Robust Dye-sensitized Overall Water Splitting System with Two-step Photoexcitation of Coumarin Dyes and Meal Oxide Semiconductors

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Photocatalytic splitting of water into H2 and O2 under visible light irradiation is achieved using a coumarin dye-adsorbed lamellar niobium oxide for hydrogen evolution.

Water splitting using semiconductor photocatalysts has been extensively studied as a candidate for hydrogen (H2) production using solar energy. Although many photocatalysts that work efficiently under ultraviolet (UV) irradiation have been developed, only a few visible light responsive photocatalysts have been reported for overall water splitting, i.e., the simultaneous production of H2 and O2.1-3 The difficulty in achieving overall water splitting using visible light is primarily due to the difficulty in tuning the band levels of inorganic, especially oxide, semiconductor photocatalysts.

Scaife pointed out in 1980 that it is intrinsically difficult to develop an oxide semiconductor photocatalyst having both a sufficiently negative conduction band level for H2 production and a narrow band gap allowing visible light absorption, because of the deeply positive level of the valence band formed by the O-2p orbital.4 Recent studies have therefore focused on the hybridization of the O-2p with other orbital such as N-2p (e.g. oxynitrides),1 as well as the construction of two-step photoexcitation systems2,3 using shuttle redox mediators such as IO3-/I-. On the other hand, various organic dyes, including Ru-complexes, have shown to possess both a sufficiently negative energy level (LUMO) for H2 production as well as visible light absorption.2 Furthermore, fine-tuning of energy levels (HOMO and LUMO) of organic dyes is much easier compared to oxides, as has been shown for dye-sensitized solar cells.5 However, such a simple dye molecule by itself cannot oxidize water into O2. The evolution of O2 from water, which requires the abstraction of four electrons, is hard for the simple dye molecules. Although non-sacrificial H2 production using a combination of a dye-sensitized photocatalyst with a reversible iodine redox mediator (I3-/I-) has been demonstrated,6 overall water splitting using a dye-sensitized photocatalyst has not yet been achieved in an aqueous solution, possibly due to the lack of stability of the dye molecule, especially in its oxidized state.

The present paper reports the first example of overall water splitting under visible light using a simple organic dye as a photosensitizer for the H2 production part. We found that coumarin dyes with an oligo-thiophene moiety between the donor and acceptor parts show reversible oxidation-reduction cycles stably even in an aqueous solution. These dyes can be used as stable photocatalysts for stoichiometric production of H2 and triiodide (I3-) from an aqueous solution containing an iodide (I-) electron donor when combined with an internally platinized layered niobium oxide (Pt/H4Nb6O17) semiconductor. Overall water splitting was then achieved by combining the coumarin dye-adsorbed Pt/H4Nb6O17 with tungsten oxide (WO3) photocatalyst, which can reduce I3- back to I- accompanied by the oxidation of water into O2 under visible light irradiation.

A coumarin dye (C343) was purchased from Aldrich. Other coumarin dyes (NKX series)6-8 were provided by Hayashibara Biochemical Laboratories, Inc. Japan. The molecular structures are shown in Fig. 1. These dye were adsorbed on the surface of internally platinated potassium niobate (Pt/H4Nb6O17), which was prepared by the previously reported method.7-9 The Detailed preparation procedures of coumarin dye-adsorbed Pt/H4Nb6O17 photocatalyst and IrO2-Pt/WO3 photocatalyst, are provided in the supporting information, with other experimental conditions for photocatalytic activity test and electrochemical measurements.

Fig. 1 Molecular structures of coumarin dyes

Fig. 2 shows the time course of H2 evolution over coumarin dye-adsorbed Pt/H4Nb6O17 photocatalysts suspended in aqueous potassium iodide (KI) solution under visible light irradiation. Steady H2 evolution proceeded over the NKX-2677 and NKX-2697 dye-adsorbed photocatalysts (Fig. 2-a), and nearly the same amount of I3- anion as H2 gas was detected in the solutions after the reaction in both cases (e.g., H2: 48 µmol; I3-: 47 µmol for NKX-2677). The molar amount of evolved H2 exceeded the amount of the dye molecules contained in 50 mg of photocatalyst powder (NKX-2677: ca. 0.55 µmol; NKX-2697: ca. 0.52 µmol). The diffuse reflectance spectra for these photocatalysts after the reaction was found to be almost the same as before the reaction, except for a slight shift of the absorption edge to a shorter wavelength, as shown in Fig. 3-a (spectra of NKX-2697 are shown in Fig. S1). This shift is attributable to the change in alignment of the dye molecules on the surface of the Pt/H4Nb6O17 semiconductor during the stirring in the aqueous solution rather than to the decomposition of dye molecules, because a similar shift was also observed when the photocatalysts were stirred in an aqueous KI solution in the
dark. The findings indicate that the following reactions took place over the NNX-2677 and NNX-2697 dye-adsorbed Pt/H4Nb6O17 photocatalysts under visible light irradiation:

1. \( S + h\nu (\lambda > 400 \text{ nm}) \rightarrow S^* \) (excitation of dye)
2. \( S^* \rightarrow S^* + e^- \) (electron injection to H_2Nb_5O_{17} )
3. \( e^- + H^+ \rightarrow 1/2 H_2 \) (H_2 production on Pt)
4. \( S^* + I^- \rightarrow S + 1/2 I_2^+ \) (regeneration of dye)

\( S^* \rightarrow S^* + e^- \) and \( e^- + H^+ \rightarrow 1/2 H_2 \) are the reactions for the overall water splitting process under visible light irradiation (Fig. 2 and 3). Considering molecular structure of these dyes, it is concluded that a thiophene moiety, especially oligo-thiophene (more than two thiophene moieties), can significantly contribute to stabilize the dyes in the oxidized form of water.

On the other hand, the rate of H_2 production gradually decreased with irradiation time in the case of other coumarin dyes (C-343, NNX-2311, and NNX-2587), as shown in Fig. 2-b, while the rates of H_2 production were relatively high in initial period. The molar amount of liberated I_3^- was smaller than the amount of H_2 evolved in each case (e.g., H_2: 32 \( \mu \text{mol}; I_3^-: 25 \mu\text{mol} \) for NNX-2311). The diffuse reflectance spectra of these dyes changed significantly by the reaction, as shown in Fig. 3. Such a significant change was not observed when the photocatalysts were stirred in the dark, indicating that the change in the spectra was caused by photochemical processes and not by physical processes such as desorption of dye molecules from the Pt/H_2Nb_5O_{17} surface. It is likely that the oxidized state (S^+) of these dyes reacted with water before accepting an electron from the I^- anions and then became photo-inactive species. It is to be noted that the rate of H_2 evolution was negligibly low when the collected photocatalyst powder was irradiated again in a fresh KI solution, while in the case of NNX-2677 and NNX-2697, the dyes exhibited almost the same rate of H_2 production again.

To examine the stability of the dye molecules in the aqueous solution, the oxidation and reduction behaviors of these dyes were analyzed by cyclic voltammetry (CV) in both aqueous and acetonitrile (AN) solutions. Since these dyes, except for C-343, are barely soluble in an aqueous solution with a neutral pH, the CV measurements were carried out using nano-porous TiO_2 electrodes with the dyes adsorbed on them. Fig. 4 shows the CV profiles of NNX-2311, NNX-2587, and NNX-2677 in water or dehydrated AN solution containing 0.1 M of LiClO_4 as a supporting electrolyte (CV curves of NNX-2697 are shown in Fig. S2). In all cases, a current peak was observed with an applied anodic potential above +0.4 V (vs. reference), which indicates oxidation of the dye molecule into an oxidized state (S^+). On the other hand, the reduction behavior strongly depended on the structure of the dye molecule. In the case of NNX-2677, a reversible current peak was observed during the reversed cathodic scanning in both solvents, indicating that the oxidized state (S^+) possesses a relatively long lifetime even in water and can be reduced back to the original state by accepting an electron during cathodic potential sweep (Fig. 4-a). Such a reversible oxidation-reduction behavior of NNX-2677 and NNX-2697 was observed even in repeated CV scanning several times. Although this reversible behavior was observed for NNX-2587 in AN, the reduction current peak was much lower than the oxidation peak in water (Fig. 4-b). In the case of NNX-2311, the reduction current peak was much lower than the oxidation peak even in AN, and no reduction peak was observed in water (Fig. 4-c). These results indicated that the oxidized state of these dyes (NNX-2311, NNX-2587) reacted with the H_2O molecules irreversibly and formed inactive species, as suggested by the results of the photocatalytic reactions (Fig. 2 and 3).

Overall water splitting under visible light was then attempted by combining the dye-adsorbed Pt/H_2Nb_5O_{17} photocatalyst with the WO_3 photocatalyst for O_2 evolution. In the present study, IrO_2 and Pt co-loaded WO_3 photocatalyst (IrO_2-Pt/WO_3) was applied to achieve steady O_2 evolution in the presence of the I_3^- anion in aqueous KI solution. It was found that the IrO_2-Pt/WO_3 showed better activity for O_2 evolution than Pt/WO_3 in the presence of I_3^- in KI solution.
As shown in Fig. 5, the combination of NKK-2677-adsorbed Pt/H2Nb5O17 and IrO2-Pt/WO3 yielded simultaneous H2 and O2 evolution in an almost stoichiometric ratio. The reaction proceeded without appreciable deactivation even after 48-h photoradiation. The total amount of evolved H2, ca. 116 µmol, exceeded the amount of dye molecules adsorbed on Pt/H2Nb5O17 (ca. 0.55 µmol). It is to be noted that no gas evolution was observed in darkness (the 4th run). Also, no H2 evolution was observed when only IrO2-Pt/WO3 was irradiated in KI solution.

![Fig. 5 Time courses of photocatalytic evolution of H2 (closed) and O2 (open) using a mixture of coumarin dye-adsorbed (circles: NKK-2677, triangles: NKK-2311) Pt/H2Nb5O17 (50 mg) and IrO2-Pt/WO3 (100 mg) suspended in a 5 mM of KI aqueous solution under visible light (λ > 400 nm). Arrows indicate evacuation of gas phase.]

These results demonstrate that overall water splitting proceeded with a two-step photoexcitation combined with a redox cycle between I3– and I–. The first step involves water reduction to H2 and I– oxidation to I3– over NKK-2677-adsorbed Pt/H2Nb5O17 photocatalyst, and the second step involves I3– reduction to I– and water oxidation to O2 over IrO2-Pt/WO3. Steady and simultaneous H2 and O2 evolution was also achieved by using NKK-2677, which has three thiophene rings (Fig. S3). On the other hand, the rate of gas evolution using NKK-2587, which has one thiophene ring, drastically decreased with prolonged irradiation time. In the case of the NKK-2311 dye, which has no thiophene ring, only a small amount of H2 was evolved in the initial period. These results again indicate that the oligo-thiophene moiety in the coumarin dyes plays an essential role to stabilize dye evolution in an almost stoichiometric ratio. The reaction proceeded without appreciable deactivation even after 48-h photoradiation. The total amount of evolved H2, ca. 116 µmol, exceeded the amount of dye molecules adsorbed on Pt/H2Nb5O17 (ca. 0.55 µmol). It is to be noted that no gas evolution was observed in darkness (the 4th run). Also, no H2 evolution was observed when only IrO2-Pt/WO3 was irradiated in KI solution.

In summary, dye-sensitized overall water splitting under visible light irradiation was demonstrated for the first time using a simple organic dye molecule as a photosensitizer for H2 evolution. The reaction was initiated in the presence of considerable amount of O2 in gas phase (e.g., 200 µmol of O2).

The results in stability test under ambient condition have also suggested that the dyes with oligo-thiophene moiety have durability to O2 molecules, not only to H2O. Actually, H2 production stably proceeded over NKK-2677 dye-sensitized photocatalysts even when the reaction was initiated in the presence of considerable amount of O2 in gas phase (e.g., 200 µmol of O2).

As shown in Fig. 5, the combination of NKK-2677-adsorbed Pt/H2Nb5O17 and IrO2-Pt/WO3 yielded simultaneous H2 and O2 evolution in an almost stoichiometric ratio. The reaction proceeded without appreciable deactivation even after 48-h photoradiation. The total amount of evolved H2, ca. 116 µmol, exceeded the amount of dye molecules adsorbed on Pt/H2Nb5O17 (ca. 0.55 µmol). It is to be noted that no gas evolution was observed in darkness (the 4th run). Also, no H2 evolution was observed when only IrO2-Pt/WO3 was irradiated in KI solution.

Notes and references

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