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Versatility of CoPcS in CoPcS/TiO₂ for MB degradation: photosensitization, charge separation and oxygen activation

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In this report, a composite photocatalyst consisting of cobalt phthalocyanine sulfate (CoPcS) and TiO₂ was prepared by a facile synthesis. Careful characterizations and measurements indicate a covalent grafting of CoPcS onto TiO₂ through Ti–O–S linkages, acquiring an intimate heterojunction between TiO₂ and CoPcS. The obtained composite was evaluated for its photocatalytic activity toward the degradation of methyl blue (MB) under visible light irradiation. The evaluation showed a significantly enhanced degradation rate of MB by CoPcS/TiO₂. The improved photocatalytic performance of CoPcS/TiO₂ was attributed to the photosensitization of TiO₂ by CoPcS, charge separation by electron transfer at the interface of the heterojunction formed between CoPcS and TiO₂, and oxygen activation via CoPcS. A synergistic mechanism in improving the photocatalytic performance of TiO₂ by CoPcS was investigated.

1. Introduction

Over the past few decades, titanium dioxide (TiO₂) has been widely studied in pollution control.¹ However, it usually shows inertness under visible light irradiation and low quantum yield in light energy utilization.² Recent strategies focused on grafting photosensitizers or semiconductors onto TiO₂ for expanding their ranges of light absorbance and inhibiting the recombination of photogenerated electron–hole pairs.^{3,4}

For an effective photosensitizer of TiO₂, two important criteria are required:⁵ the photoactive compound should have a high extinction coefficient in the visible region, and be capable of being adsorbed on the TiO₂ surface *via* physical/chemical interaction. In constructing heterojunctions, the band gap of the semiconductor used to modify TiO₂ should be narrow, and its conduction and valence band positions should be matched with that of TiO₂, respectively.⁴ On these accounts, metal phthalocyanines (MPcs, M = Fe, Co) are benign candidates for the modification of TiO₂. More interestingly, the M–N₄ structure in MPcs can increase the O–O length of oxygen, which would play an important role in promoting the production of superoxide radical (·O₂[–]) from O₂.⁶ Many efforts have been devoted to coupling of MPcs with TiO₂.^{3,7,8} However, the recognition on the versatility of MPcs in photocatalysis is insufficient, especially, the function of MPcs in activating oxygen in the process of degrading organic pollutants.

In this report, cobalt phthalocyanine sulfate (CoPcS) was composited with TiO₂, and the experiments on MB degradation

over CoPcS/TiO₂ were conducted. The multiple roles of CoPcS in composite were investigated and synergy in photosensitization, charge separation and oxygen activation was proposed.

2. Experimental

2.1. Synthesis of samples

All the reagents used in this experiment were received without further purification. The CoPcS/TiO₂ composite was fabricated *via* a hydrothermal route. In a typical preparation, 60 mg CoPcS (optical) and 20 ml absolute ethyl alcohol were mixed and ultrasounded for 30 min to get a homogeneous turbid liquid. Subsequently, another 16 ml absolute ethyl alcohol, 3.2 ml acetic acid and 10 ml Ti(C₄H₉O)₄ were added into the mixture, followed by dropwise addition of 2 ml deionized water under vigorous stirring for 1 h. Then, the compound was loaded into a 100 ml stainless steel autoclave, sealed and moved into an oven and kept at 180 °C for 10 h. After cooling the autoclave to room temperature, the precipitate was washed with ethanol and deionized water thrice, and then dried at 80 °C for 24 h. Finally, the solid was annealed at 300 °C for 2 h in purity N₂. For comparison, TiO₂ were prepared under same procedure without adding of CoPcS.

2.2. Characterizations and measurements

X-ray diffraction (XRD) analysis were performed on a Shimadzu-3A diffractometer at 40 kV and 30 mA with Cu K α radiation ($\lambda = 0.15418$ nm). The morphologies were examined by transmission electron microscopy (TEM, JEM-2100CX, JEOL). Infrared spectra (FT-IR) were acquired with an 8400S spectrometer (Shimadzu) in the transmission mode. X-ray photoelectron spectra (XPS)

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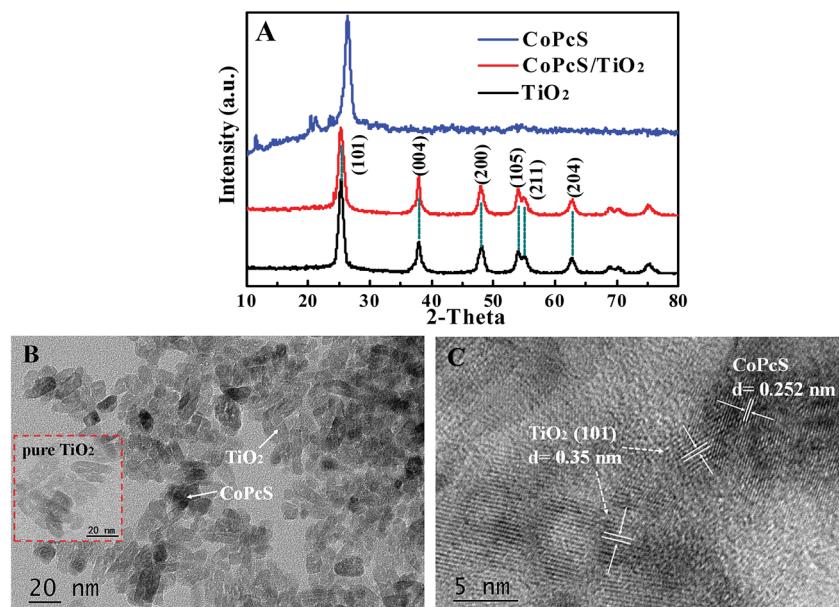


Fig. 1 XRD patterns of samples (A), TEM (B) (inset is that of pure TiO₂) and HRTEM (C) image of CoPcS/TiO₂.

were obtained by a PHI 5000 Versa Probe spectrometer (ULVAC-PHI) operated at a voltage of 13 kV and an emission current of 28 mA using Al K α as exciting source (1486.6 eV). The binding energies were referenced to C 1s at 284.5 eV. The UV-vis absorption spectra of samples were obtained from a Shimadzu UV-3600 spectrophotometer equipped with an integrating sphere using BaSO₄ as reference. Photoluminescence (PL) spectra were recorded on F-7000 fluorescence spectrophotometer (Hitachi) with a laser excitation of 420 nm. Electron paramagnetic resonance (EPR) signals of paramagnetic species spin-trapped with DMPO were recorded at ambient temperature (298 K) with a Bruker EPR 300E spectrometer, the irradiation source ($\lambda = 532$ nm) was a Quanta-Ray Nd:YAG (10 pulses per second) laser system.

2.3. Photocatalytic oxidation experiments

The visible-light-driven photocatalytic activity of the as-prepared samples was monitored from the results of the degradation of MB. For each photocatalytic activity measurements, 10 mg of as-prepared catalysts were dispersed into 100 ml of MB solution initialized at 5 mg L⁻¹. The light comes from a 300 W xenon lamp (CEL-HXF-300, Education Au-light Co., Ltd., Beijing, China) equipped with a UV cutoff filter ($\lambda \geq 400$ nm). The photocatalytic reactions took place in the reactor connected to a water bath to main the solution at about 25 °C and the reaction aqueous slurries were magnetic stirred and bubbled with air at a flow rate of 40 ml min⁻¹. The suspension was stirred in the dark for 1 h to obtain adsorption equilibrium of MB before illumination. During the photo-reaction, samples were collected at selected time intervals. The catalyst powders were removed by filtration and the residual concentration of MB was determined by the spectrophotometer. Quenching experiments were conducted under same conditions except the existence of each scavenger in 10 mM of ethylenediamine

tetraacetic acid disodium (EDTA-Na₂, for $\cdot\text{O}_2^-$), *tert*-butyl alcohol (tBA, for $\cdot\text{OH}$) and *p*-benzoquinone (pBQ, for h^+).

3. Results and discussion

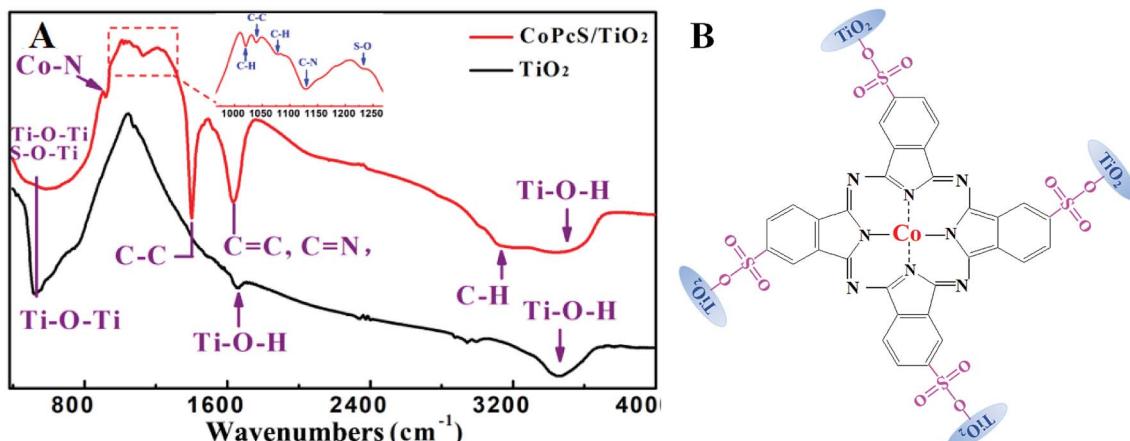
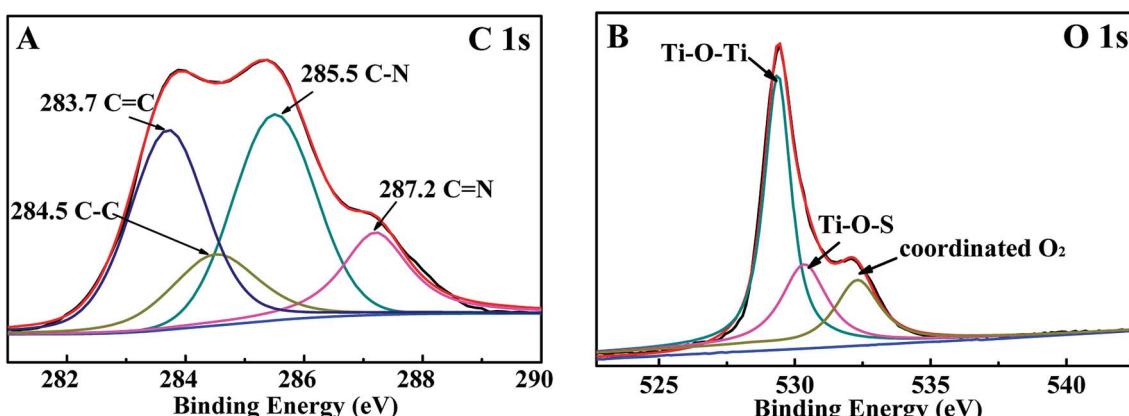
3.1. Morphology and structure

3.1.1. XRD and TEM analysis. Fig. 1A shows the XRD patterns of the as-prepared samples. The spectrum of bare TiO₂ and CoPcS/TiO₂ show the typical peaks of anatase phase (JCPDS no. 21-1272), while the diffraction peaks of CoPcS were not observed on the XRD pattern of CoPcS/TiO₂ probably due to the low loading mass or small size of loaded CoPcS.⁹ The average crystallite sizes of pure TiO₂ and CoPcS/TiO₂ were calculated to be 9.9 and 9.2 nm, respectively, based on the Scherrer formula. TEM observations of CoPcS/TiO₂ (Fig. 1B) indicate an intimate coating of CoPcS on TiO₂, and particle sizes roughly matched to that from XRD. As shown in Fig. 1C, the HRTEM image of CoPcS/TiO₂ displays two types of clear lattice fringes, one set of the fringe spacing (d) was *ca.* 0.35 nm, corresponding to the (101) plane of the anatase crystal structure of TiO₂;¹⁰ another set of stacking feature ($d \approx 0.252$ nm) corresponds to the CoPcS.¹¹ The result agrees well with that from the XRD analysis.

3.1.2. FTIR analysis. The surface structures of resultant samples were revealed by FT-IR spectra as shown in Fig. 2A. The spectrum of pure TiO₂ shows the Ti–O–Ti at 539 cm⁻¹, Ti–O–H at 1654 and 3468 cm⁻¹.^{12,13} The spectrum recorded on CoPcS/TiO₂ shows distinct difference from what on pure TiO₂ with C–C at 1404,¹⁴ C=C and C=N at 1638 cm⁻¹.^{15,16} The peak centered at 917, 1040 and 1232 cm⁻¹ is attributed to Co–N,¹⁷ C–N¹⁴ and S–O¹⁸ in CoPcS, sequentially. The broad peak at 608 cm⁻¹ is induced by Ti–O–Ti and Ti–O–S. This is a strong evidence of covalent attaching of CoPcS on TiO₂. The linkage between CoPcS and TiO₂ is proposed as Fig. 2B.

3.1.3. XPS analysis. The surface structure of CoPcS/TiO₂ was confirmed by XPS. In Fig. 3A, the peaks of C 1s in CoPcS/



Fig. 2 FT-IR spectra on TiO_2 and $\text{CoPcS}/\text{TiO}_2$ (A) and the possible linkage between CoPcS and TiO_2 (B).Fig. 3 High-resolution XPS spectra of C 1s (A) and O 1s (B) in $\text{CoPcS}/\text{TiO}_2$.

TiO_2 can be deconvoluted into four lines peaked at 283.7, 284.5, 285.5 and 287.2 eV, corresponding to $\text{C}=\text{C}$, $\text{C}-\text{C}$, $\text{C}-\text{N}$ and $\text{C}=\text{N}$ in CoPcS , respectively.^{19–22} The O 1s (Fig. 3B) composed of three peaks, the deconvoluted peak observed at 529.3 eV corresponds to the $\text{Ti}-\text{O}-\text{Ti}$ in TiO_2 . The peak at a binding energy of 530.4 eV is attributed to $\text{Ti}-\text{O}-\text{S}$,²³ indicating a covalent linkage between CoPcS and TiO_2 . An obvious component with the binding energy at 532.4 eV can be assigned to the oxygen (${}^* \text{O}_2$) coordinated by CoPcS .²⁴

3.2. Photocatalytic activity of samples

As shown in Fig. 4A, the removal of MB by direct photolysis or photocatalytic degradation on CoPcS was observed negligible. Pure TiO_2 exhibited nearly 28.3% of MB degradation mainly attributed to their visible-light-driven activity under self-photosensitization of MB.²⁵ The $\text{CoPcS}/\text{TiO}_2$ exhibited superior performance on the MB degradation, with the degradation rate of 88% and the pseudo-first-order rate constant of 0.0091 min^{-1} (almost 6.2 times of that on pure TiO_2). Remarkably, obvious decrease in MB degradation was observed on $\text{CoPcS}/\text{TiO}_2$ under anaerobic conditions (by bubbling N_2), suggesting that O_2 was crucial in the reaction.

3.3. Versatility of CoPcS in $\text{CoPcS}/\text{TiO}_2$ for MB degradation

3.3.1. Photosensitization. As depicted in Fig. 5A, the absorption spectrum recorded on TiO_2 exhibited a typical behavior of a wide-band-gap oxide semiconductor, with no absorption in visible region. However, the $\text{CoPcS}/\text{TiO}_2$ exhibited strong absorption of light in whole wavelength region. Moreover, the spectrum showed an obvious red-shift of absorption edge to approximately 445 nm, and typical peaks of Q band from dimer and monomer CoPcS at 603 and 669 nm^{-1} ¹⁷ resulted from the excitation from their HOMO to the LUMO.^{26,27} Compared to the regular CoPcS , the peaks in Q band of $\text{CoPcS}/\text{TiO}_2$ exhibited red and blue shifts slightly, suggesting the electronic coupling between CoPcS and TiO_2 due to the $\text{Ti}-\text{O}-\text{S}$ linkage indicated by IR and XPS.^{28,29} The energy band gaps from the UV-vis DRS spectra were deduced from the Tauc plot using the Kubelka-Munk theory, and the result was shown as Fig. 5B. The band gap energy of TiO_2 was determined as $\sim 3.2 \text{ eV}$, while that of $\text{CoPcS}/\text{TiO}_2$ was calculated to be $\sim 2.7 \text{ eV}$, which matched well with the absorption edge at 445 nm.

Under visible light irradiation of $\text{CoPcS}/\text{TiO}_2$, the singlet excited state (S_1) of CoPcS would typically generated from the ground state (S_0) and then transformed to triplet excited state

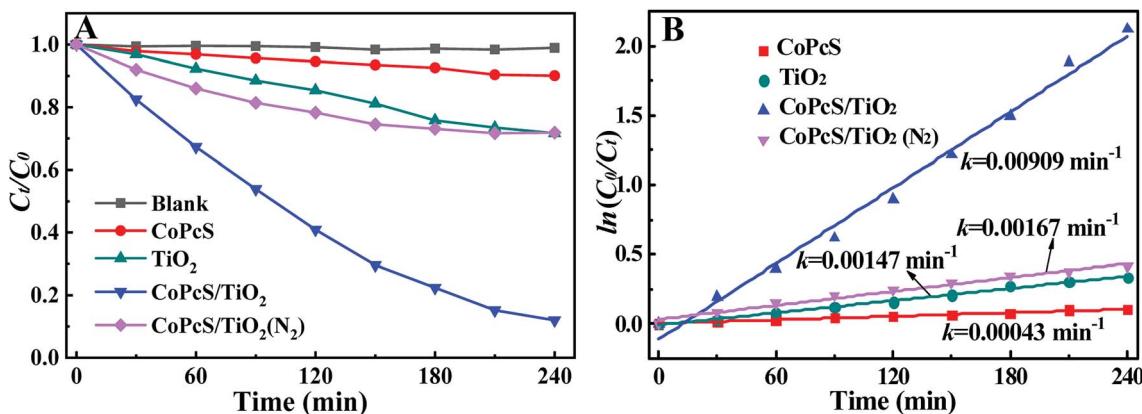


Fig. 4 Photocatalytic degradation of MB on samples (A) and pseudo-first order fitting of the photocatalytic data (B), (C_0 in (A and B) represent the actual concentrations of MB after their adsorption–desorption equilibrium in the dark).

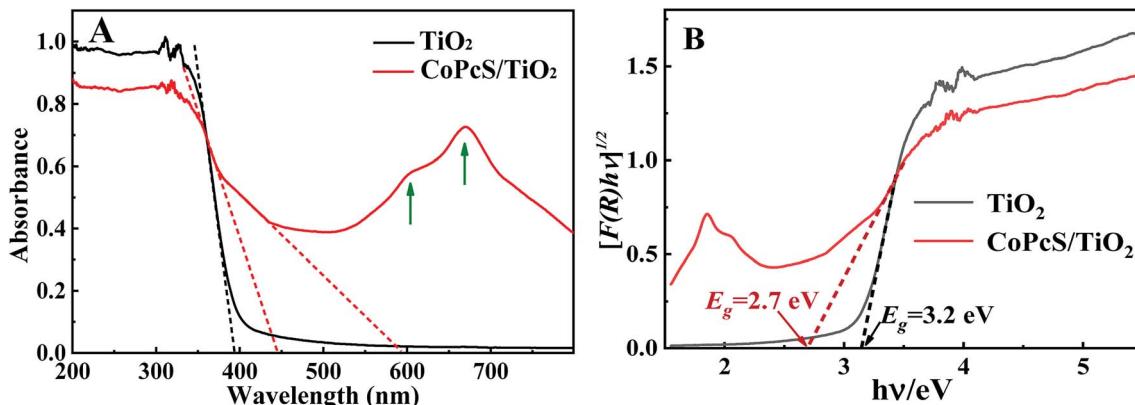


Fig. 5 UV-vis diffuse reflectance absorption spectra (A) and their Tauc plot (B) of TiO₂ and CoPcS/TiO₂.

(T₁) through innersystem crossing.³⁰ The redox potential of S₀, S₁ and T₁ of CoPcS are around 0.46, -1.35 and -0.75 eV (vs. NHE), respectively.^{31,32} The generation of S₁ is normally negligible due to their short lifetime (ns),³³ but the excited CoPcS in T₁ (ms) can inject charges into the conduction band of TiO₂, generating cation radicals of CoPcS (CoPcS⁺). The CoPcS⁺ can participate directly in the degradation of MB³³ and contributes

to the enhanced activity of CoPcS/TiO₂ showed by Fig. 4. Herein, the photosensitization of TiO₂ by CoPcS can be expressed as follows:

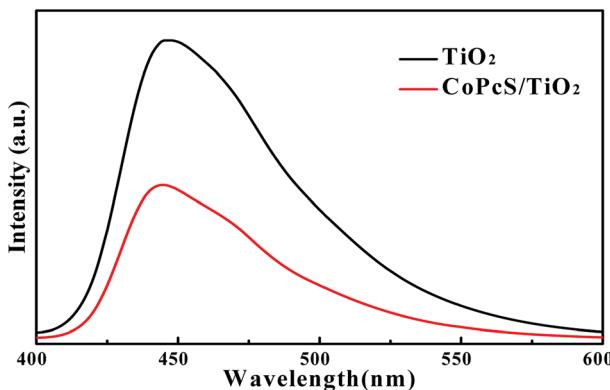
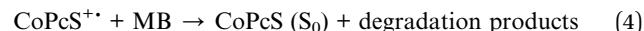


Fig. 6 PL spectra of TiO₂ and CoPcS/TiO₂.

3.3.2. Charge separation. It is well accepted that CoPcS is a typical narrow-band-gap semiconductor with its E_g of about 2.1 eV.³⁴ Coupling TiO₂ with CoPcS also contributed to the absorption of visible light on CoPcS/TiO₂. As indicated in Fig. 5, the CoPcS/TiO₂ showed significant light adsorption in 445–595 nm, which was consistent with the band gap of CoPcS. In addition, the formed heterojunction between CoPcS and TiO₂ played an important role in the separation of photogenerated electron–hole pairs. The conduction band edges of TiO₂ and CoPcS are -0.5 and -1.05 eV, respectively.^{35–38} The

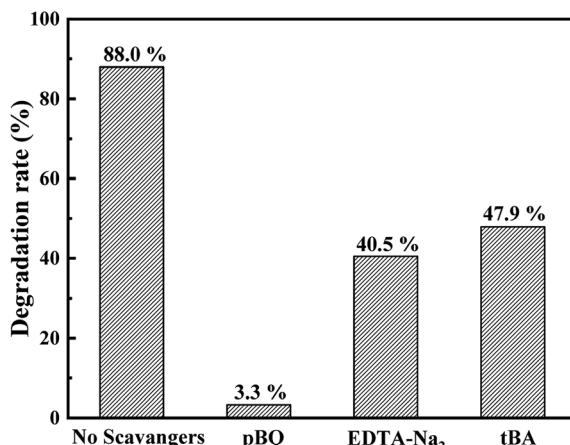


Fig. 7 Degradation rates of MB over CoPcS/TiO₂ in solutions with and without scavengers.

photogenerated electrons were able to transfer from the conduction band of CoPcS to that of TiO₂, leaving holes on the valence band of CoPcS. In this way, the photogenerated electron-hole pairs on CoPcS got separated.

Charge separation on the heterojunction was confirmed by PL measurement. As demonstrated by Fig. 6, the remarkable decrease in PL intensity demonstrated that deposition of CoPcS onto TiO₂ decreased the carrier recombination rate and improves the separation efficiency of photogenerated electrons and holes, which was favorable to the degradation of MB.³⁹

3.3.3. Oxygen activation. As identified by the quenching experiments illustrated in Fig. 7, ·O₂[−], ·OH and h⁺ all played significant roles in proceeding MB degradation, especially the ·O₂[−], which is generated predominantly through the trapping of photo-excited electrons by dissolved molecular oxygen. For the redox potential of holes on the valence band of CoPcS is negative than E (H₂O/·OH), we deduce that ·OH is generated from ·O₂[−].⁴⁰

The presence of ·O₂[−] and ·OH radicals was further confirmed by the electron spin response (ESR) experiments of CoPcS/TiO₂ with 5,5-dimethyl-1-pyrroline (DMPO) as a scavenger in a methanol and an aqueous solution. The four

characteristic peaks of DMPO-·O₂[−]⁴¹ (Fig. 8A) and the system signature (1 : 2 : 2 : 1 signals) of DMPO-·OH radical adducts⁴² (Fig. 8B) were both observed. In contrast, no DMPO-·O₂[−] and DMPO-·OH signals emerged for bare TiO₂ dispersion.

According to the above results, we consider that oxygen in the reaction is activated by the Co-N₄ structure in CoPcS. The electronic configuration of 3d orbital of free Co²⁺ (in spherical field) is diagrammatically presented as Fig. 10 (a). In a square-planar crystal field offered by CoPcS in Fig. 2B, the degenerate energy level of 3d-orbitals split into four levels as sketched as (b).⁴³ Coordination of dioxygen (as a fifth ligand⁴⁴) to Co²⁺ surrounded by the macrocyclic ligand as CoPcS cause a further rearranging of energy into two levels with e_g and t_{2g} symmetry as (c) in Fig. 9.⁴⁵ However, this octahedral symmetric configuration in a non-liner molecular is instable due to the non-full occupation in 3d orbital of Co²⁺,⁴⁶ the configuration will be distorted as (d) by a Jahn-Teller effect.⁴⁷

In such a configuration, most of the interpretations of experimental and theoretical investigation coincided in the conclusion that the 3d_{z²} orbital is half filled.⁴⁸ A σ-rich orbital of O₂ donates electron density to 3d_{z²} of Co²⁺, forming a σ-type bond, while a π interaction is produced between the d_π (d_{xz}, d_{yz}) orbitals and π* orbitals of dioxygen, with charge transfer from metal to O₂.⁴⁹ This electrons rearranging get oxygen activated and increase the O–O bond length from the usual 1.21 to ~1.30 Å.⁶ According to literature, the redox potential of oxygen in ground state E (O₂⁰/O₂[−]) is around −0.048 eV.⁵⁰ However, with the activation, the potential value can increase to ~0.77 eV,⁶ which is more positive than that of E_{CB} in TiO₂.

Based on the above results, the synergy of photosensitization, charge separation and oxygen activation on CoPcS/TiO₂ was proposed as Fig. 10. The electrons generated by photosensitization and charge separation on the conduction band of TiO₂ can be more easily trapped by the activated oxygen (*O₂), derivating more ·O₂[−] species participating in degrading MB. Some of the ·O₂[−] reacts with H⁺, followed by producing ·OH of a redox potential of 2.4 eV. The redox potentials of generated CoPcS⁺ and holes were 1.2 and 1.05 eV, respectively.^{37,38} Thus, the MB was oxidized by ·OH, CoPcS⁺ and holes. By this way, the photocatalytic activity of CoPcS/TiO₂ in degrading MB was enhanced.

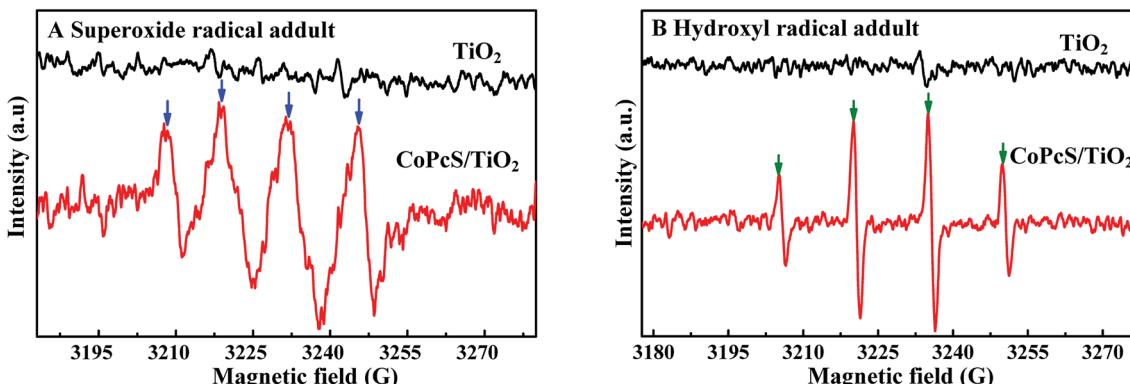


Fig. 8 DMPO spin-trapping ESR spectra recorded with as-prepared samples in (A) methanol dispersion (for DMPO-·O₂[−]) and (B) aqueous dispersion (for DMPO-·OH) under visible light irradiation.



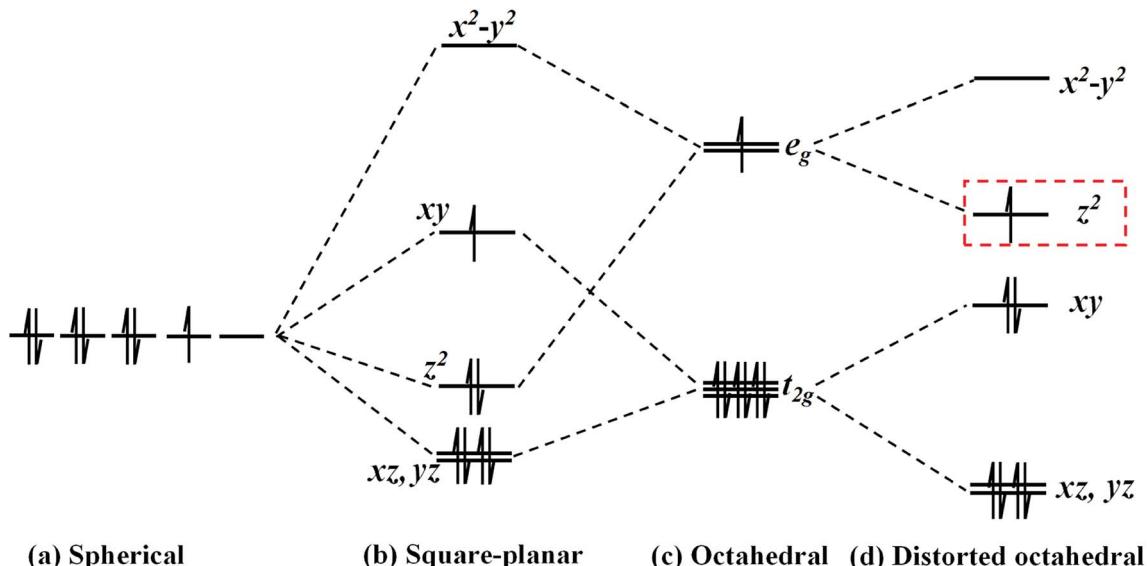


Fig. 9 Sketch of the energy splitting of Co^{2+} in different crystal field.

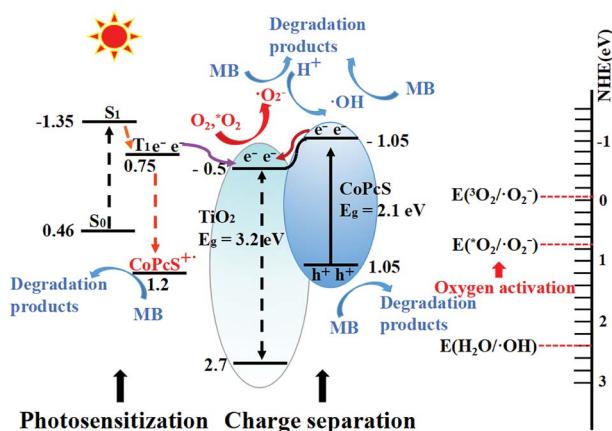


Fig. 10 A schematic diagram of the synergistic mechanism in MB degradation on CoPcS/TiO₂.

4. Conclusion

In this work, TiO₂ was composited with CoPcS *via* the Ti–O–S linkage. The photosensitization of TiO₂ by CoPcS and charge separation on the heterojunction were promoted. At the same time, the oxygen was activated by CoPcS. Due to the versatility of CoPcS on TiO₂, the degradation rate of MB over CoPcS/TiO₂ reached 88% under visible light in 4 h. This synergy is of great potential for design of high-photoreactive catalysts using CoPcS as a component.

Conflicts of interest

There are no conflicts to declare.

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