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View Article Online
DOI: 10.1039/C7CC07310K

Journal Name

COMMUNICATION

Unprecedented rearrangement of diketopyrrolopyrroles leads to structurally unique chromophores

Received 00th January 20xx,
Accepted 00th January 20xx

DOI: 10.1039/x0xx00000x

www.rsc.org/

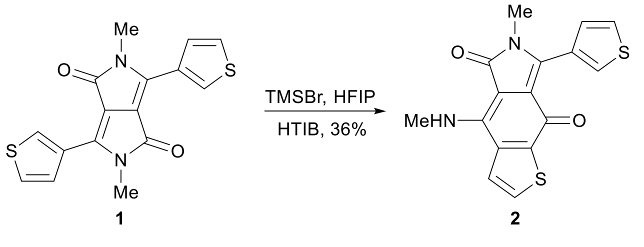
Olena Vakuliuk,[a] Shota Ooi,[a] Irena Deperasińska,[b] Olga Staszewska-Krajewska,[a] Marzena Banasiewicz,[b] Bolesław Kozankiewicz,[b] Oksana Danylyuk[c] and Daniel T. Gryko*,[a]

Diketopyrrolopyrroles possessing thienyl, furyl and benzofuryl substituents undergo unprecedented skeletal rearrangement in the presence of trimethylsilyl bromide forming thieno[2,3-*f*]isoindole-5,8-diones and furo[2,3-*f*]isoindole-5,8-diones. These relatively small dyes possess favorable photophysical properties with the emission maxima within the range of 573–624 nm, large fluorescence quantum yields, moderate sensitivity of emission to solvents polarity and HOMO-LUMO gap ca. 1.8 eV.

Organic electronics and fluorescence imaging place demands for the heterocycles with π-extended conjugation.[1] Rational design, aided by combinatorial and diversity-orientated approaches, provides invaluable routes toward novel functional materials.[2] Nonetheless, certain sets of chromophores evade even the best designed retrosynthetic analysis and serendipity factor tends to play a role in the discovery of new dyes.[3] Depending on the targeted application, fluorophores possessing different combinations of properties are desirable. Small red-emitters are pivotal for applications in live fluorescent imaging.[4]

As a part of a larger project aimed at the synthesis of novel fluorophores, we investigated oxidative aromatic coupling of diketopyrrolopyrroles (DPPs, Figure S1).[5] We focused on iodine(III) reagents which efficiently promote such transformations, making them often the reagents of choice.[6] During this study, we observed that subjecting 2,5-dimethyl-1,4-diketo-3,6-di(thien-3-yl)pyrrolo[3,4-*c*]pyrrole (**1**) to hydroxy(tosyloxy)iodobenzene (Koser's reagent, HTIB) and TMSBr led to the formation of purple compound as the sole isolable product (Scheme 1, Table 1, Entry 1).[7] Surprisingly, while the exact mol. mass of a new compound turned out to be equal to the mol. mass of substrate, the ^{1}H NMR data revealed the loss of symmetry in the product (Figure S2). Such findings are consistent only with the rearrangement of the DPP **1**.

NMR analysis provides structural information about the synthesized compound. ^{13}C NMR shows two signals in the carbonyl region (171.1 ppm and 165.6 ppm) along with two signals in the aliphatic region (32.8 ppm and 28.7 ppm). Moreover, ^{1}H NMR spectrum shows a singlet at 3.38 ppm and a doublet at 3.42 ppm, which we ascribe as methyl groups. The difference in the chemical shifts as well as the multiplicity of the signals reconfirms the formation of the asymmetric product. The character of the proton signal at 8.82 ppm (^{1}H NMR, broad quartet), reveals the opening of one γ-lactam ring and the presence of an NH-CH_3 moiety in the product. Moreover, COSY experiments support a 3+2 spin system with one uncorrelated downfield signal. The reaction on one of the carbons adjacent to the sulfur atom can rationalize this finding. Thorough analysis of ^{1}H^{13}C HSQC and ^{13}C^{13}C HMBC spectra finally uncover that the structure of **2** possesses the thieno[2,3-*f*]isoindole-5,8-dione core, thus far never described in the literature (Scheme 1). The final proof came from single crystal X-ray analysis (Figures S2-S3).



Scheme 1. The rearrangement of DPP **1** into thieno[2,3-*f*]isoindole-5,8-dione **2**.

Encouraged by the unique structure of the prepared dye, we started a systematic study of the discovered transformation. The mixture of TMSBr and HTIB provides only moderate yields of the expected product, strongly emphasizing the need for optimization of the reaction conditions (Table 1, Entry 1). In

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[a] Dr O. Vakuliuk, S. Ooi, Dr O. Staszewska-Krajewska, Prof. D. T. Gryko Institute of Organic Chemistry, Polish Academy of Sciences, Kasprzaka 44/52, 01-224 Warsaw (Poland). E-mail:dtgryko@icho.edu.pl.
[b] Prof. I. Deperasińska, Dr M. Banasiewicz, Prof. B. Kozankiewicz,Institute of Physics, Polish Academy of Sciences, Al. Lotników 32/46, 02-668 Warsaw (Poland).
[c] Dr O. Danylyuk Institute of Physical Chemistry, Polish Academy of Sciences, Kasprzaka 44/52, 01-224 Warsaw (Poland).

Electronic Supplementary Information (ESI) available: see DOI: 10.1039/x0xx00000x

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DOI: 10.1039/C7CC07510X

fact, iodine(III) reagent does not support the formation of dye **2** product which suggests the non-oxidative character of this transformation. Rather, the HTIB causes the decomposition of the desired product when added in excess (Table 1, Entries 1-3). Conversely, the reaction does not proceed in the absence of TMSBr (Table 1, Entry 4). We also elaborated the study of the discovered transformation to exhibit strong solvent dependence, which points to the importance of an acidic medium (Table 1, Entries 3, 5-7). In addition, improved solubility of the parent DPP aids a favorable outcome.

Table 1. Influence of the reaction conditions on the rearrangement of DPP **1** into dye **2**.[a]

Entry	Lewis acid,	Additive, eq.	Solvent	Yield,[b] %
1	TMSBr	HTIB (2)	HFIP	36
2	TMSBr	HTIB (0.05)	HFIP	75
3	TMSBr	-	HFIP	73
4	-	HTIB (2)	HFIP	0
5	TMSBr	-	TFE[c]	75
6	TMSBr	-	MeOH	0
7	TMSBr	-	DCM	0
8	$BF_3\cdot Et_2O$	-	HFIP	53
9	$BF_3\cdot Et_2O$[d]	-	TFE[c]	72

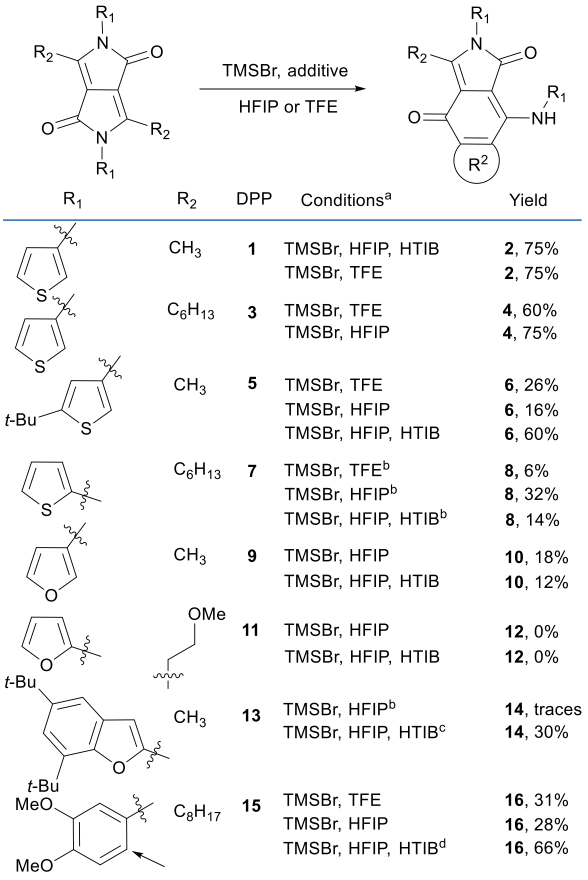
[a]Unless otherwise noted, reactions were performed with **1** (0.15 mmol), Lewis acid (0.15 mmol), solvent (1 ml), 50 °C, 17 h; [b]isolated yields are reported; [c]reaction was performed at 70˚C; [d]2 eq. of the Lewis acid was utilized.

Aiming to increase the yield of the desired product, we tested a stronger Lewis acid, $BF_3\cdot Et_2O$. Experimental investigations have proven the formation of dye **2** in up to 72% yield (Table 1, Entries 8-9). It is noteworthy that the use of $BF_3\cdot Et_2O$ requires a higher loading and elevated temperature to achieve a reasonable yield of the rearranged product. Other Lewis acids such as $POCl_3$, TfOH, TFA or BCl_3 do not mediate this rearrangement (Table S1).

Adopting conditions 2 and 5 (Table 1), we undertook the synthesis of analogues of heterocycle **2**. Experimental findings uncovered a negligible effect of alkyl substituents on the discovered transformation (Scheme 2). Notably, in this case the reaction medium plays an important role. We observed a significant improvement in the yield of dye **4** (60% *versus* 75%) when HFIP was used in place of TFE. Variations in the solubility of the substrate in the tested solvents can probably rationalize this finding. Surprisingly, the transformation of DPP **5**, bearing additional *tert*-butyl groups, does not proceed as expected in either TFE or HFIP. Unexpectedly, the presence of HTIB in a catalytic amount leads to significant improvement of the reaction outcome (Scheme 2).

2,5-Di(*n*-hexyl)-1,4-diketo-3,6-di(thien-2-yl)pyrrolo[3,4-*c*]pyrrole (**7**) affords desired product **8** at a minuscule 6% yield even if the reaction is conducted for 3 days. The addition of Koser's reagent improves reactivity of DPP **7**, however, probably due to the oxidative character, this reagent induces the decomposition of the product or intermediates. Luckily, the replacement of TFE with HFIP and lowering the reaction temperature to 50 °C lead to the desired product in 32% yield.

Diketopyrrolopyrroles bearing 2-furyl and 3-furyl groups (**9** and **11**) display lower reactivity comparing to **1** and **7**, respectively. The desired product was obtained in low yield only for the DPP **9**. The attempts to improve the reaction outcome (HTIB, prolongation of the reaction time) did not bring about positive results. DPP **13**, possessing a peripheral benzofuran moiety displays poor reactivity as well. Fortunately, significant stability of the rearranged product allowed for the prolongation of the reaction time as well as utilization of the iodine(III) catalyst and, in consequence, we could achieve a higher yield of **14**. Under similar conditions, the rearrangement occurs for DPP **15** (Scheme 2), bearing 3,4-dimethoxyphenyl groups. *N*-Alkylated DPPs bearing less electron-rich aryl substituents do not undergo this rearrangement.



R1	R2	DPP	Conditions[a]	Yield
	CH_3	**1**	TMSBr, HFIP, HTIB TMSBr, TFE	**2**, 75% **2**, 75%
	C_6H_{13}	**3**	TMSBr, TFE TMSBr, HFIP	**4**, 60% **4**, 75%
	CH_3	**5**	TMSBr, TFE TMSBr, HFIP TMSBr, HFIP, HTIB	**6**, 26% **6**, 16% **6**, 60%
	C_6H_{13}	**7**	TMSBr, TFE[b] TMSBr, HFIP[b] TMSBr, HFIP, HTIB[b]	**8**, 6% **8**, 32% **8**, 14%
	CH_3	**9**	TMSBr, HFIP TMSBr, HFIP, HTIB	**10**, 18% **10**, 12%
		11	TMSBr, HFIP TMSBr, HFIP, HTIB	**12**, 0% **12**, 0%
	CH_3	**13**	TMSBr, HFIP[b] TMSBr, HFIP, HTIB[c]	**14**, traces **14**, 30%
	C_8H_{17}	**15**	TMSBr, TFE TMSBr, HFIP TMSBr, HFIP, HTIB[d]	**16**, 31% **16**, 28% **16**, 66%

[a]Unless otherwise noted, reactions were performed with TMSBr (0.15 mmol), solvent (1 ml), 17 h at 50 °C (for HFIP) or 70 °C (for TFE). Isolated yields are reported; [b]reaction was conducted for 2 days; [c]reaction was conducted for 3 days; [d]reaction was performed with 2 eq. of Lewis acid.

Scheme 2. Scope of the diketopyrrolopyrroles' rearrangement.

With the library of new dyes in hand, we conducted a series of photophysical studies, which reveal that the absorption bands corresponding to the lowest energy absorption are located in the 530–606 nm region (Table 2, Figure 1), displaying bathochromic shifts in comparison to the parent DPPs. Emission maxima are red-shifted to the orange-red part of the visible spectra. Compounds **2**, **4** and **6** exhibit only small differences in absorption and emission maxima. Nevertheless, the type and position of the heteroatom influence the λ_{abs} and λ_{em}

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significantly. Different charge distribution in the molecules can rationalize both the red-shift of the absorption and emission maxima when regioisomeric products **2** and **8** are superimposed and the blue-shift of λ_{abs} and λ_{em} for dyes possessing furan unit (**2** versus **10**). Dye **14** possessing π-expanded core characterizes by the most bathochromically shifted emission and absorption in the analyzed series.

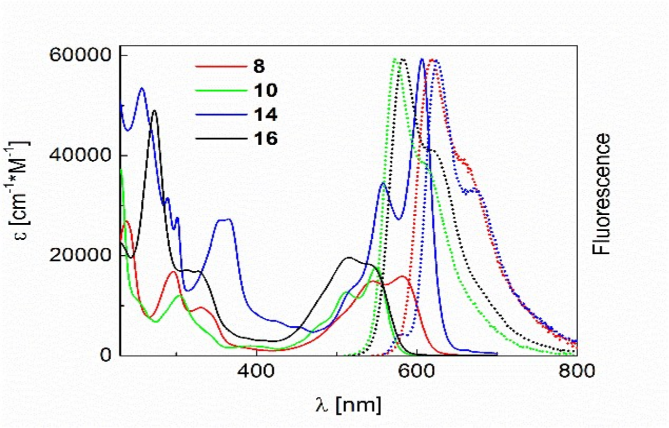

Figure 1. Absorption and fluorescence spectra for **8**, **10**, **14** and **16** in DCM.

Table 2. Photophysical properties of novel dyes measured in dichloromethane.

Dye	λ_{abs} [nm]	λ_{em} [nm]	ε_{max} [M^{-1}cm^{-1}]	Φ [%]	ΔS [cm^{-1}]	τ [ns]	k_r, [10^7s^{-1}]
2	570	601	25500	48^a	900	8.21	5.9
4	569	605	17200	49^a	1100	7.78	6.3
6	571	602	17300	47^a	900	6.45	7.3
8	582	619	16000	15^a	1000	2.25	6.7
10	549	573	17500	13^b	800	2.33	5.6
14	606	624	59400	20^c	500	2.24	8.9
16	541	582	18200	57^b	1300	7.25	7.9

^{a}Calculated with respect to Rh101 in MeOH; ^{b}calculated with respect to Rh6G in EtOH; ^{c}calculated with respect to SRh101 in EtOH.

Fluorescence responses for the majority of new dyes are rather high (Table 2). Fluorescence quantum yields (Φ) and λ_{em} are modestly influenced by the solvent polarity (Table S2). In the exemplary case of **2**, Φ changes from 56% in toluene to 28% in methanol (Table 3). This outcome is due to their moderately polarized electronic structure.

Table 3. Optical properties of **2** in various solvents.

Solvent	λ_{abs} [nm]	λ_{em} [nm]	ΔS [cm^{-1}]	Φ^a, %
hexane	566	581	500	-
toluene	573	599	800	56
DCM	570	601	900	48
ACN	566	603	1100	42
MeOH	565	617	1500	28

^{a}Calculated with respect to Rh101 in MeOH.

To rationalize these spectra, we performed additional quantum chemistry calculations for dye **2**, which concurred with experimental data (Figure 2). According to our findings, the second excited S_2 state locates around 7000 cm^{-1} above the S_1, meaning that the lowest excited S_1 state is well separated from the higher located, electronically excited states (Figures 2 and S5, Tables S3-S4). Moreover, the electronic transition $S_0 \rightarrow S_1$ is of the $\pi \rightarrow \pi^*$ character and corresponds to excitation from the HOMO to the LUMO level (Figure 3).

In order to get more information about the reasons for smoothing the fluorescence spectra (lack any well resolved vibrational structure even at 5K) and the possible depopulation channels we simulated the vibrational structure of the fluorescence spectrum of **2** (Figure S5). Calculation of the Franck-Condon (FC) factors (Figure S6) shows that the vibrational structure of the absorption and fluorescence spectra are obscured by the three low frequency vibrations: 37, 59 and 100 cm^{-1}. These vibrations are characterized by high shift parameters[8] and contribute to the spectrum in their common combinations as well as in combination with other vibrations.

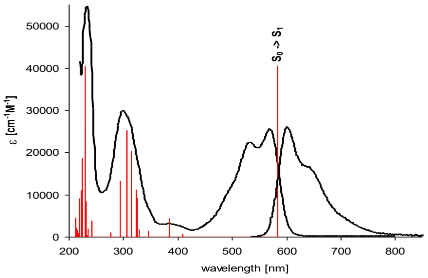

Figure 2. Experimental absorption and fluorescence spectra of **2** in DCM. Calculated transition energies from the ground S_0 to the electronically excited states are given by vertical solid lines with the heights proportional to the oscillator strength of the transition (see Table S3 for the details). Vibronic structure is smoothed by low frequency vibrations (for interpretation see Fig. S6).

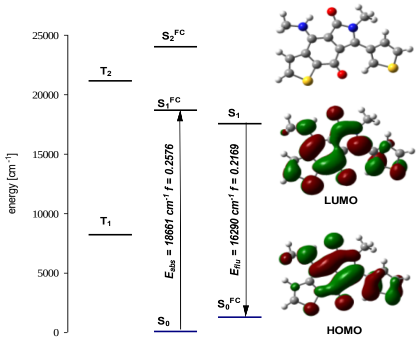

Figure 3. Energy diagram with the transition energies for absorption from the ground S_0 state to the S_1^{FC} and fluorescence from the relaxed S_1 state to S_0^{FC} for 2. On the right - the orbitals HOMO and LUMO of 2. Electronic configuration HOMO→LUMO describes the transition $S_0 \rightarrow S_1$.

To elucidate the influence of the solvent polarity on the absorption and fluorescence spectra, we calculated dipole moments for **2** in the isolated form as well as in solution. The comparison of HOMO and LUMO orbitals clearly depicts the charge shift in the excited S_1 state (Figure 3). This shift causes the increase of the dipole moment (for *ca.* 1.5-2.2 D) and the bathochromic shift of both absorption and emission maxima in the polar solvents (Table S5).

DOI: 10.1039/C7CC07310K

The performed calculations also provide information on the origin of the remaining non-radiative depopulation channel. We found the excited S_1 state is located about 9500 cm^{-1} above the triplet T_1 and 2500 cm^{-1} below the T_2 states. Such an energetic situation precludes efficient intersystem crossing pathway for the $S_1 \rightarrow T_1$ depopulation. Thus, the main non-radiative depopulation channel of the S_1 state should proceed *via* internal conversion. This result concurs with our unsuccessful effort to detect phosphorescence emission at 5 K.

Our calculations also indicate that **2** possesses a planar core with the peripheral thiophene ring rotated around a single bond by around 25° with respect to the molecular plane (Table S4). Thus, new heterocycles are planar, structurally rigid fluorophores, the structure of which does not change substantially upon electronic excitation. As a consequence of the small conformational changes following the transition between S_0 and S_1 states in these compounds (additional computational data in Table S6) the Stokes' shifts are small.

To verify the potential use of discovered dyes for optoelectronic applications we performed a series of cyclic voltammetry (CV) measurements, which depict the influence of structural changes on their susceptibility towards oxidation and reduction. In the majority of cases, the investigated molecules show reversible reduction and quasi-reversible oxidation waves (Table 4, Figure S5). The exception to the rule is observed only for **10** (irreversible oxidation). It is noteworthy that no changes were perceived with increasing number of redox cycles and the direction of the CV-measurement.

Table 4. Redox potentials of the dyes **2**, **4**, **6**, **8**, **10**, **14** and **16** measured in dichloromethane.^{a}

Dye	E_{ox}^{pa}, V	IP, eV	$E_{red}1/2$, V	E_{red}^{onset}, V	EA, eV
2	0.90	-5.1	-1.10	-1.02	-3.3
4	0.96	-5.1	-1.15	-1.06	-3.3
6	0.86	-5.1	-1.17	-1.07	-3.3
8	0.92	-5.1	-1.15	-1.03	-3.3
10	0.94	-5.2	-1.20b	-1.05	-3.3
14	0.89	-5.1	-0.93	-0.81	-3.5
16	0.80	-5.0	-1.28	-1.19	-3.2

^{a}Measurement conditions: electrolyte (NBu_4ClO_4, c= 0.1M); DCM_{dry}, potential sweep rate: 100 mVs^{-1}, working electrode: glassy carbon (GC); auxiliary electrode: Pt wire; reference electrode: Ag/AgCl; all measurements were conducted at room temperature; $^b E_{red}^{pc}$ in V for **10**.

We calculated both ionization potential (IP) and electron affinity (EA) values from the corresponding onset potentials. The results clearly indicate that peripheral substituents, as well as the electronic nature of the aromatic rings participating in the rearrangement, have significant influence neither on the ionic potential (-5.1±0.1 eV) nor on the electron affinity (-3.3±0.2 eV).

Herein, we have introduced structurally unique dyes possessing an isoindolodione core, linearly fused with a thiophene, furan, or benzene ring. We have demonstrated that diketopyrrolopyrroles possessing moderately electron-rich aryl substituents undergo heretofore unknown rearrangements initiated by mild Lewis acids. Strong emission of red light combined with straightforward synthesis, relatively small molecular mass, and potential chemical reactivity may open doors for these dyes in applications in fluorescence microscopy (bioimaging).

The financial support of the Polish National Science Centre (MAESTRO-2012/06/A/ST5/00216), Foundation for Polish Science and and by the Global Research Laboratory Program (2014K1A1A2064569) through the National Research Foundation (NRF) funded by the Ministry of Science, ICT & Future Planning (Korea) is cordially acknowledged.

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