Check for updates

www.advopticalmat.de

Super Phosphorescence Resonance Energy Transfer (PRET) of Clusterization-Triggered Emission Enables Full-Spectrum Dynamic Room-Temperature Afterglow

Peilong Liao, Tongyue Wu, Cheng Ma, Jianbin Huang, and Yun Yan*

Clusterization-triggered emission is emerging as a powerful strategy leading to useful luminescence such as room-temperature phosphoresce (CTE-RTP), yet people's recognition on CTE-RTP is still very limited, so that it remains challenging to achieve multicolor CTE-RTP due to the difficulty in tailoring the clustering state of the atoms with lone pair electrons. The authors report that phosphorescence resonance energy transfer (PRET) can occur in the CTE-RTP system, which enables fine-tuning the color of the CTE-RTP. Since the CTE-RTP is a broad band in the range of 400–700 nm, and the dipole orientations are diverse in the CTE material, PRET can always occur between the CTE-RTP and arbitrary fluorescent dyes to obtain delayed fluorescence ranging from green to near infrared. Because the lifetime of the delayed fluorescence depends on their molecular structure, dynamic afterglow can be facilely achieved in the ensemble of a PRET-CTE-RTP system, making it very appealing in anticounterfeiting.

1. Introduction

Clusterization-triggered emission (CTE) have attracted increasing attention in recent years,^[1] which can be obtained from natural compounds^[2–5] and through synthesis.^[6] Different from conventional emissions that requires certain conjugated π groups, CTE originates from the through-space conjugation (TSC) of electron-rich atoms in a nonconjugated molecule, such as N, O, S, P, and Si.^[7–10] Since these elements are very common in most biological and simple synthetic molecules, CTE materials possess the advantages of facile synthesis, good water solubility, and low biological toxicity,^[11–14] and they are very promising in many fields, such as color tunable light-emitting,^[15–20] bioimaging and chemical sensing.^[13,21–27]

However, so far, the knowledge about CTE is still very limited. Very recently, a number of CTE materials are reported to display room-temperature phosphorescence (CTE-RTP) when

Peking University

Beijing 100871, China

E-mail: yunyan@pku.edu.cn

D The ORCID identification number(s) for the author(s) of this article can be found under https://doi.org/10.1002/adom.202202482.

DOI: 10.1002/adom.202202482

they are in solid state, owing to the significant spin-orbital coupling (SOC) effect endowed by the electron-rich atoms.^[28-30] In this framework, many commercial molecules that have been extensively used in industries for decades were found to display RTP.^[31,32] Unfortunately, the color of the CTE-RTP for both natural and synthetic materials usually ranges in a narrow band from blue to green due to the difficulties to control the clustering states of the CTEgens and the synthetic challenges to create CTE materials with controlled clustering states. Although some extraordinary CTE materials with tunable fluorescence have been developed,[33] few CTE-RTP other than green was reported.^[30,34,35]

Föster resonance energy transfer (FRET) is well-known for classical fluorescence. It states that if the donor and

acceptor chromophores are within 1–10 nm in space and oriented rationally, the fluorescence energy will transfer from the donor to the acceptor, thus generating red-shifted fluorescence. Recently, phosphorescence resonance energy transfer (PRET) is also proved possible for organic phosphors.^[36–41] When the phosphorescence donor coexists with a fluorescent acceptor dye, the acceptor may give emissions with similar lifetimes to that of the donors. This inspires that if CTE-RTP could undergo PRET, the color of the CTE-RTP would become tunable. However, this scenario has not been verified due partly to the unimaginable photophysical process of the energy resonance in CTE systems, and partly to the difficulty in introducing acceptor molecules to solid CTE-RTP systems.

Herein, we for the first time achieved PRET using CTE-RTP with the strategy of solid-phase molecular self-assembly (SPMSA) recently developed in our lab.^[42–45] First, CTE-RTP was created with a pair of electrostatically interacted CTE polymers. Upon mixing their aqueous solutions, the additional interactions between the CTE polymers facilitate the formation of densely woven network with meshes around 1 nm, which endows the network with considerable hydrophobicity and oxygen resistance. As a result, the molecular motion for the CTE polymers is confined effectively in the precipitates, which allows to generate CTE-RTP. Furthermore, PRET occurs between the CTE-RTP substrate and the doped fluorescent dyes, leading to afterglow emissions with lifetimes similar to the CTE-RTP. It is amazing to find that different from PRET in classical dyes that requires specific dipole orientation and

P. Liao, T. Wu, C. Ma, J. Huang, Y. Yan

Beijing National Laboratory for Molecular Sciences (BNLMS) College of Chemistry and Molecular Engineering



rational distance between the donor and acceptor, the diversified clustering states of the CTEgens offer 100% possibilities of PRET with arbitrarily doped acceptor, without specific aligning requirements. Since the CTE-RTP is in the broad range of 400–700 nm, it can serve as super energy donor for almost all the classical fluorescent dyes. We show that by doping classical fluorescent molecules in the densely woven polymeric network displaying CTE-RTP, phosphorescence resonance energy transfer from the CTE-RTP to arbitrary guest dyes (CTE-PRET) can always be realized. Since the lifetime of the CTE-PRET is tunable by variation of the doping ratio of the acceptor, smart dynamic afterglow can be obtained. The current work not only allows us to generate tunable dynamic emission color of the CTE-RTP from blue to near IR but also opens a new paradigm of CTE-PRET, which may further broaden our horizon on CTE.

2. Results

2.1. Generating CTE-RTP through SPMSA

Since RTP often occurs in solid materials that are resistant to water and oxygen, we decide to generate CTE-RTP using the strategy of solid-phase molecular self-assembly (SPMSA) developed in our lab.^[42–45] **Figure 1**a shows the schematic diagram of SPMSA by mixing the negatively charged APAM (anionic

polyacrylamide) and positively charged PHMB (polyhexamethylene biguanidine hydrochloride). Both polymers display characteristic CTE features in solution, which is evidenced by the increased fluorescence with increasing solution concentration, and excitation-dependent emission maximum (Figure S1, Supporting Information). However, no RTP is available in these solutions due to the significant nonirradiative energy dissipation aroused from molecular motion and hydration effect.^[46] Upon mixing, bulk precipitates are formed immediately as the charge ratios approaching to 1:1. The fresh wet precipitates displays strong CTE (Figure S2, Supporting Information), but still without RTP. Considering the sensitivity of RTP to water, oxygen, and molecular motion, the precipitates were condensed to a flake with a pressure of 5 MPa and dried in a desiccator overnight. X-ray diffraction (XRD) measurements revealed the lack of obvious diffraction peaks, indicating its amorphous nature (Figure S3, Supporting Information). Under 365 nm UV light, the flake displays significant blue emission at 437 nm, with the lifetime and quantum yield being 3.05 ns and 13.9%, respectively (Figure S4, Supporting Information). However, as the UV is switched off, green afterglow lasting for 3 s are observed (Figure 1a). This strategy of SPMSA is general for creating CTE-RTP materials (Figure S5, Supporting Information), but the CTE-RTP resulted from APAM-PHMB flake is the strongest. Figure 1b and Figure S6 (Supporting Information) show that the broad phosphorescence band of the APAM-PHMB flake ranges



Figure 1. a) Systematically illustration of electrostatic self-assembly and intermolecular force of APAM and PHMB. b) Excitation-fluorescence mapping of APAM-PHMB flake. c) Schematic diagram of energy-level structure of APAM-PHMB with wavelength-dependent fluorescence and wavelength-independent phosphorescence. d) Excitation-phosphorescence mapping of APAM-PHMB flake.



from 400 to 700 nm, with the peak wavelength locating stably at 513 nm. The lifetime and quantum yield for this CTE-RTP is 291.5 ms and 2.3%, respectively. It is noticed that the CTE fluorescence maximum for the APAM-PHMB flake is excitationdependent (Figure 1c and Figure S7, Supporting Information). As the excitation wavelength increases from 300 to 370 nm, the emission shifts from 340 to 440 nm (Figure 1c). According to the through-space conjugation (TSC) theory,^[28,29] this is due to the polydispersed clustering states of the clusteroluminogens. Since each of these states has distinct excited energy levels (S_a, S_b, S_c, etc.), the resulting emission is also different. However, the CTE-based phosphorescence emission peak remains constant at 513 nm as the excitation wavelength varies (Figure 1b and Figure S6, Supporting Information), only the lifetime of phosphorescence decreases from 379.7 to 229.0 ms with the red shift of excitation wavelength from 320 to 380 nm (Table S1, Supporting Information). This means that the triplet energy levels for different clusters are almost the same(Figure 1d), so that the current CTE-RTP did not display excitation dependence like what occurs in other CTE-RTP systems.^[47]

2.2. The Humidity Resistance and Oxygen Resistance of the APAM-PHMB Flake

Phosphoresce is usually easily quenched by moisture since water often promotes the dynamics and the vibrational dissipation of the phosphors.^[46] However, the APAM-PHMB flake prepared by SPMSA has good humidity resistance, although both APAM and PHMB are hydrophilic polymeric materials. We have compared the contact angle and phosphorescence of the APAM-PHMB flake with that of the casting films of individual APAM and PHMB. It reveals that contact angle of water on the surfaces of the casted APAM film and PHMB film are $22 \pm 1^{\circ}$ and $60 \pm 1^{\circ}$, respectively (Inset in Figure 2a,b). As a result, their phosphorescence intensity will decrease rapidly with the increase of humidity and disappeared at relative humidity (RH) of 29% (Figure 2a,b and Figure S8, Supporting Information). However, after SPMSA, the contact angle of APAM-PHMB is $111 \pm 1^{\circ}$. As the RH rises to 57%, the phosphorescence intensity is still 71% of that at RH = 0(Figure 2c), and the lifetime remains 145.0 ms (Figure S9, Supporting Information). In a certain humidity environment, the lifetime of the flake will reach equilibrium after 2 days and remain stable in extending storage time, which further confirms the super resistance to humidity (Figure S10, Supporting Information). In addition, APAM-PHMB flake shows excellent resistant to wide pH range (pH 1-13) and NaCl solution (<0.1 mol L⁻¹) (Figures S11–S12, Supporting Information). Since merely ionic interaction would not result in such excellent moisture resistance,^[42-45] we speculate that the strong interaction between APAM and PHMH have forced the hydrophobic hydrocarbon groups in the polymers in close vicinity, so that they are enriched to the surface of the APAM-PHMB flake to decrease the interface energy (Figure 2d). Indeed, the N-H vibrational band at 2173 cm⁻¹ in the FT-IR spectra is broadened considerably upon the self-assembly (Figure S13, Supporting Information).



Figure 2. a–c) The contact angle and phosphorescence of (a) APAM-dropping film, (b) PHMB-dropping film, and (c) APAM-PHMB flake under different relative humidity (%). d) Systematically illustration of humidity resistance of APAM-PHMB flake. e) Systematically illustration of oxygen resistance of APAM-PHMB flake. f) The phosphorescence of APAM-PHMB freeze-dried precipitates and SPMSA flake under air, vacuum and N₂ atmosphere. g,h) The TEM picture of (g) SPMSA flake and (h) APAM-PHMB freeze-dried precipitates.



Excitingly, the APAM-PHMB flake prepared by SPMSA also exhibited excellent oxygen resistance (Figure 2e). Excited phosphors would undergo quenching through collision with O_2 .^[48] It is noteworthy that the SPMSA flake has almost the same phosphorescence intensity and lifetime under air, vacuum, and N₂ (Figure 2f), and the corresponding lifetime is 290.0, 362.4, and 352.2 ms, respectively (Figure S14, Supporting Information). In contrast, the phosphorescence of the freezedried fluffy powders in the air is very weak, and only becomes strong in vacuum and N₂ (Figure 2f). The lifetime in the air is 54.3 ms, and raise to 360.0 and 350.8 ms in vacuum and N₂ (Figure S15, Supporting Information). The excellent oxygen resistance of the flake is attributed to its densely woven network structure with mesh sizes smaller than 1 nm as revealed by TEM (Figure 2g) and SEM (Figure S16, Supporting Information), which is in clear contrast with the extensive 20–50 nm large pores in the fluffy powder system (Figure 2h). This means that the hydrogen bonding and electrostatic interaction sites are paired fairly well (Figure 2d) in the SPMSA flake.

2.3. CTE-PRET

The robust CTE-RTP generated by the strategy of SPMSA allows facilely check the possibility of PRET from the CTE-RTP to acceptor dyes. The yellow fluorescent dye DFF is chosen as the model acceptor (inset in **Figure 3**a). The absorption range of DFF is about 410–520 nm, which overlaps well



Figure 3. a) Normalized absorption of DFF solution (red) and phosphorescence spectra of APAM-PHMB flake (green, $\lambda_{ex} = 365$ nm). b) Normalized afterglow spectra of APAM-PHMB \supset DFF flakes ($\lambda_{ex} = 365$ nm). c) Lifetime of the peak of APAM-PHMB \supset DFF flakes with different mass fraction (wt‰) of DFF ($\lambda_{ex} = 365$ nm). d) Fluorescence and afterglow spectra of APAM-PHMB \supset DFF (2.43‰) ($\lambda_{ex} = 365$ nm). e) Systematically illustration of the energy transfer process of CTE-PRET.



with the phosphorescent emission band (400-700 nm) of APAM-PHMB, indicating it is a good acceptor for the APAM-PHMB CTE-RTP donor (Figure 3a and Figure S17, Supporting Information). Upon addition of the DFF solution to the aqueous solution of PHMB, DFF is introduced to the original APAM-PHMB precipitates, which can then be pressed into a homogeneous flake. Figure 3b shows that as the content of DFF in the flake ranges from 0 to 17.8%00, the intensity of CTE-RTP peak decreases and the RTP intensity of DFF increases, corresponding to the change of afterglow color from green to yellow (inset in Figure 3c). In line with this, the lifetime of the CTE-RTP decreases continuously (Figure 3c and Table S2, Supporting Information). On the meanwhile, DFF gains similar lifetimes. Clearly, PRET has occurred between the CTE-RTP of the APAM-PHMB flakes and the doped DFF acceptor, and the energy transfer rate is 44.3% at the optimum DFF doping ratio of 2.43%00, where its afterglow intensity is the strongest. Considering that the afterglow emission peak of DFF overlaps perfectly with its fluorescence (Figure 3d), the PRET has occurred between the triplet state of the lone-pair clusters of the APAM-PHMB and the S1 state of DFF, as demonstrated in Figure 3e.

2.4. Generality of the CTE-PRET for Arbitrary Acceptors

The extremely broad phosphorescent emission range of 400–700 nm for the APAM-PHMB flake allows the occurrence of PRET to nearly all the doped fluorescent dyes, since most

of them have absorption in this range (Figure S18, Supporting Information). Figure 4a shows that the CTE-PRET is widely applicable to almost any dyes doped in the APAM-PHMB flake. Regardless it is cation, anion, or neutral, all fluorescent acceptor dyes can achieve characteristic long afterglow emission in the APAM-PHMB flake. Clearly, the diversified states of the CTE clusters would avoid the direct electron transfer between the donor and acceptor, and the irregular clusters have arbitrary dipole orientations in the entire space, so that the doped dyes can always receive the excitation energy of the donor via resonance. Namely, the sea of the ill-defined CTE clusters is capable of offering the reasonable donor-acceptor distance and the donor-acceptor dipole-dipole interactions, which facilitate universal energy transfer (Figure 4b). With its super CTE-PRET, the afterglow can be tuned from blue to deep red. Part of the molecular structure, emission wavelength, and lifetime information are shown in Figure S19 and Tables S3-S4 (Supporting Information).

Benefiting from the super PRET ability of the CTE-RTP and the afterglows with different lifetimes, these CTE-PRET materials hold great promise for dynamic display in the fullspectrum. As exampled in Figure 4c, when a spliced footprint and concentric circles were constructed with APAM-PHMB films doped with different dyes, both the pattern and color evolve with time owing to the variations in afterglow lifetimes of different dyes. It is worth noting that the phosphorescent materials based on CTE have good light stability, suitable for application in anticounterfeiting (Figure S20, Supporting Information).



Figure 4. a) The long afterglow and luminescence photos of APAM-PHMB⊃Dyes under 365 nm UV light. b) Mechanism of the super PRET ability of the CTE-RTP. c) The dynamic afterglow of the CTE-PRET materials based on APAM-PHMB⊃Dyes.



ADVANCED OPTICAL MATERIALS www.advopticalmat.de

3. Conclusion

In summary, CTE-RTP is a super donor that is able to transfer its excitation energy to random acceptor dyes without specific requirements on the array and distance between donor and acceptor. Because the clusters that give emission is not welldefined, no π - π interaction between the cluster donor and the molecular acceptor could occur, which avoids the direct electron transfer between the donor and acceptor. Furthermore, the irregular clusters have arbitrary dipole orientations in the entire space, so that the doped dyes can always receive the excitation energy of the donor via resonance. We envision that the CTE-PRET would open up a new paradigm of CTE materials and makes it possible to achieve random dynamic room-temperature afterglow in the full-spectrum of visible-near infrared region.

4. Experimental Section

Solid-Phase Molecular Self-Assembly of APAM-PHMB: Anionic polyacrylamide (APAM, Mw: ~12 000 000) was purchased from Sangon Biotech. Polyhexamethylene biguanidine hydrochloride (PHMB) was purchased from Bide Pharmatech Ltd. The experimental water was ultrapure water (Milli-Q water) with a resistivity of 18.2 M Ω · cm obtained by a Millipore ultrapure water machine. An aqueous solution of PHMB and an aqueous solution of APAM were added, reaching final concentrations of 50 mM for the ammonium-positive charges of PHMB and 50 mM for the carboxylate-negative charges of APAM. White precipitates were immediately formed after mixing. The collected precipitates were then treated in two parallel ways: subjected to a pressure imposed by finger pressing and noodle machine manufacturing under ambient environment.

Dyes Doping: 2 mM dyes aqueous solution was added to 20 mL, 50 mM (structural unit) PHMB aqueous solution in different volumes and mixed uniformly, and then mixed with 20 mL, 50 mM (structural unit) APAM aqueous solution to obtain APAM-PHMBDyes precipitates. Then, the precipitates were condensed with a pressure of 5 MPa and dried in a desiccator overnight to get APAM-PHMBDyes flakes with different doping ratios.

Estimation of the Efficiency of the Transfer: FRET and PRET could be detected in several ways.^[49-53] Energy transfer caused quenching of donor fluorescence/phosphorescence and sensitized fluorescence/phosphorescence of the acceptor. It also reduced the donor lifetime and decreased the rate of irreversible photobleaching of the donor. In this work, experimental FRET/PRET efficiencies (*E*) were obtained from steady-state measurements using

$$E = 1 - \frac{\tau_{\rm DA}}{\tau_{\rm D}} \tag{1}$$

where $\tau_{\rm DA}$ and $\tau_{\rm D}$ are the measured donor lifetimes in absence and in presence of acceptor, respectively.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

Acknowledgements

P.L. and T.W. contributed equally to this work. The authors are grateful to National Natural Science Foundation of China (grant Nos. 22172004 and

21972003) and the Beijing National Laboratory for Molecular Sciences (BNLMS) for financial support.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

afterglow, clusterization-triggered emission, phosphorescence resonance energy transfer, room-temperature phosphorescence

> Received: October 20, 2022 Revised: November 24, 2022 Published online:

- H. K. Zhang, Z. Zhao, P. R. McGonigal, R. Q. Ye, S. J. Liu, J. W. Y. Lam, R. T. K. Kwok, W. Z. Yuan, J. P. Xie, A. L. Rogach, B. Z. Tang, *Mater. Today* **2020**, *32*, 275.
- [2] X. Dou, Q. Zhou, X. Chen, Y. Tan, X. He, P. Lu, K. Sui, B. Z. Tang, Y. Zhang, W. Z. Yuan, *Biomacromolecules* **2018**, *19*, 2014.
- [3] L. Xu, J. Cao, S. Zhong, Y. Gao, X. Cui, J. Agric. Food Chem. 2021, 69, 7680.
- [4] L. Xu, J. Cao, S. Zhong, J. Wang, Y. Yang, Y. Gao, X. Cui, Int. J. Biol. Macromol. 2021, 182, 1437.
- [5] L. Xu, X. Liang, S. Zhong, Y. Gao, X. Cui, ACS Sustainable Chem. Eng. 2020, 8, 18816.
- [6] X. Dou, T. Zhu, Z. Wang, W. Sun, Y. Lai, K. Sui, Y. Tan, Y. Zhang,
 W. Z. Yuan, Adv. Mater. 2020, 32, 2004768.
- [7] S. X. Tang, T. J. Yang, Z. H. Zhao, T. W. Zhu, Q. Zhang,
 W. B. W. Hou, W. Z. Yuan, *Chem. Soc. Rev.* 2021, 50, 12616.
- [8] Z. Yuan, J. Wang, L. Chen, L. Zou, X. Gong, X. Ma, CCS Chem. 2020, 2, 158.
- [9] J.-X. Wang, H. Zhang, L.-Y. Niu, X. Zhu, Y.-F. Kang, R. Boulatov, Q.-Z. Yang, CCS Chem. 2020, 2, 1391.
- [10] Y. Wen, H. Liu, S.-T. Zhang, G. Pan, Z. Yang, T. Lu, B. Li, J. Cao, B. Yang, CCS Chem. 2021, 3, 1940.
- [11] Q. Wang, X. Y. Dou, X. H. Chen, Z. H. Zhao, S. Wang, Y. Z. Wang, K. Y. Sui, Y. Q. Tan, Y. Y. Gong, Y. M. Zhang, W. Z. Yuan, Angew. Chem., Int. Ed. 2019, 58, 12667.
- [12] Y. Z. Wang, X. Bin, X. H. Chen, S. Y. Zheng, Y. M. Zhang, W. Z. Yuan, Macromol. Rapid Commun. 2018, 39, 1870060.
- [13] X. Y. Dou, Q. Zhou, X. H. Chen, Y. Q. Tan, X. He, P. Lu, K. Y. Sui, B. Z. Tang, Y. M. Zhang, W. Z. Yuan, *Biomacromolecules* **2018**, *19*, 2014.
- [14] X. H. Chen, W. J. Luo, H. L. Ma, Q. Peng, W. Z. Yuan, Y. M. Zhang, Sci. China Chem. 2018, 61, 351.
- [15] S. Y. Zheng, T. W. Zhu, Y. Z. Wang, T. J. Yang, W. Z. Yuan, Angew. Chem., Int. Ed. 2020, 59, 10018.
- [16] C. Shang, Y. X. Zhao, J. Y. Long, Y. Ji, H. L. Wang, J. Mater. Chem. C 2020, 8, 1017.
- [17] B. Liu, B. Chu, Y. L. Wang, Z. Chen, X. H. Zhang, Adv. Opt. Mater. 2020, 8, 1902176.

ADVANCED SCIENCE NEWS

www.advancedsciencenews.com

- [18] D. Jia, L. Cao, D. Wang, X. Guo, H. Liang, F. Zhao, Y. Gu, D. Wang, *Chem. Commun.* 2014, 50, 11488.
- [19] C. Shang, N. Wei, H. Zhuo, Y. Shao, Q. Zhang, Z. Zhang, H. Wang, J. Mater. Chem. C 2017, 5, 8082.
- [20] Z. Guo, Y. Ru, W. Song, Z. Liu, X. Zhang, J. Qiao, Macromol. Rapid Commun. 2017, 38, 1700099.
- [21] P. Liu, W. Fu, P. Verwilst, M. Won, J. Shin, Z. Cai, B. Tong, J. Shi, Y. Dong, J. S. Kim, Angew. Chem., Int. Ed. 2020, 59, 8435.
- [22] F. T. S. Chan, G. S. Kaminski Schierle, J. R. Kumita, C. W. Bertoncini, C. M. Dobson, C. F. Kaminski, *Analyst* **2013**, *138*, 2156.
- [23] L. L. Du, B. L. Jiang, X. H. Chen, Y. Z. Wang, L. M. Zou, Y. L. Liu, Y. Y. Gong, C. Wei, W. Z. Yuan, *Chinese J. Polym. Sci.* **2019**, *37*, 409.
- [24] M. Li, X. N. Li, X. F. An, Z. J. Chen, H. N. Xiao, Front. Chem. 2019, 7, 447.
- [25] X. H. Chen, X. D. Liu, J. L. Lei, L. Xu, Z. H. Zhao, F. Kausar, X. Y. Xie, X. Y. Zhu, Y. M. Zhang, W. Z. Yuan, *Mol. Syst. Des. Eng.* **2018**, *3*, 364.
- [26] S. Koley, S. Ghosh, Phys. Chem. Chem. Phys. 2016, 18, 24830.
- [27] Q. Zhou, Z. Y. Wang, X. Y. Dou, Y. Z. Wang, S. E. Liu, Y. M. Zhang, W. Z. Yuan, *Mat. Chem. Front.* **2019**, *3*, 257.
- [28] W. Z. Yuan, Y. M. Zhang, J. Polym. Sci. Pol. Chem. 2017, 55, 560.
- [29] Q. Zhou, B. Cao, C. Zhu, S. Xu, Y. Gong, W. Z. Yuan, Y. Zhang, Small 2016, 12, 6586.
- [30] T. W. Zhu, T. J. Yang, Q. Zhang, W. Z. Yuan, Nat. Commun. 2022, 13, 2658.
- [31] S. X. Tang, Z. H. Zhao, J. Q. Chen, T. J. Yang, Y. Z. Wang, X. H. Chen, M. Lv, W. Z. Yuan, Angew. Chem., Int. Ed. 2022, 61, e2021173.
- [32] Y. Chen, Y. J. Xie, Z. Li, J. Phys. Chem. Lett. 2022, 13, 1652.
- [33] Y. B. Feng, H. X. Yan, F. Ding, T. Bai, Y. F. Nie, Y. Zhao, W. X. Feng, B. Z. Tang, Mater. Chem. Front. 2020, 4, 1375.
- [34] B. Chu, H. K. Zhang, K. L. Chen, B. Liu, Q. L. Yu, C. J. Zhang, J. Z. Sun, Q. Yang, X. H. Zhang, B. Z. Tang, J. Am. Chem. Soc. 2022, 144, 15286.
- [35] J. Y. Zhang, P. Alam, S. W. Zhang, H. C. Shen, L. R. Hu, H. H. Y. Sung, I. D. Williams, J. W. Sun, J. W. Y. Lam, H. K. Zhang, B. Z. Tang, Nat. Commun. 2022, 13, 3492.

[36] Q. X. Dang, Y. Y. Jiang, J. F. Wang, J. Q. Wang, Q. H. Zhang, M. K. Zhang, S. M. Luo, Y. J. Xie, K. Y. Pu, Q. Q. Li, Z. Li, *Adv. Mater.* 2020, 32, 2006752.

WANCED

www.advopticalmat.de

- [37] Y. S. Wang, J. Yang, M. M. Fang, Y. S. Yu, B. Zou, L. W. Wang, Y. Tian, J. X. Cheng, B. Z. Tang, Z. Li, *Matter-Us* **2020**, *3*, 449.
- [38] S. Kuila, S. J. George, Angew. Chem., Int. Ed. 2020, 59, 9393.
- [39] Y. L. Ning, J. F. Yang, H. Si, H. Z. Wu, X. Y. Zheng, A. J. Qin, B. Z. Tang, Sci. China Chem. 2021, 64, 739.
- [40] R. Gao, M. S. Kodaimati, D. P. Yan, Chem. Soc. Rev. 2021, 50, 5564.
- [41] H. Gui, Z. Huang, Z. Yuan, X. Ma, CCS Chem. **2022**, *4*, 173.
- [42] M. Xie, Y. Che, K. Liu, L. Jiang, L. Xu, R. Xue, M. Drechsler, J. Huang, B. Z. Tang, Y. Yan, *Adv. Funct. Mater.* 2018, 28, 1803370.
- [43] H. Jin, M. Xie, W. Wang, L. Jiang, W. Chang, Y. Sun, L. Xu, S. Zang, J. Huang, Y. Yan, L. Jiang, CCS Chem. 2020, 2, 98.
- [44] W. Wang, M. Xie, H. Jin, W. Zhi, K. Liu, C. Ma, P. Liao, J. Huang, Y. Yan, Mater. Chem. Front. 2020, 4, 1530.
- [45] S. Gao, W. Wang, T. Wu, S. Jiang, J. Qi, Z. Zhu, B. Zhang, J. Huang, Y. Yan, ACS Appl. Mater. Interfaces 2021, 13, 34843.
- [46] S. Garain, B. C. Garain, M. Eswaramoorthy, S. K. Pati, S. J. George, Angew. Chem., Int. Ed. 2021, 60, 19720.
- [47] S. Y. Zheng, T. W. Zhu, Y. Z. Wang, T. J. Yang, W. Z. Yuan, Angew. Chem., Int. Ed. 2020, 59, 10018.
- [48] D. B. Papkovsky, R. I. Dmitriev, Chem. Soc. Rev. 2013, 42, 8700.
- [49] R. J. Grainger, D. G. Norman, D. M. J. Lilley, J. Mol. Biol. 1999, 288, 585.
- [50] A. K. Kenworthy, M. Edidin, J. Cell Biol. 1998, 142, 69.
- [51] C. Madeira, L. M. S. Loura, M. R. Aires-Barros, A. Fedorov, M. Prieto, *Biophys. J.* **2003**, *85*, 3106.
- [52] Z. Wang, C. Y. Zhu, J. T. Mo, P. Y. Fu, Y. W. Zhao, S. Y. Yin, J. J. Jiang, M. Pan, C. Y. Su, Angew. Chem., Int. Ed. 2019, 58, 9752.
- [53] C. Zhang, Z.-P. Yan, X.-Y. Dong, Z. Han, S. Li, T. Fu, Y.-Y. Zhu, Y.-X. Zheng, Y.-Y. Niu, S.-Q. Zang, *Adv. Mater.* **2020**, *32*, 2002914.