional cognitive way. But, the



intermediate states formed by SWs with the overlapping of p orbitals of O atoms provide the alternative channels for the reverse electron transfer between Au and Ag<sup>+</sup>, thus the anti-galvanic replacement reaction was observed.<sup>[84-86]</sup> The discovery of these dynamic interface states also provides a completely new insight to understand the nature of heterogeneous catalysis and/or interface state (bonding), beyond the conventional metal-centered d band theory.<sup>[69-71, 87, 88]</sup>

## Conclusion

In summary, bimetallic Ag-Au@DT NCs with well-resolved dual-emission (440 nm and 630 nm) were successfully achieved through a facial one-pot approach. The newly boosted blue emission is the consequence of the doping of silver atom as Ag(I)-thiolate into the staple motif site of Au NCs, which is confirmed by the XPS and TEM characterization. Very interestingly, Ag<sub>1</sub>Au@DT NCs can sense a reversible dual-emission signal changes in the environmental pH, which enabled it as a potential ratiometric nanoprobe for pH sensing. The combined characterizations of absorption, excitation and emission spectrum confirm that, the true emitters of dual-emission of Ag<sub>1</sub>Au@DT NCs are structural water molecules (SWs) confined on the surface of metal NCs core with varied stability. This answer the PL properties of metal NCs are extremely susceptible to the surrounding microenvironments of SWs, such as the dosing of Ag<sup>+</sup>, pH, and packing mode of surface ligands. Since the adsorption of SWs at nanoscale interface is a ubiquitous phenomenon in nature, the concept of 'SWs as emitters' could be used as a based modal to elucidate the origin of PL of other low-dimensioned quantum dots, such as carbon, semiconductor and perovskites type materials. In addition, the concept of 'surface electronic states' formed by space overlapping of p orbitals of O atoms in SWS, could act as an alternative channel for concerted electron and proton transfer, which provide new insights to in-depth understanding of heterogeneous catalysis and/or the nature of interface states (or interfacial bondings).<sup>[57, 69-71]</sup>

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# Supporting information

## Silver cation-mediated dual-emissive Au–Ag bimetallic nanoclusters for pH ratiometric sensing

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### Experimental section

#### Materials

All reagents used were purchased from Sinopharm Chemical Reagent Co., Ltd. except Glutathione in the reduced form (GSH), which was purchased from aladdin (Shanghai, China). All chemicals were used as received without any further purification. Deionized water was used in all experiments.

**Synthesis of Ag<sub>x</sub>Au@DT NCs with different ratio of Ag to Au.** The synthesis of luminescent Ag-Au NCs refers to modified literature reports[1]. Typically, freshly prepared alcoholic solutions of DT (3.6 ml, 50 mM) and AgNO<sub>3</sub> (x ml, 25.4 mM) were mixed well under vigorous stirring for 10 min, the solution was opacified due to the formation of Au(I)-thiolate. Freshly prepared alcoholic solutions of HAuCl<sub>4</sub> (0.2 ml, 25.4 mM) were then added into the mixture solution, the mixture stirred for another 12 h and then incubated overnight at room temperature. The feeding ratio of Ag to Au varied from 0 to 4, in which the volume of HAuCl<sub>4</sub> precursor was constant only change the volume of AgNO<sub>3</sub> solution from 0 ml to 0.8 ml). The samples denoted as Ag<sub>x</sub>Au@DT NCs, which the X represented the feeding ratio of Ag to Au. The as synthesized Ag<sub>x</sub>Au@DT NCs were used without purification.

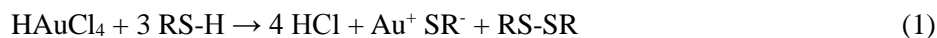
#### Characterization

Ultraviolet visible (UV-vis) spectroscopy was conducted with a UV2700 UV-vis spectrophotometer. Fluorescence was measured by using a FluorMax-4 fluorimeter (Horiba, Japan). HR-TEM images of NCs were collected with a JEOL JEM 2010 microscope operating at 200 kV. Fluorescence lifetime was measured with a homebuilt time-correlated single photon counting (TCSPC) system with a time resolution of sub-100 ps. Phosphorescence lifetime was excited with a  $\mu$ F2 lamp and measured with FLS 980 spectrofluorimeter (Edinburgh Instruments). Thermogravimetric analysis (TGA) was conducted on a NETZSCH STA449F3 analyzer under air atmosphere (flow rate of 50 mL min<sup>-1</sup>). Inductively coupled plasma (ICP) atomic emission spectroscopy was performed on a Thermo IRIS Intrepid II XSP atomic emission spectrometer. X-ray photoelectron spectra (XPS) were measured on an AXIS

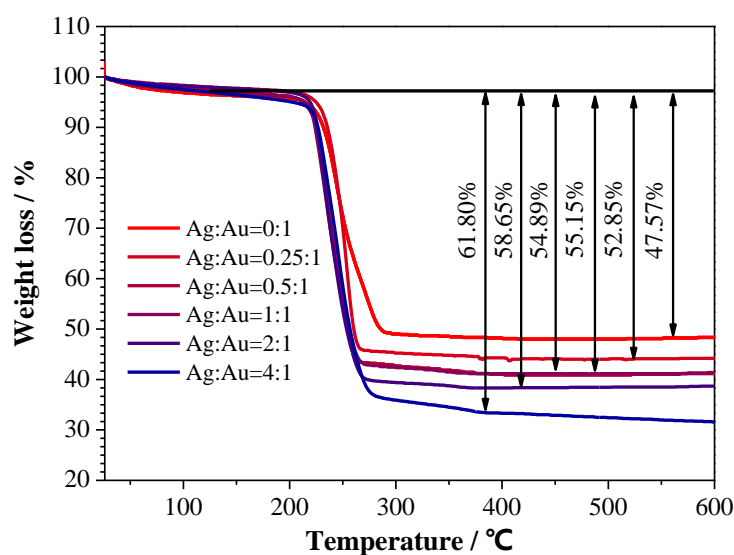
SUPRA instrument with X-Ray monochromatisation.

### pH Sensing

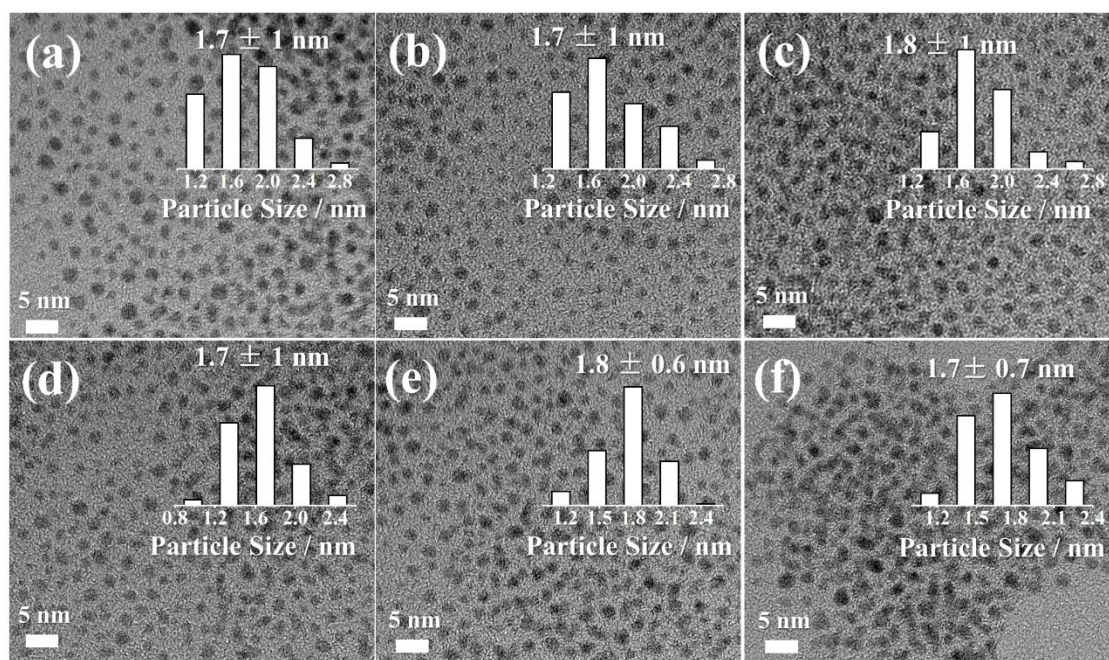
The stock solution of as-synthesized Ag<sub>1</sub>Au@DT NCs was acidic due to the reduction of Au (III) precursors and the formation of thiolate as the following two chemical equations:



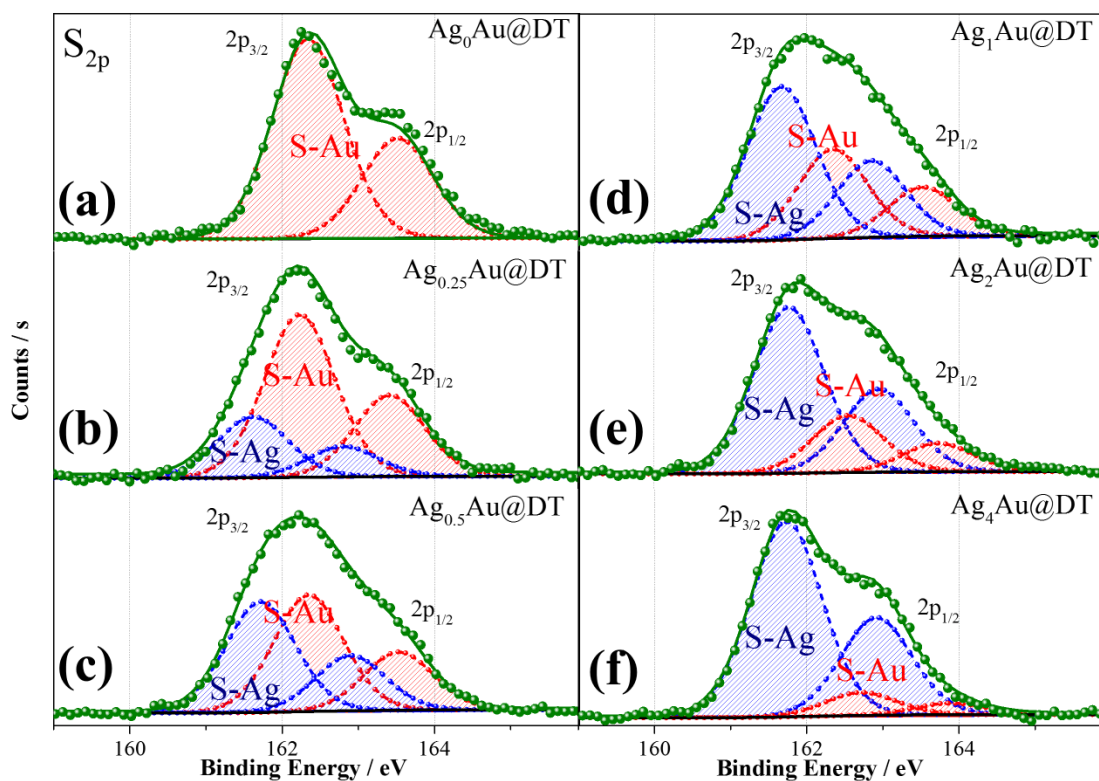
The mole amount of H<sup>+</sup> of the stock solution (4 ml) of as-synthesized Ag<sub>1</sub>Au@DT can be estimate about 0.025 mmol according to the equations. To evaluate the sensitivity of pH for as-synthesized Ag<sub>1</sub>Au@DT, 0.3 ml stock solution, which contained 1.875 nmol of H<sup>+</sup>, was diluted by adding 1.5 ml ethanol. Different volume of 50 mM NaOH aqueous solution (0 ul, 10 ul, 15 ul, 20 ul, 25 ul, 30 ul, 35 ul, 40 ul and 45 ul corresponding to 0 nmol, 0.5 nmol, 0.75 nmol, 1.0 nmol, 1.25 nmol, 1.5 nmol, 1.75 nmol, 2.0 nmol and 2.25 nmol of OH<sup>-</sup>, respectively). The photoluminescence emission spectra of OH<sup>-</sup> adjusted Ag<sub>1</sub>Au@DT NCs solution after standing overnight were record. The cyclic switching of the pH regulated PL intensity were performed by adding 50 ul 50 mM NaOH and 50 ul 50 mM HCl aqueous solution circularly. The solution of each cycle was ultrasonically treated 5 min before recording the photoluminescence emission spectra.



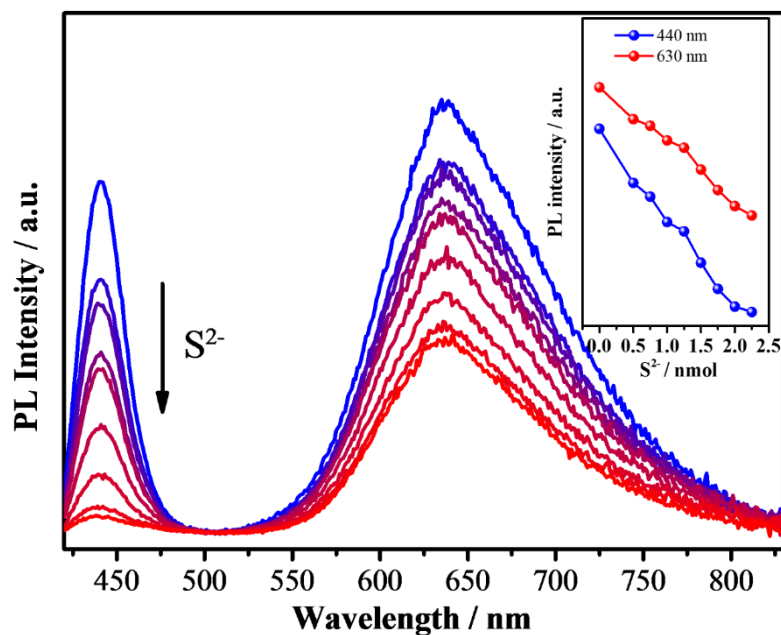
**Figure S1.** Thermalgravimetric analysis (TGA) of Ag<sub>x</sub>Au@DT NCs with different ratio of Ag to Au.



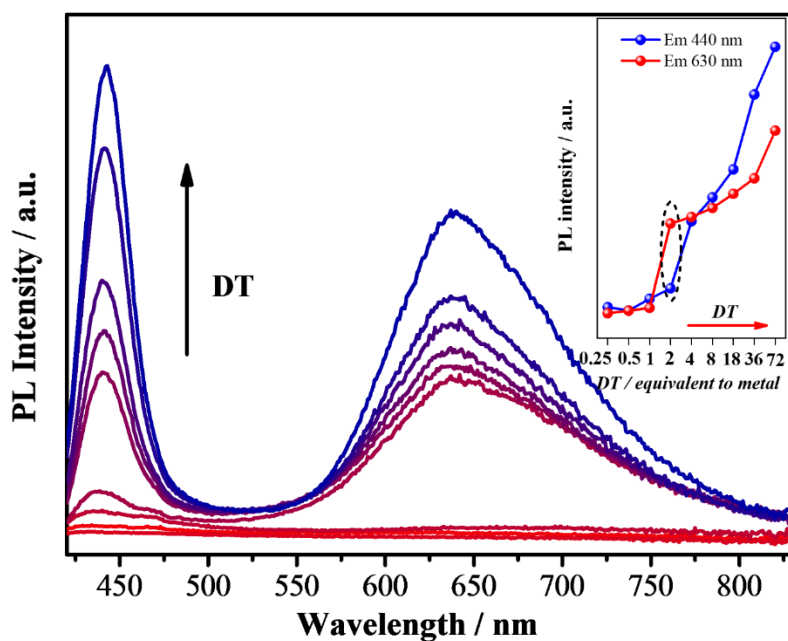
**Figure S2.** HRTEM micrograph of  $\text{Ag}_0\text{Au@DT}$  (a),  $\text{Ag}_{0.25}\text{Au@DT @DT}$  (b),  $\text{Ag}_{0.5}\text{Au@DT}$  (c),  $\text{Ag}_1\text{Au@DT}$  (d),  $\text{Ag}_2\text{Au@DT NCs}$  (e) and  $\text{Ag}_4\text{Au@DT NCs}$  (f), respectively. The scale bar is 10 nm. The inset shows the size distribution.



**Figure S3.** XPS spectrum of S 2p for  $\text{Ag}_0\text{Au@DT}$  (a),  $\text{Ag}_{0.25}\text{Au@DT @DT}$  (b),  $\text{Ag}_{0.5}\text{Au@DT}$  (c),  $\text{Ag}_1\text{Au@DT}$  (d),  $\text{Ag}_2\text{Au@DT NCs}$  (e) and  $\text{Ag}_4\text{Au@DT NCs}$  (f), respectively.



**Figure S4.** Photoluminescence spectra of as-synthesized Ag<sub>1</sub>Au@DT NCs after adding increasing amount (0, 0.5, 0.75, 1.0, 1.25, 1.5, 1.75, 2.0 and 2.25 nmol) of 50 mM K<sub>2</sub>S aqueous solution. The inset displays the relationship between photoluminescence (440 nm and 630 nm) intensity and the added mole amount of K<sub>2</sub>S.



**Figure S5.** PL emission spectra of Ag<sub>1</sub>Au@DT NCs synthesized at increasing DT concentration (0.25, 0.5, 1, 2, 4, 8, 18, 36 and 72 equivalent to metal, respectively). The inset displays the relationship between photoluminescence (440 nm and 630 nm) intensity and the amount of DT equivalent to metal.

**Table S1.** The ratio of Ag to Au of Ag<sub>x</sub>Au@DT NCs determined by ICP-OES analysis.

<i>Sample</i>	<i>The molar ratio of Ag-Au</i>		<i>Stoichiometric Formula<sup>a</sup></i>
	<i>Feed</i>	<i>ICP</i>	
<i>Ag<sub>0</sub>Au@DT NCs</i>	<i>0</i>	<i>-</i>	<i>Ag<sub>0</sub>Au<sub>1</sub>DT<sub>0.9</sub></i>
<i>Ag<sub>0.25</sub>Au@DT NCs</i>	<i>0.25</i>	<i>0.11</i>	<i>Ag<sub>0.1</sub>Au<sub>1</sub>DT<sub>1.2</sub></i>
<i>Ag<sub>0.5</sub>Au@DT NCs</i>	<i>0.5</i>	<i>0.23</i>	<i>Ag<sub>0.2</sub>Au<sub>1</sub>DT<sub>1.4</sub></i>
<i>Ag<sub>1</sub>Au@DT NCs</i>	<i>1</i>	<i>0.47</i>	<i>Ag<sub>0.5</sub>Au<sub>1</sub>DT<sub>1.5</sub></i>
<i>Ag<sub>2</sub>Au@DT NCs</i>	<i>2</i>	<i>1.02</i>	<i>Ag<sub>1</sub>Au<sub>1</sub>DT<sub>2.2</sub></i>
<i>Ag<sub>4</sub>Au@DT NCs</i>	<i>4</i>	<i>1.25</i>	<i>Ag<sub>1.3</sub>Au<sub>1</sub>DT<sub>2.7</sub></i>

<sup>a</sup>Stoichiometric formula was estimated by the calculation of DT to metal weight ratio (TG analysis) and Ag to Au molar ratio (ICP analysis) of Ag<sub>x</sub>Au@DT NCs.

**Table S2.** XPS peak parameters for the S state (Fig. S4) of Ag<sub>x</sub>Au@DT NCs.

<i>Sample</i>	<i>Atom</i>	<i>Item</i>	<i>Position (eV)</i>	<i>Content (%)</i>
<i>Ag<sub>0</sub>Au@DT NCs</i>	<i>S 2p</i>	<i>Ag(I)-SR</i>	<i>161.6</i>	<i>-</i>
		<i>Au(I)-SR</i>	<i>162.3</i>	<i>100</i>
<i>Ag<sub>0.25</sub>Au@DT NCs</i>		<i>Ag(I)-SR</i>	<i>161.6</i>	<i>27.3</i>
		<i>Au(I)-SR</i>	<i>162.2</i>	<i>72.7</i>
<i>Ag<sub>0.5</sub>Au@DT NCs</i>		<i>Ag(I)-SR</i>	<i>161.7</i>	<i>48.7</i>
		<i>Au(I)-SR</i>	<i>162.3</i>	<i>51.3</i>
<i>Ag<sub>1</sub>Au@DT NCs</i>		<i>Ag(I)-SR</i>	<i>161.7</i>	<i>63.2</i>
		<i>Au(I)-SR</i>	<i>162.3</i>	<i>36.8</i>
<i>Ag<sub>2</sub>Au@DT NCs</i>		<i>Ag(I)-SR</i>	<i>161.8</i>	<i>74.4</i>
		<i>Au(I)-SR</i>	<i>162.5</i>	<i>25.6</i>
<i>Ag<sub>4</sub>Au@DT NCs</i>		<i>Ag(I)-SR</i>	<i>161.7</i>	<i>88.5</i>
		<i>Au(I)-SR</i>	<i>162.7</i>	<i>10.5</i>

**Table S3.** XPS peak parameters for the O (Fig. 4b) states of Ag<sub>x</sub>Au@DT NCs

<i>Sample</i>	<i>Atom</i>	<i>Item</i>	<i>Position (eV)</i>	<i>Content (%)</i>
<i>Ag<sub>0</sub>Au@DT NCs</i>	<i>O 1s</i>	<i>Au<sup>+</sup>-OH</i>	<i>531.8</i>	<i>52.4</i>
		<i>Ag<sup>+</sup>-H<sub>2</sub>O</i>	<i>-</i>	<i>-</i>
		<i>Au<sup>0</sup>-H<sub>2</sub>O</i>	<i>533.2</i>	<i>47.6</i>
<i>Au<sup>+</sup>-OH</i>		<i>531.8</i>	<i>39.7</i>	
<i>Ag<sub>0.25</sub>Au@DT NCs</i>		<i>Ag<sup>+</sup>-H<sub>2</sub>O</i>	<i>532.3</i>	<i>25.0</i>
<i>Au<sup>0</sup>-H<sub>2</sub>O</i>		<i>533.2</i>	<i>35.3</i>	
<i>Au<sup>+</sup>-OH</i>		<i>-</i>	<i>-</i>	
<i>Ag<sub>0.4</sub>Au@DT NCs</i>		<i>Ag<sup>+</sup>-H<sub>2</sub>O</i>	<i>532.3</i>	<i>100</i>
<i>Au<sup>0</sup>-H<sub>2</sub>O</i>		<i>-</i>	<i>-</i>	

1. Ye, T. and X. An, *Synthesis and properties of Au–Ag bimetallic nanoclusters with dual-wavelength emission*. New J. Chem., 2019. **43**(2): p. 569-572.