Recent advances in room temperature phosphorescence of crystalline boron containing organic compounds

Hannah E. Hackney | Dmitrii F. Perepichka

Department of Chemistry, McGill University, Montreal, QC, Canada

Correspondence
Dmitrii F. Perepichka, Department of Chemistry, McGill University, Montreal, QC H3A 0B8, Canada.
Email: dmitrii.perepichka@mcgill.ca

Funding Information
Natural Sciences and Engineering Research Council of Canada

Abstract
In organic compounds, room temperature phosphorescence (RTP) is a rare, yet highly desirable, property that is important for a wide variety of applications, including tissue imaging, anticounterfeiting technologies, photodynamic therapy, and organic light-emitting devices. While most organic RTP molecules rely on heavy atoms or carbonyl functional groups to accelerate singlet-to-triplet intersystem crossing, in the past few years there have been several reports of RTP induced by boron-containing functional groups. This minireview covers the recent literature on RTP of crystalline boroorganic compounds and analyzes the connections between molecular structure, intermolecular interactions, and the resulting phosphorescence.

Keywords
luminescence, organic crystals, organoboron chemistry, room temperature phosphorescence

1 | INTRODUCTION

Phosphorescence occurs when an excited electron flips its spin, transforming the singlet to the triplet excited state (intersystem crossing, ISC), and then relaxes back to the ground state emitting a photon. Room temperature phosphorescent (RTP) materials show promise for a variety of applications, including sensors, tissue imaging, organic light-emitting diodes (OLEDs), photodynamic therapy, and anticounterfeiting.

Though RTP organic molecules are relatively rare, they have several advantages over organometallic or inorganic phosphors, such as longer RTP lifetimes, lower toxicity, greater resource availability, and applicability to low-cost industrial printing technologies.

Both ISC and radiative emission of the triplet are spin-forbidden processes that are slow in organic compounds. Since triplet excited states can also relax to the ground state nonradiatively through thermal vibrations, achieving efficient phosphorescence requires restricting these motions, as in a frozen solution or a rigid polymer matrix. The solid state can also minimize interactions with oxygen, which quenches triplet excited states via energy transfer (forming singlet oxygen). In principle, these motions can also be restricted at room temperature in the crystalline lattice of the phosphorescent compounds, although one also has to manage competing deactivation via triplet-triplet annihilation.

While a growing number of crystalline RTP materials are being reported, our understanding of how to engineer organic RTP solids is still very limited. At a molecular level, efficient ISC and phosphorescence require strong spin-orbit coupling (SOC) between S1/T1 and T1/S0 states, respectively. Enhancing the SOC in organic compounds requires incorporation of heavy atoms such as Br, I, or Te or functional groups that can couple transitions of different orbital momentum. The latter effect has long been known in aromatic ketones, and was generalized in El-Sayed’s rule.

In the last few years there have been several reports that the RTP can also be observed in boroorganic materials without any of the above “phosphorogenic” groups. Many boroorganics are luminophores, widely used in fluorescence imaging and electroluminescence technologies.

Their unique properties stem from boron’s low electronegativity, which makes it a σ-bond donor, and its vacant p-orbital, which makes it a π-bond acceptor. As discussed below, this unusual electronic structure may also be the reason for the RTP observed in some boroorganic solids.

The efficiency of RTP in some boroorganic solids is comparable to those reported in more traditional organic phosphors based on aromatic ketones or heavy heteroatoms. However, the unique electronic properties bestowed by boron functional groups and lack of elemental toxicity make them an attractive, even if not yet fully understood, structural motif.
for the growing field of organic RTP materials. Much of the reactivity (electrophilinic and oxidative/protodeborylation) and instability of organoboron compounds is associated with the p₂ orbital. Therefore, four coordinate boron compounds tend to be more stable than their three coordinate counterparts as the orbital is no longer vacant. Nonetheless, there are stereric and electronic strategies available to improve the stability of tricoordinate boron, such as mesityl substituents, enforced planarity, or lone pair conjugation.

As is the case for other types of organic RTP materials, the exact mechanisms for efficient ISC and triplet emission in boroorganic compounds are still a subject of debate. However, it seems reasonable that the change of orbital momentum associated with σ→π* transitions at the boroorganic chromophore can increase the SOC between S₁/T₁ and T₁/S₀ states, which is the key for efficient phosphorescence. The extension of π-conjugation (via tricoordinate boron) or rigidification of the molecule (in tetracoordinate boroganics such as boron difluorides complexes) can lead to increased oscillator strength of radiative transitions and suppress the vibrational relaxation, respectively. Both of these factors contribute to efficient luminescence of boroorganic compounds in general.

This minireview assesses the emerging literature on the RTP of crystalline boroorganic compounds and highlights the observed relationships between the structure of the boron functional group, the crystal packing, and the phosphorescence properties. The article is organized in three sections, which discuss RTP in boron difluorides, boronic acids and esters, and finally triarylboranes.

1.1 Boron difluorides

Among many boroorganic luminophores, boron difluoride stands as one of the most robust and versatile functional groups and they have been integrated into a variety of scaffolds (most famously, in BODIPY dyes). It is thus not surprising that boron difluoride derivatives were the earliest examples of phosphorescent boroorganic solids. In 2007, the Fraser lab reported that boron difluoride appended lactide polymer 1a (Scheme 1) exhibited long-lived RTP (phosphorescence lifetime τ₀ = 0.17 s) under vacuum below its glass transition temperature. Heating the polymer above its glass transition temperature (52 °C) leads to the disappearance of the phosphorescence, highlighting the importance of a rigid environment for organic RTP. The dual RTP/fluorescence emission of an iodinated derivative of polymer 1a was later used by the same group in bioimaging. A selective quenching of the RTP channel by oxygen (with stable fluorescence emission) provided a convenient ratiometric imaging of tumor hypoxia.

One of the first examples of efficient RTP in a crystalline BF₂ derivative was compound 1b. Although the quantum yield of emission was not reported, the steady-state photoluminescence at room temperature revealed that the phosphorescence band (λₘₐₓ = 500 nm, τₚ = 215 ms) was stronger than the fluorescence (λₘₐₓ = 452 nm). Note that, according to El-Sayed’s rule, efficient ISC would also be expected in the parent β-ketoester due to enhanced SOC on the carbonyl group. However, the BF₂ complexation rigidifies the molecule and extends the π-conjugation through the enolate resonance form. These factors increase the efficiency of both fluorescent and phosphorescent transitions and also red-shift the emission into visible range of the spectrum.

In 2016, Sakai and coworkers reported RTP in crystals of iodinated boron diketone 1c. The introduction of heavy atoms accelerates ISC and two emission bands were observed in crystals of 1c at room temperature: fluorescence at 460 nm and phosphorescence at 527 nm (τₚ = 1.3 ms). TD-DFT calculations on the crystallographically observed dimers of 1c reveal a very important role of the crystal packing: while the fluorescence is allowed in a single molecule (the S₁ → S₀ electronic transition has an oscillator strength f = 0.66), it is forbidden in the dimer (f = 0.00), and this suppression of fluorescence due to π-stacking interactions enables the competing phosphorescence.

Recently, Wei Huang and coworkers reported the remarkably efficient ultralong (τ₀ ~ 0.3 s) RTP boron diketone 2 Linking the electron-donating carbazole groups with the acceptor diketone moiety in a twisted geometry leads to a low singlet-triplet gap and enables reverse intersystem crossing (RISC). As a result, the crystals of 2 reveal both phosphorescence (500–600 nm) and thermally activated delayed fluorescence (TADF, at 475 nm) in the afterglow with a remarkable photoluminescence quantum yield of 45%. As expected, the phosphorescence is enhanced and the delayed fluorescence is suppressed at lower temperatures, confirming the thermally activated process (Figure 1A). The authors attribute the ultralong afterglow emission time to the aggregation-induced “stabilized” T₁* states in the crystal. The crystallographic analysis shows H-aggregation in the solid state (Figure 1B), which stabilizes triplet excitons and was presumed to be the origin of the ultralong-lived T₁* state (Figure 1C). It should be noted that ultralong RTP often arises from lower-gap exciton traps. For example, the recent work from Bin Liu and coworkers shows that ultralong RTP of many carbazole derivatives is due to small amounts (≤0.5%) of benzof/furindole impurity present in most commercial carbazole samples.
SCHEME 2  Boron appended tellurophenes[35]

S 1
n = 1, 3a
n = 2, 3b

Bpin

Te

Bpin

Bpin

Bpin

Bpin

Bpin

Bpin

Bpin

Te

Bpin

O

O

O

Bpin = \sim B

1.2  Boronic acids and esters

Despite their enormous popularity as synthetic intermediates, boronic acids and esters have only recently found application as luminophores.[30–34] To our knowledge, the earliest example of efficient RTP (phosphorescence quantum yield \(\sim 12\%\)) in boronic esters was reported by Rivard and coworkers for tellurophene derivatives 3a–c with BPin substituents (Scheme 2).[35] The heavy Te atom was shown to be essential for accelerating the ISC and the phosphorescence transition (\(\tau_p = 0.17\) ms) as no RTP was observed for thiophene and selenophene analogues. On the other hand, the importance of the boron ester group for RTP was established by replacing the BPin group with 2-thienyl substituents which resulted in a nonemissive material.

In 2017, two groups independently published the first reports of the RTP of heavy-atom free crystalline arylboronic acids and esters. Yuasa and coworkers examined a few boronic acids and esters (4a–4b, 7a)[36] while the Fukushima lab reported a library of various phenylboronic acid derivatives (5–8, Scheme 3).[37] The majority of the studied compounds revealed blue-to-green RTP (450–540 nm) in the solid state.
state with $\tau^P$ in the range of 0.20–1.85 s. However, no clear relationships could be drawn between the molecular structure and RTP efficiency. The authors have also analyzed crystal structure of several of these derivatives, but admit that the reasons behind different RTP properties of various derivatives “remain elusive”.[37]

Yuasa and coworkers measured the RTP of benzenedi-boronic acid 4b crystals in varied magnetic field and observed a modest but measurable (up to 4%) increase of phosphorescence above $\sim$30 mT (Figure 2).[36] The authors proposed that the ISC is facilitated by the weakened spin–spin interaction in the delocalized excitons in the crystal. This allows for spin flipping to be induced by the local magnetic field of the nuclei (hyperfine coupling) and further accelerated in the external magnetic field. This hypothesis was rationalized using TD-DFT calculations on clusters (trimer) of 4b using crystallographic geometry.

A series of similar substituted phenyboronic acids and anhydrides (4c–4k, 9a–9j) was studied by Chai et al., focusing on the relationship between the crystal packing and RTP.[38] It was suggested that strong intermolecular interactions and dense crystal packing, induced by the network of hydrogen bonds between boronic acids, help reduce the nonradiative decay. Notably, the compounds’ RTP was not strongly affected by exposure to air, suggesting that a rigid crystal matrix impedes penetration of triplet-quenching oxygen.

The phenylboronic acid 4d with electron-donating MeO group exhibits blue-green RTP emission and a remarkably long lifetime of $\sim$2 s.[38] Using TD-DFT calculations on different $\pi$-stacking geometries, the authors suggested that strong/close $\pi$–$\pi$ stacking decreases the energy of the $S_1$ state to a greater degree than the $T_1$ state, leading to narrowing $\Delta E_{ST}$ gap. Effective intermolecular orbital overlap also increases electron delocalization and stabilizes triplet excitons, which explains the red shifted emission of crystals compared to that of doped polymers (solid solutions). This hypothesis appears consistent with the trend in lifetimes observed for compounds 4c–4g, where the shortest lifetime is associated with the poorest $\pi$–$\pi$ stacking.

In contrast, the triphenylboroxine derivatives 9a–9j show less efficient $\pi$-stacking in crystal and lack H-bonding interactions, which together lead to a less rigid intermolecular packing compared to the corresponding boronic acids. This difference in crystal packing was cited as a reason for the shorter triplet lifetimes and a less efficient RTP of boroxines.
Triarylboranes have long been used in organic optoelectronic materials, especially in donor–acceptor systems, and some have found application in OLEDs.[17] Most recently, Todd Marder and coworkers discovered that simple triarylboranes (Scheme 4) without any lone pairs can display RTP.[46] This differs from typical organic RTP, which is facilitated by $1(n, \pi^*) \rightarrow 3(\pi, \pi^*)$ transitions. The accelerated ISC is explained by mixing between the boron’s $\sigma$-bond and empty $p$-orbital, in a $\sigma (\pi, p) \rightarrow (\pi, p)$ type transition, which was supported by TD-DFT calculations (Figure 5a).

When comparing the phosphorescence of the compounds in crystals versus a frozen solvent glass, the emission showed a considerable redshift that could not be explained by temperature effects alone. A similar shift of the RTP band was also observed upon increasing the concentration in doped films, pointing to an aggregation-induced phenomenon. While all four triarylboranes phosphoresced at low temperature, only $\lambda_{\text{max}} = 420 \text{ nm}$ crystals of 11 lose their crystalline order and display a yellow emission ($\lambda_{\text{max}} = 540 \text{ nm}$). This mechanoluminescence property has been observed in many pyrene derivatives and is associated with the formation of excimers in the amorphous solids.[34,43] However, crystalline 11 also exhibited weak RTP (quantum yield < 3%) at ~550 nm with a remarkably short (for organic compounds) $\tau_P$ of 34 $\mu$s. There was no $\pi$-stacking apparent in the crystal structure, likely due to the steric bulk of the four Bpins, and the authors speculate that the large distance between pyrene molecules (~6.96 Å) could prevent phosphorescence quenching via triplet–triplet annihilation. TD-DFT calculations revealed a small $\Delta E_{\text{el}}$ of 0.08 eV, which would also facilitate ISC.

Zhang et al. synthesized different esters of p-carbazolophenylboronic acid with the goal of exploring the effect of packing on their RTP properties (Figure 4).[44] In this series, the electronic character of the ester is almost identical, but the substituent size is varied so that the difference in luminescence properties can be attributed to packing. While the parent p-carbazolophenylboronic acid and its Bpin ester exhibited no afterglow, esters 12a–12d exhibited weak yellow RTP at ~550 nm (total luminescence quantum yield < 0.5%). Interestingly, six-membered esters 12c and 12d showed more efficient RTP and much longer lifetimes than 12a and 12b. The crystallographic analysis was performed for all 4 esters, although no clear reasons for the different RTP behavior were identified.

The reports on boronic acids and esters in this section can be contextualized by a 2021 paper revealing a weak but long lived (0.3 s) RTP at ~450 nm of crystalline boric acid $\text{H}_3\text{BO}_3$.[45] This molecule packs in stacks of planes formed by a hexagonal network of hydrogen bonded molecules. TD-DFT calculations suggest delocalization of the frontier orbitals throughout the layer, as through-space conjugation involving lone pairs (n) of the oxygen atoms and vacant $p_z$ orbitals of boron atoms, and it explains the low energy emission wavelength of such a small molecule. Most likely, the ISC is facilitated by coupling of $n \rightarrow \sigma^*$ and $n \rightarrow p_z$ transitions, associated with the change of the orbital angular momentum.

### 1.3 Triarylboranes

Boranes have long been used in organic optoelectronic materials, especially in donor–acceptor systems, and some have found application in OLEDs.[17] Most recently, Todd Marder and coworkers discovered that simple triarylboranes 13a–d (Scheme 4) without any lone pairs can display RTP.[46] This differs from typical organic RTP, which is facilitated by $1(n, \pi^*) \rightarrow 3(\pi, \pi^*)$ transitions. The accelerated ISC is explained by mixing between the boron’s $\sigma$-bond and empty $p$-orbital, in a $\sigma (\pi, p) \rightarrow (\pi, p)$ type transition, which was supported by TD-DFT calculations (Figure 5a).

When comparing the phosphorescence of the compounds in crystals versus a frozen solvent glass, the emission showed a considerable redshift that could not be explained by temperature effects alone. A similar shift of the RTP band was also observed upon increasing the concentration in doped films, pointing to an aggregation-induced phenomenon. While all four triarylboranes phosphoresced at low temperature, only...
**FIGURE 4** RTP of the boronic esters under UV excitation (EE = 12a, IPE = 12b, PE = 12c, DME = 12d, TME = Bpin substituted). Inset shows PL decay curves. Reprinted with permission: Copyright The Royal Society of Chemistry 2018[41]

**SCHEME 4** Triarylboranes 13a–d and their RTP properties (λ_{max}, τ)

13a and 13c showed substantial RTP (quantum yields ~0.3% and ~1.2%, respectively, Figure 5B). The RTP efficiency correlates with the strength of intermolecular interactions, as probed by Hirshfield surface analysis of crystallographic structures as well as magnitude of the photoluminescence shift from solution to the solid state.

2 | CONCLUSION AND OUTLOOK

Boroorganic compounds exhibit highly attractive RTP properties, justifying their increasing application in the field. Though in most reported examples the photoluminescence is dominated by the fluorescent band and the phosphorescence is a minor component manifested in the time-gated measurements, the resulting afterglow can be readily observed with the naked eye. Many boron derivatives exhibit ultralong RTP (e.g., τ = 2.2 s for 4d[38]). Phosphorescence appears to be the dominant emission channel of boron diketonates 1b,[24] 1c,[25] and 2,[26] and the latter showed one of the highest afterglow quantum yields of 45% (total luminescence efficiency 54%). However, there remain a number of open questions and possibilities for future work. First, it is considerably more difficult to predict RTP of crystalline molecular materials compared to phosphorescence of individual molecules (e.g., as observed at low temperature or in solid solution). Although there are good computational tools, based on TD-DFT, to assess a molecule’s ISC and SOC in gas phase at absolute zero temperature (i.e., without considering molecular motion), their effectiveness in describing the dynamics of excited states in molecular crystals is questionable.[47] Further, the crystal packing and its effect on phosphorescence (especially at room temperature) cannot currently be predicted with any degree of reliability. Though aggregation is often considered detrimental to solid state fluorescence, strong π–π interactions and electronic coupling between molecules do not preclude, and often are essential for RTP. For example, H-aggregation of the molecules in the crystal suppresses the radiative fluorescence transition and may promote RTP. More information is constantly arising...
with respect to these open questions, as crystal engineering, boroorganic luminescence, and RTP are research areas growing rapidly in popularity. Though there are yet only a handful of examples of high-efficiency RTP in crystalline boroorganic compounds, the future appears bright.

ACKNOWLEDGMENTS

This work was supported by the Natural Sciences and Engineering Research Council of Canada through a Discovery Grant (D.F.P.) and an Alexander Graham Bell Ph.D. scholarship (H.E.H).

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ORCID

Dmitrii F. Perepichka https://orcid.org/0000-0003-2233-416X

REFERENCES

1. S. Hirata, Adv. Opt. Mater. 2017, 5, 1700116.
2. Y. Su, S. Z. F. Phua, Y. Li, X. Zhou, D. Jana, G. Liu, W. Q. Lim, W. K. Ong, C. Yang, Y. Zhao, Sci. Adv. 2018, 4, eaas9732.
3. J. Zhi, Q. Zhou, H. Shi, Z. An, W. Huang, Chem.—Asian J. 2020, 15, 947.
4. X. Yu, H. Zhang, J. Yu, Aggregate 2021, 2, 20.
5. Y. Xiong, Z. Zhao, W. Zhao, H. Ma, Q. Peng, Z. He, X. Zhang, Y. Chen, X. He, J. W. Y. Lam, B. Z. Tang, Angew. Chem. Int. Ed. 2018, 57, 7997.
6. E. Hamzehpoor, D. F. Perepichka, Angew. Chem. Int. Ed. 2020, 59, 9977.
7. Y. Zhang, S. R. Forrest, Chem. Phys. Lett. 2013, 590, 106.
8. E. Hamzehpoor, C. Ruchlin, Y. Tao, J. E. Ramos-Sanchez, H. M. Titi, G. Cosa, D. F. Perepichka, J. Phys. Chem. Lett. 2021, 12, 6431.
9. S. Mukherjee, P. Thilagat, Chem. Commun. 2015, 51, 10988.
10. T. Wang, Z. Hu, X. Nie, L. Huang, M. Hui, X. Sun, G. Zhang, Nat. Commun. 2021, 12, 1364.
11. L. Qiao, G. Gao, J. Wang, X. Gong, Q. Peng, Y. Tian, Y. Fan, H. Guo, D. Ding, Q. Li, Z. Li, Angew. Chem. Int. Ed. 2020, 59, 9946.
12. H. Li, H. Li, W. Wang, Y. Tao, S. Wang, Q. Yang, Y. Jiang, C. Zheng, W. Huang, R. Chen, Angew. Chem. Int. Ed. 2020, 59, 4576.
13. H. Yuasa, S. Kuno, BCSJ 2017, 91, 223.
14. W. Zhao, Z. He, B. Z. Tang, Nat. Rev. Mater. 2020, 5, 869.
15. Z. Wu, J. Nitsch, T. B. Marder, Adv. Opt. Mater. 2021, 9, 21004111.
16. M. A. El-Sayed, J. Chem. Phys. 1963, 38, 2834.
17. S. K. Mellerup, S. Wang, TRECHEM 2019, 1, 77.
18. M. J. D. Boddet, W. E. Piers, Can. J. Chem. 2009, 87, 8.
19. C. D. Entwistle, T. B. Marder, Angew. Chem. Int. Ed. 2002, 41, 2927.
20. Z. Zhou, A. Wakahiyama, T. Kushida, S. Yamaguchi, J. Am. Chem. Soc. 2012, 134, 4529.
21. A. Louden, K. Burgess, Chem. Rev. 2007, 107, 4891.
22. G. Zhang, J. Chen, S. J. Payne, S. E. Kooi, N. Demas, C. L. Fraser, J. Am. Chem. Soc. 2007, 129, 8942.
23. G. Zhang, G. M. Palmer, M. W. Dewhirst, C. L. Fraser, Nat. Mater. 2009, 8, 747.
24. X. Zhang, T. Xie, M. Cui, L. Yang, X. Sun, J. Jiang, G. Zhang, ACS Appl. Mater. Interfaces 2014, 6, 2279.
25. A. Sakai, E. Ohta, Y. Matsuhi, S. Ikeda, ChemPhysChem 2016, 17, 4033.
26. J. Jin, H. Jiang, Q. Yang, L. Tang, Y. Tao, Y. Li, R. Chen, C. Zheng, Q. Fan, K. Y. Zhang, Q. Zhao, W. Huang, Nat. Commun. 2020, 11, 842.
27. M. Kasa, H. R. Rawls, M. Ashraf El-Bayouni, Pure Appl. Chem. 2016, 11, 371.
28. Z. An, C. Zheng, Y. Tao, R. Chen, H. Shi, T. Chen, Z. Wang, H. Li, R. Deng, X. Liu, W. Huang, Nat. Mater. 2015, 14, 685.
29. C. Chen, Z. Chi, K. C. Chong, A. S. Batsanov, Z. Yang, Z. Mao, Z. Yang, B. Liu, Nat. Mater. 2021, 20, 175.
30. A. G. Crawford, A. D. Dwyer, Z. Liu, A. Steffen, A. Bueby, L.-O. Päls-son, D. J. Tozer, T. B. Marder, J. Am. Chem. Soc. 2011, 133, 13349.
31. K. Kato, H.-A. Lin, M. Kuwayama, M. Nagase, Y. Segawa, L. T. Scott, K. Itami, Chem. Sci. 2019, 10, 9038.
32. T. Katayama, S. Nakatsuka, H. Hirai, N. Yasuda, J. Kumar, T. Kawai, T. Hatakeyama, J. Am. Chem. Soc. 2016, 138, 5210.
33. M. Numano, N. Nagami, S. Nakatsuka, T. Katayama, K. Nakajima, S. Tatsumi, N. Yasuda, T. Hatakeyama, Chem.—Eur. J. 2016, 22, 11574.
34. T. Wang, N. Zhang, K. Zheng, J. Dai, W. Bai, R. Bai, Chem. Commun. 2016, 52, 9679.
35. G. He, W. Torres Delgado, D. J. Schatz, C. Merten, A. Mohammad-pour, L. Mayr, M. J. Ferguson, R. McDonald, A. Brown, K. Shankar, E. Rivard, Angew. Chem. Int. Ed. 2014, 53, 4587.
36. S. Kuno, T. Kanamori, Z. Yijing, H. Ohtani, H. Yuasa, ChemPhotoChem 2017, 1, 102.
37. Y. Shoji, Y. Ikabata, Q. Wang, D. Nemoto, A. Sakamoto, N. Tanaka, J. Seino, H. Nakai, T. Fukushima, J. Am. Chem. Soc. 2017, 139, 2728.
38. Z. Chai, C. Wang, J. Wang, F. Liu, Y. Xie, Y.-Z. Zhang, J.-R. Li, Q. Li, Z. Li, Chem. Sci. 2017, 8, 8536.
39. W. Wang, Y. Zhang, W. J. Jin, Coord. Chem. Rev. 2020, 404, 213107.
40. J. Zhou, L. Stojanovic, A. A. Berezin, T. Battisti, A. Gill, B. M. Kariuki, D. Bonifazi, R. Crespo-Otero, M. R. Wasielewski, L.-W. Yu, Chem. 2021, 12, 767.
41. M. Li, X. Cai, Z. Qiao, K. Liu, W. Xie, L. Wang, N. Zheng, S.-J. Su, Chem. Commun. 2019, 55, 7215.
42. V. C. Wakchaure, K. C. Ranjesh, Goudappagouda, T. Das, K. Vanka, R. Gonnade, S. S. Babu, Can. J. Chem. 2018, 96, 6028.
43. Y. Xie, Z. Li, Mater. Chem. Front. 2020, 4, 317.
44. K. Zhang, Q. Sun, L. Tang, Y. Wang, X. Fan, L. Liu, S. Xue, W. Yang, J. Mater. Chem. C 2018, 6, 8733.
45. H. Zheng, P. Cao, Y. Wang, X. Lu, P. Wu, Angew. Chem. Int. Ed. 2021, 60, 9500.
46. Z. Wu, J. Nitsch, J. Schuster, A. Friedrich, K. Edkins, M. Loebnitz, F. Dinkelbach, V. Stepelenko, F. Württem, C. M. Marian, L. J. T. B. Marder, Angew. Chem. Int. Ed. 2020, 59, 17137.
47. N. J. Bestand, F. C. Spano, Chem. Rev. 2018, 118, 7069.
**Hannah Hackney** obtained her MSc from University of Alberta in 2020 under the supervision of Dr. D.G. Hall. She is currently pursuing her PhD in Dr. Dmitrii Perepichka’s group at McGill University, where her research focuses on the synthesis and device applications of luminescent organic semiconductors.

**Dmitrii Perepichka** (Ukraine, 1972) is William MacDonald professor of chemistry at McGill University, Montreal. He obtained his PhD from the Institute of Physical Organic & Coal Chemistry in Ukraine and worked as a postdoctoral fellow at the University of Durham (with Prof. Bryce) and UCLA (with Prof. Wudl) before moving to Canada. His group focuses on synthetically driven research of π-electron functional materials (including small molecules, polymers, 2D materials, and COFs) and understanding their behavior in optoelectronic devices.

**How to cite this article:** H. E. Hackney, D. F. Perepichka, *Aggregate 2022*, 3, e123. https://doi.org/10.1002/agt2.123